Advancements in combi heat pumps with thermal storage - a cornerstone solution for equitable and efficient grid-interactive electrification in cold climates

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ABSTRACT

As we continue to decarbonize buildings and our electricity supply, it is critical to advance electric heating, cooling, and hot water systems with thermal storage to enable demand flexibility. It is equally important that these solutions streamline retrofits and prioritize affordability to ensure an equitable energy transition. In this paper we compare various strategies to use heat pumps with thermal storage; and we discuss their unique advantages and disadvantages. We explore one system type in greater detail – a modular "combi" air-to-water heat pump with phase change thermal storage. A "combi" heat pump – a.k.a. "multi-function", or "combo" heat pump – uses a single heat pump to provide heating, cooling, and domestic hot water. We document the design of this system as installed for a pilot evaluation, and we explore its benefits thoroughly through building energy simulations, and through a cost and feasibility assessment. We explain how this technology addresses many of the pain points and limitations with current heat pumps, especially in multifamily buildings; and we articulate a vision for how this technology can better enable electrification and grid interactive control for all residential end uses. Through these investigations we show how the technology – compared to typical heat pump retrofits – can: 1) lower required heat pump capacity, 2) decrease number and footprint of equipment, 3) reduce maximum electricity demand, 4) lessen the number of electrical circuits, 5) minimize consumption during peak pricing periods, 6) avoid the need for supplemental heat, 7) reduce the use of refrigerant, 8) shorten distribution piping, 9) improve resilience, 10) extend cold climate performance, 11) lower embodied greenhouse gas emissions, 12) simplify system installation, and 13) consolidate trades to expedite retrofits.

Introduction

Buildings are responsible for approximately 40% of global greenhouse gas emissions, with the residential sector accounting for about 25% of this total. The three largest end uses within buildings are space heating, cooling, and hot water, which collectively account for approximately 60% of onsite energy consumption. Among these end uses, 70% of greenhouse gas emissions are associated with onsite combustion (IPCC 2023, IEA 2019). In the United States, electrification of heating and hot water promises to reduce the 100 year global warming potential from the residential sector by 44-60% (Pistochini 2022), which would reduce national greenhouse gas emissions by 5%–9%. There is large variability associated with local climate, building efficiency, equipment efficiency, and electric grid characteristics such as emissions factors and the future adoption of renewable energy. For example, Wilson et al. find that adoption of standard efficiency heat pumps would currently reduce energy bills in 59% of households, but savings could be had for 81% of households with simultaneous envelope improvements, or 95% of households with adoption of higher efficiency heat pumps (Wilson 2024).

However, a broad transition to heat pumps for heating and hot water will increase electricity demand with patterns that may not align with the availability of renewable energy (Buonocore et al., 2021). Also, research indicates that the increased electricity end uses may: 1) increase regional peak electricity demands, 2) increase wholesale electricity prices and price variability, and 3) require costly upgrades for transmission and distribution systems (Cooper et al., 2016; Liu et al., 2016; Deetjen et al., 2019; Vaishnav et al., 2020; Bolin et al., 2022; Liang et al., 2022). These concerns will likely be most acute in cold climates (Mai et al., 2018; Satchwell et al., 2021).

Therefore, as we continue to decarbonize buildings and the electricity supply it is critical to also advance energy storage. There are many types of energy storage, and they can be applied at various scales. Located in coordination with renewable generators, energy storage can buffer the intermittency of generator output, help to reduce curtailment, and optimize the wholesale market value of electricity generated. Although these benefits are essential, grid scale energy storage does not help to address transmission and distribution capacity requirements, which are driven by peak electricity end uses. Distributed energy storage, on the other hand, can transform the patterns of end-use electricity demand, to reduce peaks, reduce distribution system upgrades, reduce energy costs, increase utilization of on-site renewables, reduce greenhouse gas emissions, and enable energy democratization (Mengelkamp et al., 2017; Parra et al., 2017; Proka et al., 2020).

Among distributed energy storage strategies, thermal energy storage offers unique benefits that battery storage does not, and could complement the transition to heat pumps by addressing several tangible barriers to electrification. In particular, thermal energy storage can reduce the design capacity for heat pumps, reduce the need for supplemental heat, reduce building electric service upgrades, reduce electric circuit upgrades, improve building resilience, and reduce the size of distributed battery storage. Retrofit electrification of heating and hot water systems is complex, and is currently not accessible for many households, even if it would be cost effective in the long term. Some of the challenges for retrofit electrification include, available space for split heat pumps, and unitary heat pump water heating equipment, electric panel upgrades, electric circuit installation, remaining lifetime for existing equipment, complexity of retrofit installation for refrigerant distribution systems, controls integrability with existing systems, needs for auxiliary heating systems, and first cost affordability.

In this paper we describe and compare four leading conceptual design strategies for integrating heat pumps and thermal energy storage. Then, we present the detailed design for one of the four strategies – a combi air-to-water heat pump with phase change thermal storage – installed as a pilot demonstration in a residence in a cold climate. We address various design decisions for the pilot system, and highlight the particular benefits of this approach compared to other strategies. Following documentation of the pilot installation, we describe an emerging approach to apply the system type for multifamily electrification. We present performance characteristics for one air-to-water heat pump studied, and we explain design and control considerations that impact system performance. Then, we present results from a building energy simulation study that compared the performance of this system design to that of typical multi-split heat pumps in a multifamily building in a cold climate. Finally, we present a cost and feasibility assessment, that uses the design characteristic from energy modeling, together with cost data from recently completed multifamily electrification projects using typical heat pump systems, to quantify the potential first cost advantages of the proposed system type compared to typical strategies for heat pump retrofits in multifamily buildings.

Alternate strategies for heat pumps with thermal storage

There are many approaches to integrate heat pumps and thermal energy storage, each with unique advantages and challenges. While only a few commercially available products exist in this technology space, more stakeholders are becoming aware of how thermal storage can complement heat pumps and address barriers to heat pump adoption, and the market appears to be evolving quickly. Figure 1 illustrates four system types as they would be applied to provide heating, cooling, and domestic hot water in a single family home. The four system types represent solutions with TRL 5-9, and our assessment of the specific benefits of each system type is based on a combination of measured performance from pilots, and expert engineering judgment about technical implications of such a system design.

