The following two papers were prepared for the [2024 Summer Study on Energy Efficiency in Buildings](). Skim these to get a sense of our lab group's ongoing research. – Prof. Helmns

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.

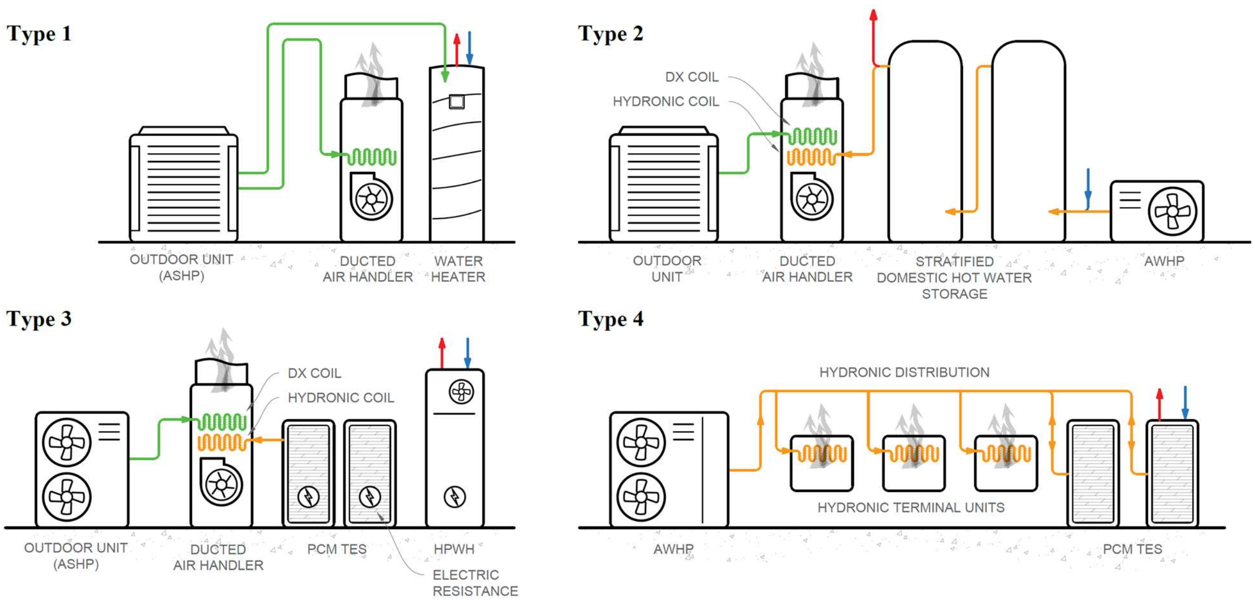

Figure 1. Single-line cartoon schematics of four alternate strategies for heat pumps with thermal storage. (Green = refrigerant distribution, orange = hydronic distribution, blue = potable water inlet, red = domestic hot water outlet).

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.