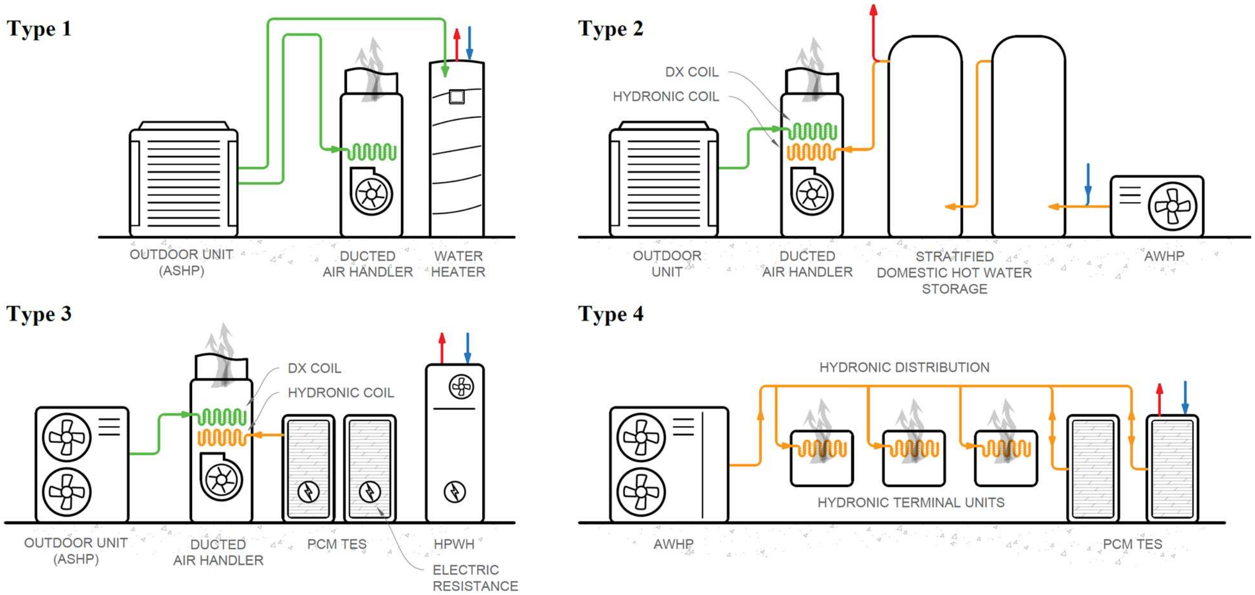

Figure 1. Single-line cartoon schematics of four alternate strategies for heat pumps with thermal storage. (Green = refrigerant distribution, orange = hydronic distribution, blue = potable water inlet, red = domestic hot water outlet).

Type 1

The Type 1 system is a combi (multi-function) split unitary air source heat pump that provides heating, cooling, and domestic hot water. The system arrangement offers a very direct replacement for the most common residential mechanical systems type – a split unitary ducted air conditioner with furnace, and a unitary tank water heater. It includes three main modules: an outdoor unit for the air source heat pump, an indoor air handler, and a domestic water heater. The system includes two separate refrigerant line sets: one between the outdoor unit and the air handler, and one between the outdoor unit and the domestic water heater. The air handler is a direct replacement for common air handlers and can be installed with existing ductwork, provided it can accommodate airflow rates needed to meet peak heating load requirements with lower supply air temperatures.

The system operates in four distinct modes: (1) space heating, (2) space cooling, (3) domestic water heating, and (4) simultaneous cooling and domestic water heating (cooling heat recovery). Heat recovery from cooling is a distinct advantage for this system type. The thermal storage is a water heating tank, it comprises a closed reservoir of water with two interweaved heat exchanger coils – one containing refrigerant, and one containing domestic water (these coils are not illustrated in the cartoon schematic). The system utilizes an atmospheric pressure tank, and adapts readily available standard efficiency single speed heat pump equipment, strategies that promise to make this technology cost competitive. Notably, the combi approach overcomes many of the challenges with unitary tank heat pump water heaters, including that it avoids indoor noise, does not require additional electrical circuit for water heating, avoids the need for condensate management, does not result in local indoor cooling, can operate in enclosed spaces without the need for air flow, and avoids the need for auxiliary electric resistance.

Currently, the electric demand flexibility capabilities for this system are limited to thermal storage for domestic hot water – the system cannot shift the time of use for space heating or cooling. Future iterations could incorporate a heat recovery type heat pump and larger capacity thermal storage to enable demand flexibility for space heating. In a recent paper, Casillas et al. present methods for sizing thermal storage to achieve different demand flexibility targets (Casillas 2024).

Type 2

The Type 2 technology uses a CO_2 air-to-water heat pump (AWHP) to provide both space- and water-heating – a major advancement for CO_2 HPs which have largely been limited to domestic water heating. The technology uses an air-to-water CO_2 HP, incorporates thermal storage to enable demand flexibility for both space- and water heating, and has demonstrated the ability to reduce energy costs and GHG emissions for heating and domestic hot water by shifting HP operation to the cheapest and cleanest times of the day (Singla 2023). The Type 2 technology includes heat exchanger design, control hardware and a system control strategy that ensures low return water temperatures from space heating – this is the critical advancement that makes it possible for the CO_2 HP to provide both space heating and domestic hot water. The technology also includes a hydronic coil that integrates with off-the-shelf residential air handlers, enabling the direct replacement of gas furnaces; this also facilitates integration with common split unitary air conditioners to provide cooling (as illustrated in Figure 1). The thermal storage for the Type 2 system comprises one or more stratified hot water tanks which are used for domestic hot water and space heating. With this system type the heat pump can be significantly smaller than the design space heating load, as the CO_2 heat pump can be sized for the 24-hour average space heating requirement, and thermal storage can output larger heating rates to meet peak space heating loads and domestic hot water demands. If the Type 2 system is paired with a split-unitary heat pump instead of an air conditioner, the combined system can provide cooling, and the two heat pumps can work in cooperation. This can optimize efficiency, extend cold climate heating capability, reduce total combined heat pump capacity, and increase the depth of demand flexibility.

The Type 2 system uses domestic water as the thermal storage medium, as the heat transfer fluid flowing through the CO_2 heat pump and the air handler. This system can integrate with a variety of space heating equipment, including ducted air handlers, ductless fan coils, and radiant floors; however the control of thermal distribution and space heating terminals is critical to ensure low return water temperatures as the CO_2 heat pump heats water to ~150°F in a single pass through the heat exchanger, and performs most efficiently when return water is <80°F (Brodal 2019).

Installed pilots of this system have demonstrated seasonal average COP = 3 for heating and hot water in mild climates, and modeling anticipates COP=2.5 in colder climates (Singla 2023, Sanden 2017). One disadvantage of this system is space, as the multiple stratified hot water storage tanks are substantially larger than a unitary tank heat pump water heater, and because the approach requires two separate outdoor units – a CO_2 heat pump and a unitary air conditioner or heat pump.

Type 3

The Type 3 system design uses a split-unitary air-source heat pump to deliver space heating and cooling, and is coordinated with a phase change material thermal energy storage system that uses low power electric resistance as the heat input. The heat pump uses refrigerant distribution between the outdoor unit and the air handler, and a hydronic coil is added to the air handler to facilitate heat output from the thermal storage.

The phase change material is heated using low power electric resistance, which is controlled to charge thermal storage when electricity is clean and inexpensive. Phase change material can have much higher energy storage density than hot water, reducing the space required for storage by 40-80%, depending on application (Lizana 2017).

Under typical scenarios, the heat pump operates to satisfy space heating loads directly when electricity is clean and lower cost, then the heat pump is disabled during periods with higher prices and heat is extracted from the phase change material. This system type can also use thermal storage to provide supplemental heat in scenarios when the heat pump is not able to satisfy heating loads. Engineering design indicates that this would avoid the need for auxiliary electric resistance heat, which in turn would reduce electric circuit needs, and reduce site peak electric demand. Since the heat pump would not need to satisfy the entire heating load during the coldest hours of the year, the heat pump could be smaller, which would improve overall heat pump efficiency by enabling more continuous operation in part load conditions (a big heat pump has to cycle inefficiently whenever load is smaller than capacity at minimum speed). Another benefit is that this strategy could enable complete electrification in scenarios where fossil fuel heating systems might otherwise be used during the coldest periods.

One disadvantage of the Type 3 system is that it doesn’t use the heat pump for domestic hot water, and it doesn’t enable demand flexibility for hot water. In Figure 1, the Type 3 system is illustrated in combination with a unitary heat pump water heater. Another potential disadvantage is that electric resistance is used as the heat input to thermal storage, so stored energy does not benefit from heat pump efficiencies. This efficiency tradeoff may be worthwhile when electricity price variation justifies arbitrage, or because the system simplicity may offer first cost advantages.

The Type 3 technology also incorporates one notably unique strategy that allows the phase change material to “supercool” to room temperature without crystallization, then to initiate crystallization on demand to bring the thermal store back to a high temperature when heating is needed (Desgrosseilliers 2017). This approach allows the system to retain a high state of charge for several days without significant thermal losses, which is especially useful in applications where the most optimal charge and discharge windows may be separated by multiple days, or in shoulder seasons when space heating needs are sporadic and the standby losses from maintaining a high state of charge for thermal storage at all times would penalize round trip efficiency.

Although the Type 3 system targets integration with split-unitary heat pumps with ducted air handlers, a variation on this system type could use the electric resistance heated phase change thermal storage to replace combustion boilers for homes with radiators, baseboard convectors, or other hydronic heating elements.

Type 4

The Type 4 system uses a modular air-to-water heat pump to provide heating, cooling, and domestic hot water from a single machine. This design strategy uses the heat pump to charge thermal storage, and the heat pump can incorporate an appropriately sized electric resistance component to provide supplemental heat if it is needed. This system type can use either water or phase change material as thermal storage – Figure 1 depicts phase change material. The thermal storage in this system is used for domestic hot water, and can enable demand flexibility for both space- and water heating. Design adaptations can allow storage for cooling. Space heating and cooling are provided through hydronic distribution and can integrate with a variety of different terminal devices, including ductless fan coil units, radiant floors and ceilings, ducted air handlers, baseboard convectors, and radiators.

This approach offers a number of advantages compared to the other system types, and thus was selected as the focus for pilot installation, for a simulation study, and for a cost and feasibility assessment. To begin with, the air-to-water heat pump contains all refrigerant in a factory-charged circuit; this requires much less refrigerant than a split heat pump with comparable capacity, greatly reduces the possibility of refrigerant leaks, and offers a safer pathway toward adoption of ultra low GWP natural refrigerants – such as R290 (propane, $GWP_{20}<1$) (Smith 2021) – which could pose significant safety concerns (flammability) if used in heat pumps that circulate refrigerant indoors. Considering the reduced refrigerant volume, and the use of moderate GWP refrigerants, we estimate the solution can reduce the potential life cycle greenhouse gas emissions from refrigerant by more than 90% compared to multi-split heat pumps and heat pump water heaters. An application using R290 would practically eliminate these greenhouse gas emissions.

Then, since air-to-water heat pumps use low pressure hydronic distribution, all thermal distribution can be installed using polymer pipe, instead of copper refrigerant line sets used for split heat pumps. In addition to using lower cost piping materials, this strategy also reduces the total length of piping that needs to be installed and insulated. Multi-split systems use a home-run piping configuration with extensive refrigerant line sets run between the outdoor unit and each indoor unit, but hydronic distribution can serve multiple indoor units with a single circulating loop. This challenge is most pernicious in multifamily buildings, where take offs from schematic layouts reveal that the Type 4 solution can reduce piping length by >50%.

Another advantage of the Type 4 solution is that hydronic systems facilitate zone thermostatic control in a way that can improve comfort, reduce heat loads, and increase system efficiency. Multi-split heat pumps also offer ductless zoning, but the smallest heat pump indoor units are larger than most room heating and cooling needs, and the low loads from these systems causes inefficient heat pump cycling. By contrast, the Type 4 solution uses thermal storage to decouple space heating and cooling loads from heat pump capacity, which should allow the heat pump to operate at an optimal speed more consistently.

The flexibility of the Type 4 system also confers the efficiency advantages of various terminal unit technologies, such as by using ductless fan coils to avoid leakage and losses from ductwork, by controlling individual zone temperatures dynamically, or by operating with moderate supply water temperatures to improve heat pump efficiency. In addition to designing emitters to operate at moderate temperature, heat pump efficiency can be further improved by adjusting the leaving water temperature setpoint to match the dynamic heating load (i.e.: "outdoor reset").

The Type 4 system utilizes either water or phase change material to store thermal energy generated by the air-to-water heat pump, and can facilitate numerous operation modes such as simultaneously heating the space and thermal storage; extracting heat from thermal storage to supplement heat pump heating; or providing space heating directly from thermal storage without heat pump operation. This system type can provide heating, and domestic hot water without the need for auxiliary electric resistance. However, where appropriate electric resistance can be included to increase the storage heating rate when electricity is inexpensive or clean, to enable heat pump downsizing, or by providing supplemental heat for the coldest days.