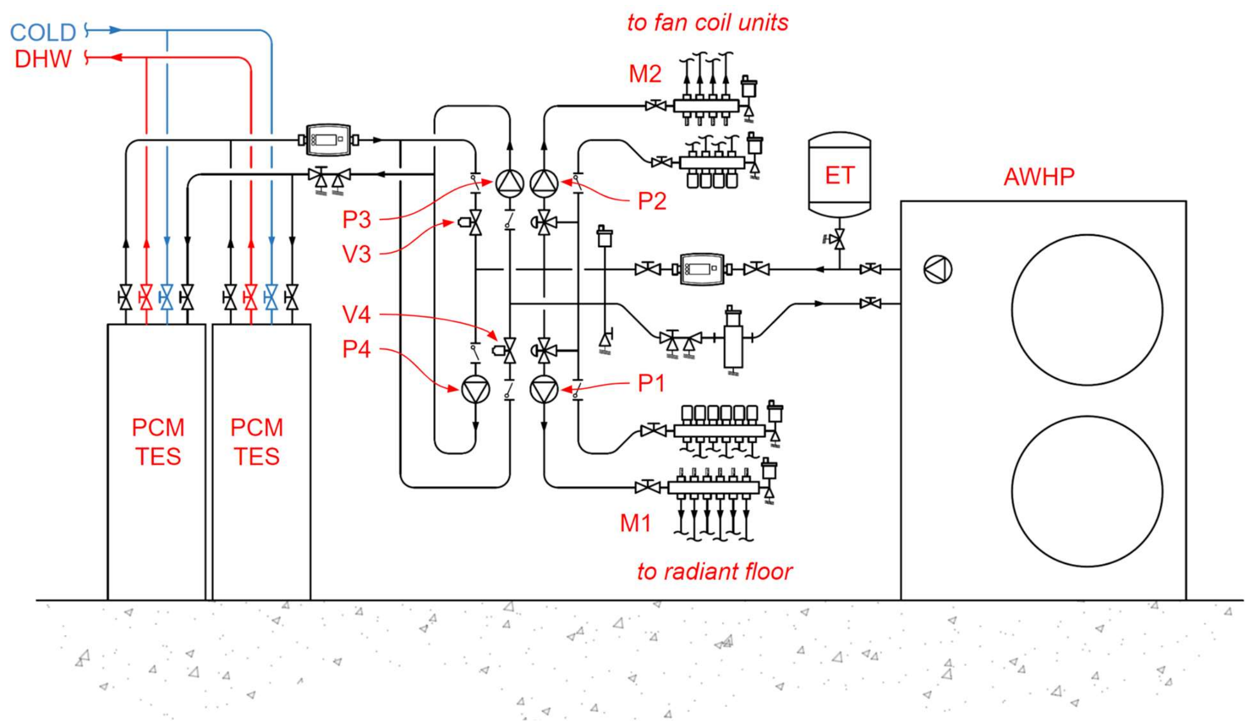

Figure 2: Schematic of Type 4 system as installed for pilot study

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

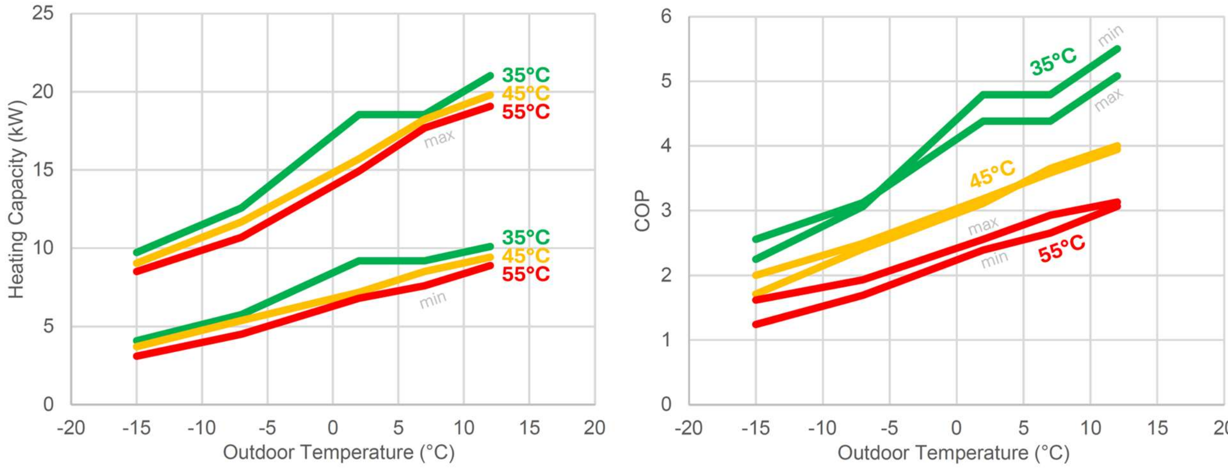

Figure 4. (left) Heating capacity and (right) COP for an air-to-water heat pump at minimum and maximum compressor speeds, and at three different leaving water temperatures (35°C, 45°C, 55°C), across a range of outdoor temperature conditions (–15°C to 12°C).