Notably, of all of the options described, Type 4 is the only system that is appropriate for integration with existing hydronic heating systems, to replace boilers that serve baseboard convectors, radiators, or radiant systems. At the same time, it is also the most flexible approach. This type of air-to-water heat pump system is modular, so several variable speed heat pumps can operate together as a staged central system; this is especially advantageous for multifamily buildings where a central group of modular combi heat pumps can greatly reduce total number of heat pumps and reduce the need for electric circuits compared to typical multi-split heat pump retrofits. As enumerated in the Cost and Feasibility Assessment section, the Type 4 solution enables electrification in multifamily without requiring circuit upgrades within each apartment.

Since this system can use phase change thermal storage, it can also address space constraints - as phase change material can reduce thermal storage volume by 40-80% compared to water as thermal storage (Lizana 2017). The difference depends on the magnitude of the temperature cycle that each storage system can reliably achieve. In regard to space constraints, the Type 4 solution offers a strategy that could have the same footprint as a split heat pump and unitary tank heat pump water heater, yet could store enough heat to provide domestic hot water and heating demand flexibility (Helmns 2022). Moreover, this storage system addresses many of the challenges with unitary tank heat pump water heaters: it eliminates indoor noise, it does not require airflow or ductwork, it does not have a minimum enclosed area beyond the immediate footprint, it does not require an additional electric circuit, and it does not require condensate management.

Moreover, of the four systems described, Type 4 is the only design concept that can feasibly provide thermal storage for both heating and cooling. However, accomplishing storage for cooling with phase change materials would require an additional thermal storage reservoir with a material selected for appropriate cooling temperature.

System design installed for pilot study

The research team designed and installed the Type 4 system with phase change thermal storage to provide heating, cooling and hot water for a single family residence in Massachusetts, at the border between climate zone 5a and climate zone 6a. This effort involved considerable innovation in design for the integrated systems and controls, as it is among the first fully featured functional integrations of an air to water heat pump with phase change thermal storage.

One notable barrier to adoption of air to water heat pumps in the US is their relative complexity, and the burden of bespoke design and install that currently rests on the installing contractor. For this reason, our design of the Type 4 system for the pilot study explored and advanced several strategies intended to package and streamline the design and installation of air to water heat pump systems. In particular, the system design (depicted in Figure 2) used several factory assembled modular subsystems, including: (1) multiport hydronic distribution manifolds with integrated air bleed, balancing valves, and zone valves, (2) pump stations with thermostatic mixing valves, backflow preventers, pressure equalizing valves, and variable flow pumps with self contained control sequences that adjust flow to maintain constant pressure rise in response to changes in circuit flow restriction associated with valve openings, (3) an innovative modular low-loss primary-secondary distribution header with integrated hydraulic separator, that simplifies the field piping and consolidates several necessary components, and (4) other integrated multi-purpose components such a fill-drain-purge valves, and combined air bleed, air separator, and strainer.

Another notable innovation in this work is the use of a low-voltage DC power system, and wireless communicating controls, for all valves, and ductless fan coil units. Instead of installing new 120v or 240v circuits to power indoor equipment, the system uses a single daisy chained 24vdc cable to power these components. Although we were not able to source 24vdc pumps for this project, we anticipate that future system design iterations will only require a single 240v circuit to power the heat pump.

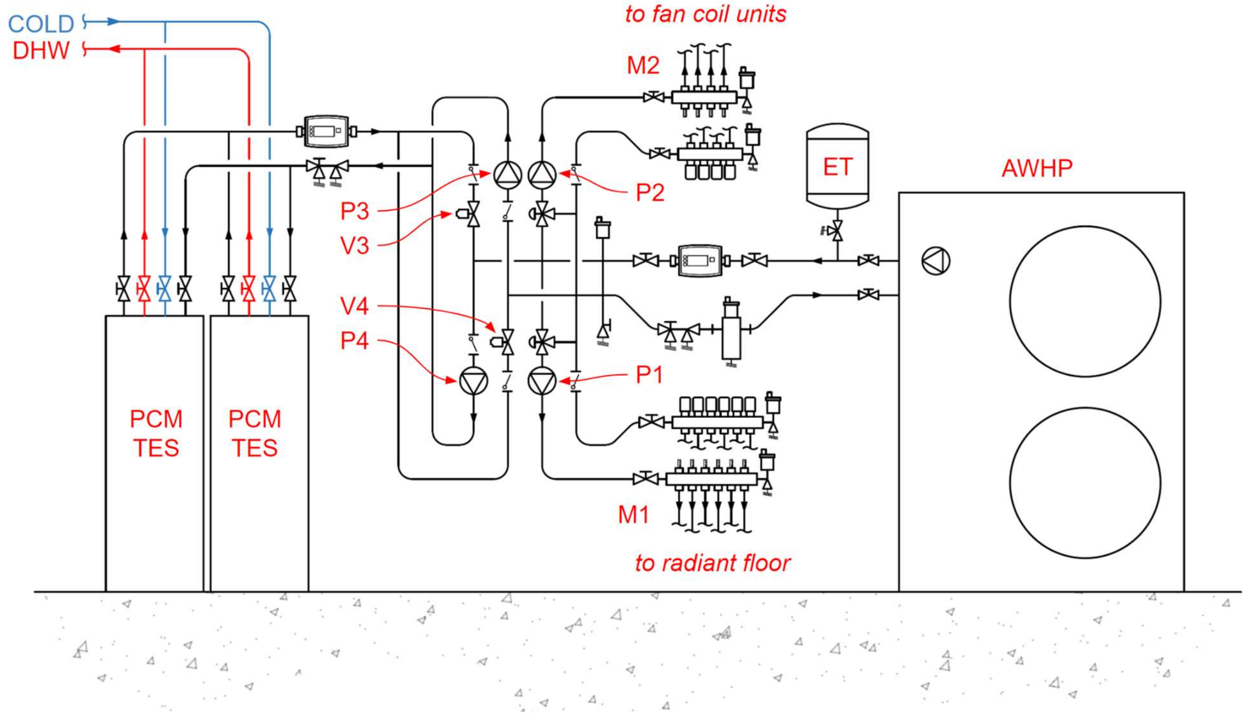

Figure 2: Schematic of Type 4 system as installed for pilot study

The design installed (illustrated in Figure 2), comprises a single closed-loop hydronic volume (with no makeup water connection), one primary-secondary distribution header, four hydraulically separated pumped circuits, one manifold serving six radiant floor loops divided into three controlled thermal zones, and a second manifold serving two ductless fan coil units connected with a home-run piping arrangement and controlled as separate thermal zones.

When the thermostat for any radiant zone on manifold M1 requests heating, the control system dispatches a wireless signal to enable pump P1 and to open the associated zone valve on the manifold; then, the pump adjusts speed to maintain a differential pressure setpoint. Similarly, when the thermostat for either fan coil unit on manifold M2 requests heating, or cooling, the control system dispatches a wireless control signal to enable pump P2 and to open the associated zone valve on the manifold; then, the pump adjusts speed to maintain a differential pressure setpoint. The pump stations for both circuit 1 and circuit 2 include thermostatic mixing valves which allow the system to maintain a secondary loop supply temperature that is different from the primary loop supply temperature. This feature is important so that the heat pump can operate at a temperature that is high enough to charge the phase change thermal storage, while the water distributed to terminal units for space heating can be lower.

The phase change thermal storage system nominally stores 24 kWh of thermal energy, and its state of charge is estimated by a group of internal temperature measurements. When the state of charge drops below a setpoint, and it is otherwise appropriate to charge the thermal storage, the control system dispatches a wireless signal to enable pump P4 and to open valve V4. When it is appropriate to extract heat from thermal storage, our control system dispatches a wireless signal to enable pump P3 and open valve V3.

Figure 3: Photos of Type 4 system installed for pilot study in Massachusetts (CZ 5a/6a)

Air to water heat pump capacity and efficiency

Figure 4 illustrates the heating capacity and COP characteristics for a variable capacity air-to-water heat pump, revealing the relationships between these performance metrics, outdoor temperature, and controlled operating parameters. For any given outdoor temperature, the heat pump can coordinate control of compressor speed, expansion valve position, circulating pump speed (and other controlled subcomponents) to target a desired leaving water temperature and a desired heating capacity. The plots in Figure 4 shows manufacturer commissioned laboratory measurement of heating capacity and COP for three different leaving-water temperatures, and two different compressor speeds. The data captures a limited range of operating conditions, and does not describe the extreme limits; the heat pump is capable of heating when outdoor temperature is as low as –25°C, and can heat water to 65°C. For a given outdoor temperature and heating load, the heat pump can generate desired heating rate at a range of leaving water temperatures, but the choice of leaving water temperature setpoint has major consequences for system efficiency, especially at part load. At 0°C outdoor temperature, operation with 35°C leaving water temperature has 20% higher capacity at minimum compressor speed than operation with 55°C leaving water temperature, and COP doubles from 2.2 to 4.4. In view of this relationship, substantial energy savings can be achieved through whole system design and control to facilitate heat pump operation at moderate leaving-water temperatures. In regard to physical systems, this entails the selection of heat emitters that can deliver sufficient space heating at design load conditions with moderate water temperatures. In regard to control, this involves avoiding excessively high heating water temperatures by adjusting the leaving water temperature throughout the season (i.e.: "outdoor reset") so that heat emitters can just match the heating load. The relationship between leaving water temperature and efficiency is also important for integration with thermal storage systems. If directing heat to a thermal store requires the heat pump to generate a more extreme leaving-water temperature than would be required to satisfy heating loads directly, the choice of whether or not to store energy must account for the efficiency penalty associated with increased leaving-water temperature – in addition to the round trip losses associated with storage.

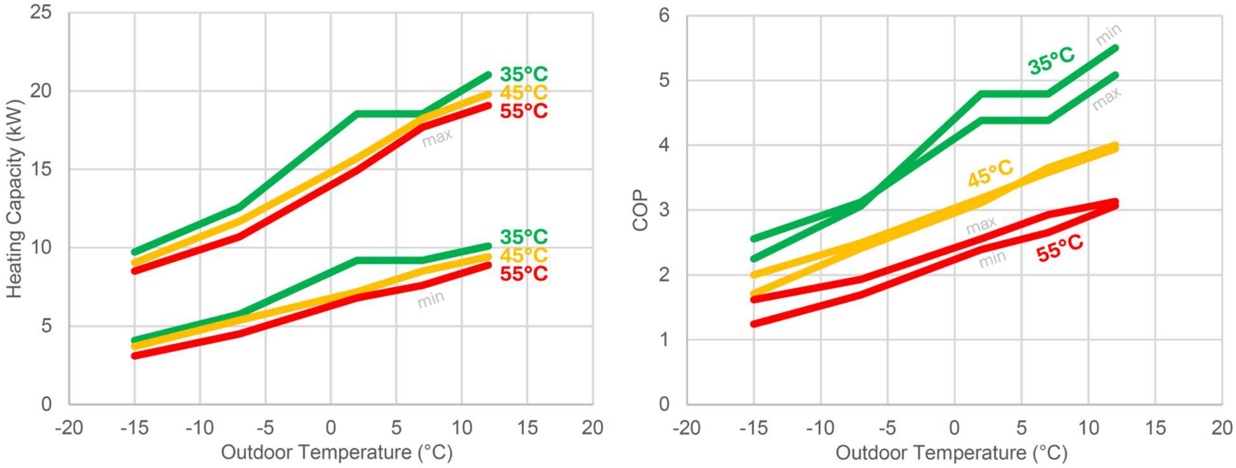

Figure 4. (left) Heating capacity and (right) COP for an air-to-water heat pump at minimum and maximum compressor speeds, and at three different leaving water temperatures (35°C, 45°C, 55°C), across a range of outdoor temperature conditions (–15°C to 12°C).

Simulation in multifamily building

To quantify the benefits of the combi air-to-water heat pump with thermal storage in multifamily buildings, we conducted building energy simulations for a 4-floor 8-apartment multifamily building in Brooklyn, NY – IECC Climate Zone 5A with ASHRAE 99.6% heating design condition 13.1°F (–10.5°C). The building and system models were developed using EnergyPlus and Modelica. Specifically, Modelica was used to develop a detailed model of the equipment and controls for a modular group of combi air-to-water heat pump systems with thermal storage - similar to Helms et. al. (2021). EnergyPlus was used to develop the building model, and to represent the baseline electrification strategy – a variable capacity multi-split heat pump for each apartment - using models developed and validated by Hong et. al. (2016). The baseline multi-split heat pump aligns with the listed performance of products that just meet NEEPs Cold Climate Air Source Heat Pump Specification (NEEP 2024). These simulations focused mainly on equipment efficiency, and used only a moderate amount of thermal storage (40 gal) for the air-to-water heat pump system to effectively decouple heat pump output from dynamic space heating loads in order to avoid cycling inefficiencies at low load.