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.

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.

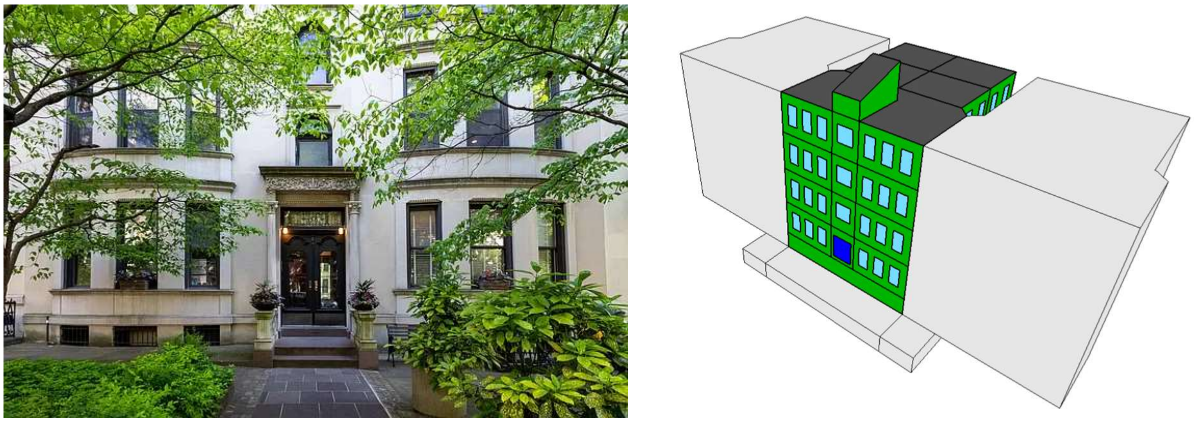

Figure 5. (left) Multifamily building in Park Slope Brooklyn, and (right) representation in EnergyPlus model

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.

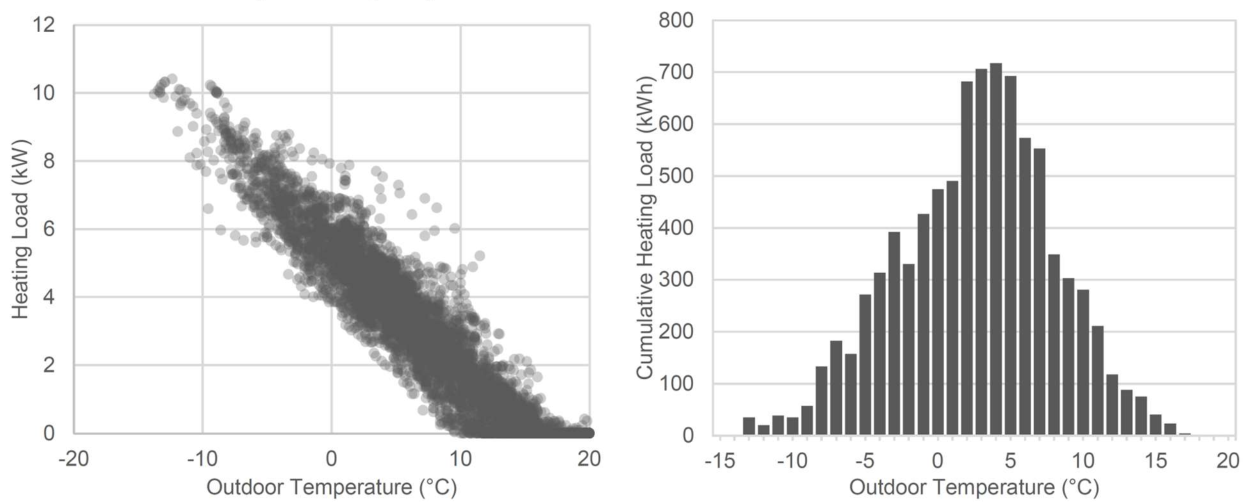

Figure 6. (left) Annual hourly heating loads as a function of outdoor temperature, and (right) annual cumulative heating load distribution in relation to outdoor temperature.