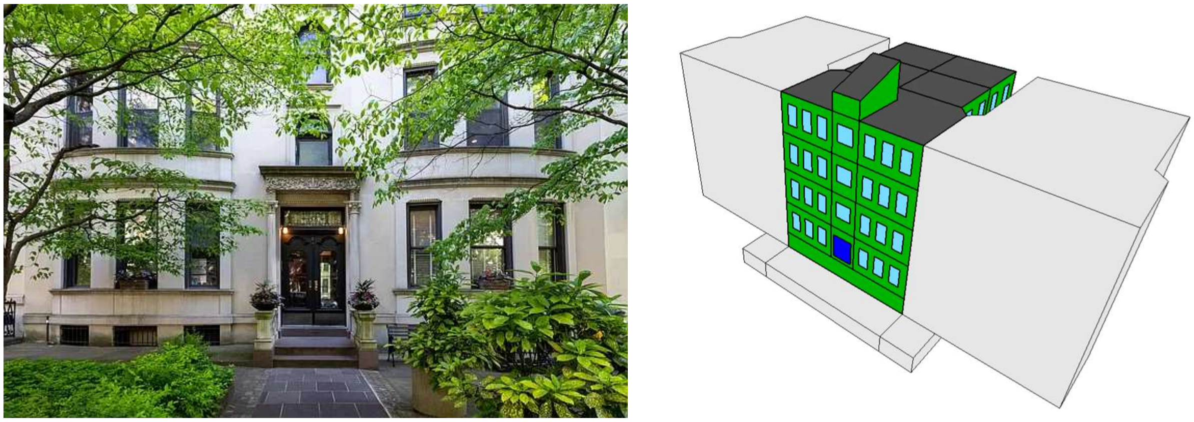

Figure 5. (left) Multifamily building in Park Slope Brooklyn, and (right) representation in EnergyPlus model

The simulations provided insight into the relationship between space heating loads and outdoor temperature, and the way that the heating load distribution corresponds with the dynamic performance for the different heat pump strategies. Figure 6 shows how the hourly heating load for the two fourth-floor apartments changes in relation to the outdoor temperature, and also shows the annual distribution of cumulative heating load across outdoor conditions. These plots reveal that while the heat pumps must be sized to satisfy heating load at –10°F, the majority of heating occurs above 0°C, where the heating load is below the continuous low speed capacity for the baseline multi-split heat pumps.

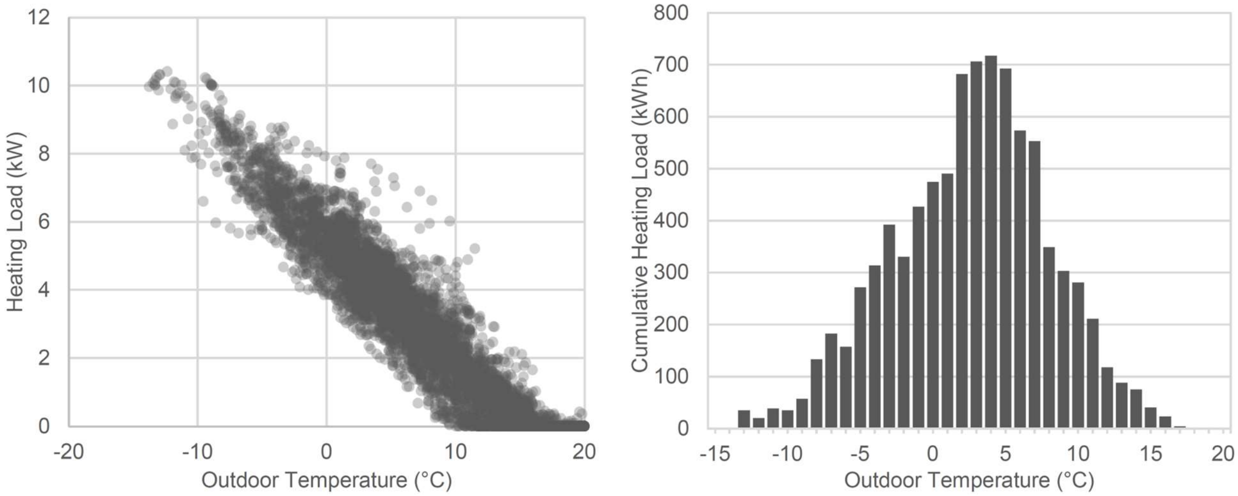

Figure 6. (left) Annual hourly heating loads as a function of outdoor temperature, and (right) annual cumulative heating load distribution in relation to outdoor temperature.

Figure 7 (left) compares heat pump COP for the two strategies across a 20 day period in the heating season, and reveals that except in the coldest conditions the air-to-water heat pump with thermal storage could achieve substantially higher COP than the baseline multi-split heat pump. At the coldest full load conditions, the air to water heat pump has moderately better COP than the multi-split heat pump. There are two main factors that contribute to this difference. The first is that the air-to-water heat pump leaving-water temperature is adjusted dynamically in relation to the outdoor air temperature – “outdoor reset” – which improves heat pump efficiency by operating more time with a moderate supply water temperature. This relationship was illustrated in Figure 4. The second factor is that above 0°C, the space heating load is below the continuous low speed limit for the mutli-split heat pump, and so it must cycle, which erodes the potential efficiency gains that could be had if it were able to operate continuously at part speed.

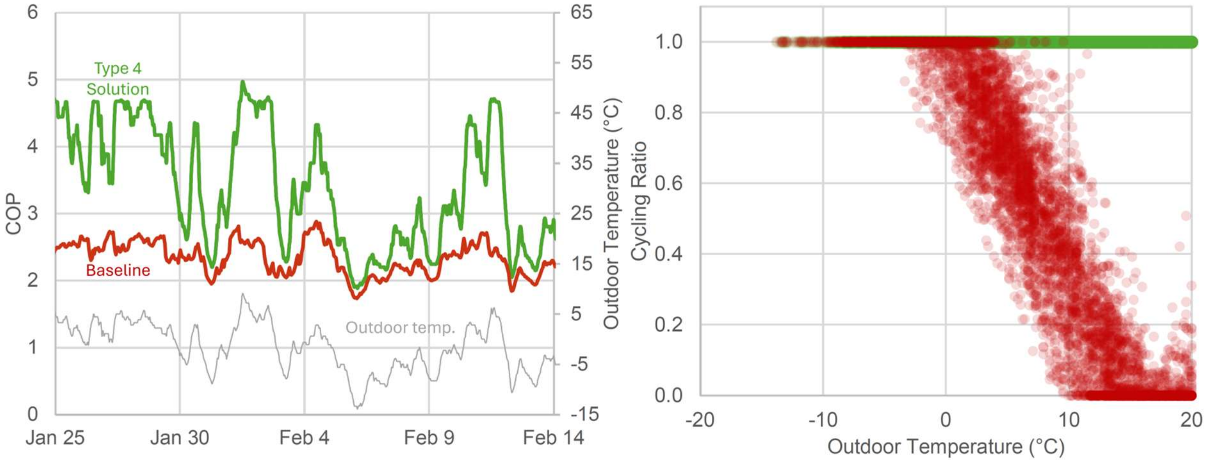

Figure 7. (left) COP for the baseline heat pump, and for the Type 4 solution for 20 days in the heating season; and (right) hourly cycling ratio for the baseline heat pump, and for the Type 4 solution plotted against outdoor temperature for all heating hours.