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.

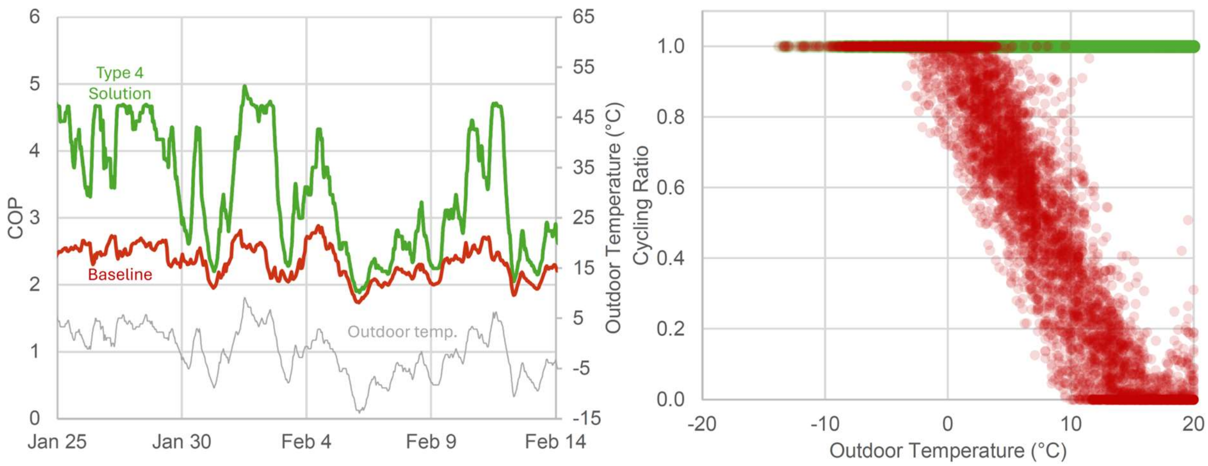

Figure 7. (left) COP for the baseline heat pump, and for the Type 4 solution for 20 days in the heating season; and (right) hourly cycling ratio for the baseline heat pump, and for the Type 4 solution plotted against outdoor temperature for all heating hours.

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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Demystifying Thermal Energy Storage Integrated Heat Pump Systems: Development of Generalized Sizing and Control Algorithms for Demand Flexibility

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ABSTRACT

As electrification and decarbonization goals become more commonplace across the country, the need for integrating thermal energy storage (TES) with HVAC to provide flexibility and load shifting is growing. Although there has been recent work related to the modeling and design of TES-integrated heat pump (HP) systems, investigation of generalized sizing and control methods for these systems remain limited. This paper details the development of generalized controls and sizing strategies applicable across different TES-integrated designs, two of which are discussed in this study. We demonstrate how model-based design enables an informed sizing and controls design process using the control-oriented Modelica language to generate high-fidelity models that accurately represent real-world behavior.

We detail our development and testing of both heuristic and model predictive control (MPC) algorithms to determine the optimal charge and discharge schedule with dynamic varying utility prices. Experimental results show MPC provides operating costs reduction of nearly 20% for a minimum TES sizing scenario. In addition, we provide a generalized and intuitive control algorithm with near-optimal performance to control HP + TES systems and test its performance in simulation. This generalized control algorithm is also used to drive the results of our cost analysis, providing insights for engineers designing new TES-integrated HVAC systems. The cost analysis demonstrates the tradeoff between higher initial hardware costs from larger equipment and the resulting operational cost benefits, and enables a cost-effective sizing method which is applicable to any system. The paper concludes with design recommendations for new integrated HP-TES control systems in buildings.

Introduction

Electrification of heating loads presents a significant decarbonization opportunity in all types of buildings. Although HP technology has become more commonplace as a means for electrifying these loads, there remain a number of barriers to scaled adoption and deployment. Among the barriers include the high cost of HP systems, compounded by potential additional costs related to electric panel upgrades and higher electricity costs (Rosenow et al., 2022). Typical air-to-water HP systems do not include any storage, preventing them from shifting electricity consumption to match times of renewable power production. Thermal energy storage systems bring the promise of higher flexibility for buildings while also serving as a remedy of the chronic oversizing seen in traditional HVAC design practices. Unlike traditional electrochemical battery systems, phase change material thermal energy storage systems are not subject to chemical degradation over time (they do not rely on a chemical reaction to store energy) and can integrate directly with an HVAC system (Gu et al., 2023). This allows the HP system to be designed to cover the majority of the conditioning hours throughout the year and can rely on the TES to provide additional capacity during peak demand hours when weather conditions are most challenging.

More importantly, these advantages allow for HPs to be downsized while maintaining the ability to adequately serve annual loads. Helmns et al's (2022) simulation study for instance, found TES to enable heat pump capacity reductions up to 60%. Recent market studies have revealed that first cost is a main driver for building owners looking to electrify their systems (Garcia et al., 2024), which currently include the procurement of the HP system (space heating and/or domestic water heating), and a possible costly panel upgrade, which may cost up to $5000 per panel (Walker, Casqueri-Moderego, and Less, 2023). In California, for example, about 30% of single-family homes have panel capacities less than 100 A thus needing panel upgrades to electrify (Pena et al. 2022), which serves as a conservative estimate for the widespread cost expected for electrifying residential buildings.

Despite the promise TES provides, it's ambiguous how to best size these systems in concert with HP systems. These gaps have been present for decades, with recommendations for standardized sizing tools dating back to the late 1980's (Dumortier et al. 1989) due to a tendency to oversize these systems, diminishing economic benefits of TES (DeForest et al. 2014). More recent studies have explored sizing methods such as Hao et al (2021) and Hirschey et al (2023) although these studies have not factored in the implications that sizing decisions have on control complexity and flexibility potential. Although multiple deployments of these systems have tried both rule-based and optimized control approaches (Behzadi 2022), controls for these systems also remain unstandardized. Standardizing these strategies allows for easier industry adoption and deployment of TES-integrated systems. Although control implementations have been demonstrated in the literature, some of the more advanced approaches can be difficult to understand or, and in the case of model predictive control, require time intensive model development, configuration and tuning to yield positive results (Cigler et al., 2013; Drgoňa et al. 2021).

The conventional process of designing and prototyping building technologies involves a series of sequential phases: system design, prototyping, limited laboratory testing, and extensive field tests (Naumann and Jenkins 1982) (Thomke 2003). Controls are typically developed independently, and the actual testing occurs in the field. This approach frequently results in suboptimal performance and the belated identification of control issues, necessitating costly measures to address these problems. As systems become more complex and involve integration of multiple technologies with high first costs, the risk of issues has more costly implications (Blum et al. 2021). A key method to de-risk these integrations is model-based design (MBD), which consists of an iterative modeling-design-simulation process, where systems and controls are developed together and validated in simulation before conducting expensive laboratory and field tests (Isermann 2014) (Wetter and Sulzer 2024). In this study we demonstrate how model-based design enables us to think about how we standardize sizing and controls of these systems and help us analyze how sizing and controls change based on how the TES is integrated.

The paper is organized as follows: (1) Methods section, describing sizing strategies, our assessment of 3 control algorithms for 2 energy system designs, and our cost analysis, (2) Results section describe the products of our methodology, (3 & 4) Discussion and conclusions.