Figure 7 shows the hourly cycling ratio for the two strategies - the cycling ratio describes the fraction of time that the heat pump must be on in an hour, at the minimum speed, to deliver enough heat to satisfy the load. When the cycling ratio is less than one, efficiency is lower than it would be at continuous minimum speed, and the greatest efficiency penalties are when cycling ratio is <0.5. As illustrated, the air-to-water heat pump strategy does not suffer this efficiency penalty at low loads, because the buffer tank allows the heat pump to operate with a cycle frequency, compressor speed, and on-state duration that minimizes part load cycling losses.

Cost and feasibility assessment for multifamily buildings

In this section we present a detailed evaluation of the estimated cost savings that could be achieved by using the Type 4 multi-function air-to-water heat pump with thermal storage in multifamily buildings, compared to using typical multi-split heat pumps and heat pump water heaters. We present two cost assessments. The first assessment focuses squarely on how the solution could reduce costs by reducing overall electric circuit upgrade requirements, and by avoiding electrical work within each apartment. The second assessment considers the total upfront costs estimated for all aspects of the system, compares this to the total upfront costs for typical heat pumps and heat pump water heaters; and projects the cost estimates for each strategy within the scope and budget of a large multifamily decarbonization project. For both assessments, the analysis draws from construction cost data from actual multifamily decarbonization projects recently completed in the Pacific Northwest.

Cost Assessment #1 - cost savings related to avoided electrical upgrades

For this cost assessment, we built upon insights gained from building energy modeling of the system in a 4-floor, 8-apartment multifamily building in Brooklyn, NY. We used these models to size and select specific heat pump equipment, to develop electrical circuit layouts, to define circuit ampacity requirements, then we used the resulting design details to guide detailed cost estimates. The Type 4 solution uses modular heat pumps to provide heating, cooling, and domestic hot water for groups of apartments in a multifamily building. The size and number of air-to-water heat pumps needed depends on climate and building characteristics; in Climate Zone 4, each air-to-water heat pump could replace 4–6 multi-split heat pumps and 4–6 heat pump water heaters, while in Climate Zone 5 each air-to-water would satisfy 2–4 apartments. Since the Type 4 system uses low voltage power distribution between the indoor controller and the fan coil units, it does not require the addition of circuits in each apartment. The heat pumps are powered from the building service, avoiding the need for electrical work inside each apartment and reducing overall electrical infrastructure requirements. This strategy also circumvents the need to upgrade electrical panels, electric meters, and service raceways throughout a building.

Older multifamily buildings often lack robust individual apartment panels, and addition of new circuits within apartments often triggers a cascade of electrical upgrade requirements, including apartment service entrances and electric meters, which can sometimes necessitate upgrades to the property's main electrical service. Even in small multifamily buildings, upgrading individual apartment subpanels, service entrance raceways, and metering infrastructure can exceed $100k. Any electrical work inside apartments is likely to trigger code-required upgrades if subpanels are not already rated for 100A service.

It is also important to underline that the extensive rework triggered by electrification most often requires vacating buildings for extended periods. One of the real electrification projects guiding the cost estimates in this section vacated a 208-apartment complex for 18 months. Not only is this disruptive to hundreds of families, but upon return, residents are often faced with increased rents.

Table 1 – Comparison of electrical upgrade costs for the Type 4 system, and for baseline heat pump systems

	Baseline Approach	**Type 4 Solution**
Electrical work inside each apartment (8 apts.)	$56,000	-
240 V 30A circuit for heat pump water heater *(each apt.)*	$1,000	-
240 V 25A circuit for multi-split (OUs and IUs) *(each apt.)*	$3,000	-
Panel upgrade from 60A to 100A *(each apt.)*	$3,000	-
Electrical work not inside apartments	$100,000	$10,000
Meter and service entrance upgrades[A]	$100,000	-
(2x) 240 V 60A circuits for AWHPs	-	$10,000
Total:	**$156,000**	**$10,000**

Table Notes:

A. *Increasing apartment subpanel capacity requires upgrade to the apartment service entrance wiring and apartment meter, which triggers code requirements for meter grouping. For a small multifamily building, the cost of these upgrades can exceed $100,000. The Type 4 solution avoids the need for apartment subpanel upgrades*

Cost assessment #2 - Type 4 system as part of a whole building electrification project

In view of the tangible challenges associated with heat pump retrofits in multifamily buildings, we conducted an assessment to estimate the total upfront costs of the Type 4 system compared to typical heat pumps and heat pump water heaters within the scope and budget of a large multifamily decarbonization project. To accomplish this, we interviewed and gathered cost data from building remodelers in the Pacific Northwest with extensive design-build experience in multifamily decarbonization projects. The costs represented are all final marked-up costs to the owner, including minimum wage requirements, design and engineering, project management, equipment and installation, and administrative costs. The baseline costs in this assessment represent the actual costs incurred for electrification of a 186-apartment complex with apartments ranging from 2–4 bedrooms. It includes building upgrades such as envelope improvements, photovoltaics, efficient lighting upgrades, electrification of heating and hot water, and the addition of cooling. The costs also cover equity-focused tenant and community engagement related to grant-funded retrofits for low- to moderate-income multifamily buildings.

The baseline approach includes a heat pump water heater, multi-split heat pump, and efficient bathroom exhaust ventilation for every apartment in the complex. Costs are included for two-head multi-split heat pumps in smaller two-bedroom apartments and five-head multi-split systems in larger apartments and townhomes. These costs come directly from subcontractor bids and include both equipment and installation.

The Type 4 solution includes 80 air to water heat pumps located in groups throughout the property, distributed thermal storage in each apartment, multiple hydronic fan coil units in each apartment, and hydronic distribution infrastructure, electrical circuits, and controls.

Table 2 – Comparison of first costs for the Type 4 system, and for baseline heat pump systems, as alternative solutions in the budget for all energy measures in an actual multifamily electrification project in Portland OR

	Baseline Approach			**Type 4 Solution**		
Measure or activity	**Cost ea.**	**Qty**	**Total**	**Cost ea.**	**Qty**	**Total**
Community meetings & focus groups			$ 162,737			$ 162,737
Resident engagement			$ 149,127			$ 149,127
Utility & air quality data collection			$ 100,000			$ 100,000
Design and engineering			$ 809,600			$ 809,600
Baseline Systems			$ 7.00 M			-
Heat pump water heater *(each apt.)*	$ 10,116	186	$ 1,881,528	-	-	-
Multi-split *(2 indoor units per apt.)*	$ 14,758	28	$ 425,115	-	-	-
Multi-split *(5 indoor units per apt.)*	$ 22,599	158	$ 4,694,194	-	-	-
Bathroom fans	$ 999	186	$ 171,808	-	-	-
Type 4 System			-			$ 3.72 M
AWHP groups on skids	-	-	-	$ 40,000	40	$ 1,600,000
Install (site prep, outdoor piping)	-	-	-	$ 10,000	40	$ 400,000
Electrical	-	-	-	$ 5,000	40	$ 200,000
Indoor TES *(1 per apt.)*	-	-	-	$ 2,000	186	$ 372,000
Install (indoor piping., wiring, controls)	-	-	-	$ 1,000	186	$ 186,000
Fan coil unit *(2-5 per apt.)*	-	-	-	$ 500	846	$ 423,000
Install (indoor piping, wiring, controls)	-	-	-	$ 2,000	186	$ 372,000
Bathroom fans	-	-	-	$ 999	186	$ 171,808
Photovoltaics	$ 3,300	647 kW	$ 2,137,287	$ 3,300	647 kW	$ 2,137,287
Roof replacement	$ 1,143	2022	$ 2,311,499	$ 1,143	2022	$ 2,311,499
LED lighting	$ 216	186	$ 43,888	$ 216	186	$ 43,888
		Total: $	**12.71 M**		**Total: $**	**9.44 M**
					Savings:	**$3.28 M**

While the budget includes the installation of new electrical circuits in each apartment, it does not include costs for upgrading apartment electrical panels, service entrances, and meter infrastructure because the building already had panels that could accommodate the additional circuits required for multi-split heat pumps and heat pump water heaters. For this 186 apartment complex, avoided electrical infrastructure upgrades discussed in Cost Assessment #1 could represent an additional $1M cost compression.

Finally, these cost estimates project reasonable forward-looking opportunities for air-to-water system cost compression, benefiting from modularity, off site fabrication, and vertical integration offered by emerging air-to-water providers. For instance, we project $500 per fan coil unit, which is somewhat lower than current retail costs, but represents a realistic cost for a vertically integrated provider selling equipment at near-wholesale prices.

Conclusions

The integration of heat pumps and thermal storage offers a strategic path to advance equitable and efficient grid-interactive electrification. There are a diverse array of emerging technology solutions in this space, and although they all target similar overall goals, each has unique advantages and disadvantages. This paper reviews the technical design and capabilities for four system types, highlighting their potential to improve energy efficiency, reduce cost, reduce greenhouse gas emissions, and streamline retrofits in residential applications. Among these, the Type 4 system – a modular multi-function air-to-water heat pump with distributed thermal storage – stood out for its compelling benefits, and was selected as the focus for pilot installation, a building energy simulation study, and a cost and feasibility assessment.

Our investigations reveal several advantages of the Type 4 system compared to incumbent heat pump technologies particularly for multifamily buildings in cold climates:

- *Responsible refrigerant use.* The system contains all refrigerant within a factory-charged outdoor unit, avoiding indoor refrigerant distribution, greatly reducing the potential for leaks, and reducing the potential life cycle emissions from refrigerant by more than 90% compared to multi-split heat pumps and heat pump water heaters.
- *Simplified installation.* Compared to multi-split heat pumps, the system design reduces the length of piping and insulation by more than 50%, and allows use of polymer pipes instead of copper pipes, which are less expensive and easier to install.
- *Reduced electrical upgrades.* Grouping modular heat pumps and consolidating heating, cooling, and hot water into a multi-function system reduces the number and complexity of new electrical circuits. Low voltage direct current power distribution to terminal units simplifies electrical work. For multifamily retrofits, the system eliminates the need for electric panel upgrades within each apartment, which offers large cost savings.
- *Reduced number and footprint of heat pumps.* The system consolidates multiple functions - heating, cooling, and hot water - into a single modular system, and for multifamily buildings groups heat pumps to serve multiple apartments. Depending on the application and climate, a pair of air-to-water heat pumps could replace the multi-split heat pumps and heat pump water heaters for a group of 4-12 apartments.
- *Energy efficiency:* The system improves heat pump efficiency by dynamically adjusting leaving water temperature based on outdoor conditions, and using moderate temperature emitters. Integrated thermal storage reduces low-load cycling losses, while efficient ductless terminal units reduce fan energy and eliminate duct losses. Additionally, the reduced likelihood of refrigerant leakage ensures long-term equipment efficiency.
- *Compatibility with existing systems*. The combi air-to-water heat pump system integrates flexibly with a variety of terminal devices, including ductless fan coil units, ducted air

handlers, radiant floors, and baseboard convectors, making it suitable for both new construction and retrofits.

- *Demand flexibility:* By integrating thermal storage, the system enables medium duration demand flexibility – for load shifting on the order of hours and days.
- *Space efficiency*: In addition to reducing the number of individual heat pumps, the use of phase change materials for thermal storage reduces the volume required for energy storage by 40-80%, enabling demand flexibility for space- and water-heating within the footprint that would typically be occupied by unitary tank heat pump water heater.
- *Reduces cost of electrification.* The cost feasibility assessment demonstrates the benefits of avoiding electrical panel upgrades, consolidating systems, using lower cost piping materials, and advancing strategic installation methods. Using cost data from a real multifamily decarbonization project in the Pacific Northwest, the assessment shows how this system type could save $3.28 M on a $12.7 M project.

In conclusion, the Type 4 combi air-to-water heat pump system with thermal storage represents a compelling technology for equitable and efficient electrification, especially for multifamily buildings. Its ability to address key barriers, such as system complexity, installation costs, and demand flexibility, positions it as a pivotal solution in the transition to a sustainable and resilient energy future. To advance the scalability of this solution and achieve its technical potential, coordinated efforts are needed to overcome adoption barriers, such as by increasing market awareness, expanding workforce training, and continuing product development to streamline design and installation.

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