Methods

In this study we describe two energy system configurations for TES-integrated systems, analyze a number of controls and sizing methods and implement these algorithms to calculate first and operational costs of both system designs. Two TES-integrated systems are sized and controlled, the first is a series-integrated TES system and the second is a parallel-integrated TES system.

Energy System Configurations

The series-integrated TES system can be seen in Figure 1, in which a phase change material (PCM) serves as TES between an air-to-water HP and a load. This series configuration uses the TES as an intermediary ensuring a stable supply of thermal energy while simultaneously decoupling space loads from HP operation, and ensuring the HP receives water at a consistent, controlled temperature. The parallel integrated system (shown at the bottom of Figure 1) in contrast can serve the load directly with the heat pump or the TES. The heat pump is also responsible for charging the TES at appropriate times.

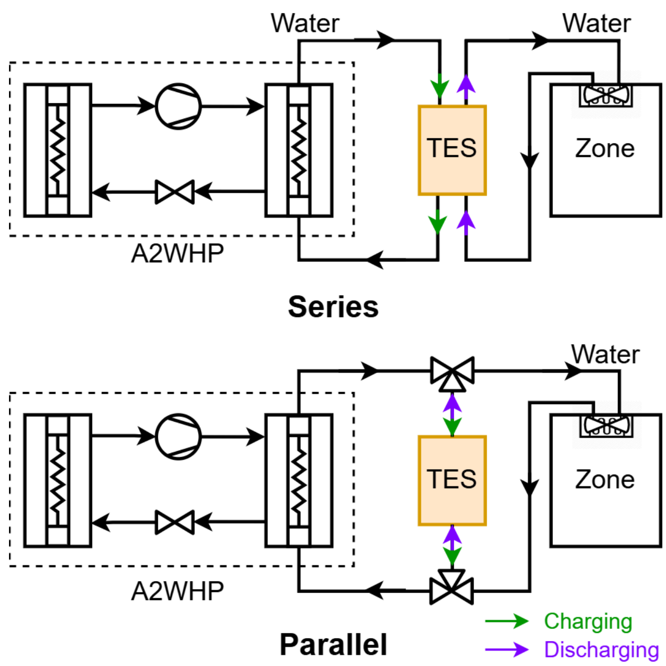


Figure 1. Conceptual diagrams of heat pump and PCM thermal energy storage system layout for both the series (top) and parallel (bottom) integrated systems

The parallel design was modeled in Modelica and tied into an experimental facility via a hardware-in-the-loop test design. This allows us to (1) test the performance of TES+HP sizing combinations using a realistic building thermal load profile, (2) determine the benefits of different control algorithms and their effect on flexibility potential. The series design was also modeled in Modelica and used to evaluate the performance of the proposed generalized control algorithm in simulation.

Operating Mode Definitions.

The series-integrated system (Figure 1 – Top) is designed similarly to a HP to buffer-tank design, where the HP's primary goal is to provide hot water to a middle storage device, while the storage device discharges to provide space conditioning to the zone. The following modes exist for this system are listed below and are summarized in Table 1:

Table 1. Summary of HP+TES control modes for both system designs

	Mode 1: Heat Pump Serves Zone Load	Mode 2: Heat Pump Serves PCM	Mode 3: PCM Serves Zone Load	Mode 4: Heat Pump Serves PCM while PCM Serves Zone Load
Series		x	x	x
Parallel	x	x	x	x

The parallel-integrated system is designed in such a manner in which the HP or the TES can provide space conditioning (Figure 1 – bottom). The TES is charged by the HP, when enabled, using a supply water temperature reset. There is another feasible mode in which the HP can provide both space conditioning and TES charging simultaneously, however in the case for PCM, the HP supply temperature would need to be exceptionally hot or cold and detrimental to system COP. An example of how the COP decreases at higher supply water temperatures can be found in publicly available manufacturer data (LG, 2020). The modes for both energy system configurations are explained below:

1. HP to Zone Mode
    a. HP provides space conditioning, no interaction with TES
2. TES Discharging Mode:
    a. TES provides space conditioning, when enabled, provided there is adequate state of charge (SOC).
    b. Capacity delivered to the zone is modulated by circulation pump controlled to a specified temperature difference
3. TES Charging Mode:
    a. Charging of TES is handled by the HP when the SOC is low and requires replenishment.
4. Simultaneous Charging and Discharging Mode
    a. Simultaneous charging and discharging is also possible in cases where the space calls for conditioning during times when the controller calls for HP charging

Control System Strategies

In addition to the two energy system configurations, three control system strategies were explored to determine the variation of performance relative to each system design. The three price-responsive algorithms, described below, determine the mode switching operation. The heuristic and MPC algorithms were conducted experimentally as part of a previous DOE-funded project, while the assessment of the generalized algorithm performance was conducted purely through simulation. We tested both control strategies in an experiment implementing the parallel design configuration. We also simulated the generalized control strategy and compared it to the heuristic baseline for the series design configuration. All control strategies are summarized in Table 2.

Table 2. Details of control strategies for testing a TES-integrated system

Strategy	Heuristic (Baseline)	MPC	Generalized
Description	Daily hour schedule based heuristic control to use PCM TES and avoid HP operation during peak cost time.	Model predictive control to minimize energy cost with respect to electricity cost signal.	Closed-loop algorithm that strives to turn on the heat pump from lowest to highest cost periods
Control Algorithm	Charges TES in low load and low-price windows, TES is discharged during high-price periods, HP is deactivated during high-price period, HP is operated to serve the load otherwise	Predicts thermal load and balances electricity price to minimize operational cost while taking full advantage of TES	Constructs an operation schedule for the HP that prioritizes the use of less expensive hours to charge the storage. Implements the first time step and repeats the process.
Price Signal	CalFlexHub Spring & Summer Highly Dynamic Price Signal (LBNL, 2024)	CalFlexHub Summer Highly Dynamic Price Signal (LBNL, 2024)	CalFlexHub Spring Highly Dynamic Price Signal (LBNL, 2024)
Evaluation Method	Simulation & Lab Experiment	Lab Experiment	Simulation

Heuristic and MPC Algorithms.

The heuristic (baseline) control strategy is schedule-based. It discharges the TES when the electricity cost is high and charges the TES overnight from 23:00 to 7:00 during the low-cost time. The cost signal used in this study has a high price during 16:00 to 22:00 and has the same profile for each day (Figure 6). Assuming the thermal load profile of an office building, the cooling load is highest in the afternoon. Therefore, the TES is set to be used for the late afternoon which has a high electricity price. Then, it is charged during the nighttime for the next day's use.

To better understand the benefits of optimized controls for a downsized TES-integrated system, a model predictive control (MPC) strategy was also tested. The MPC is designed to provide the optimal sequence of charge, discharge, and HP-only modes during the day based on the electricity cost signal and the predicted cooling load. After setting up the 3-zone gray-box (combination of data-driven and physics-based models) model, a black-box (data-driven model) optimizer is used to find the optimal sequence of mode profiles for a day.

The evaluation of the heuristic and MPC price-responsive algorithms was conducted in for the parallel system involved gathering experimental data from LBNL's FLEXLAB facility (McNeil, Kohler, and Lee 2014). FLEXLAB is a highly instrumented and customizable testing environment, which allows researchers to implement a wide range of energy efficient technologies against an identical baseline cell to efficiently evaluate their added benefit to building performance. The experiments were set up in two identical building cells (X1A and X1B) in FLEXLAB with two identical HVAC systems. The HIL strategy in this FLEXLAB experiment uses physical HVAC distribution and delivery systems supplied by a physical water chiller, but the chiller and a downstream heating element are controlled by Modelica-based models running on a local server. The experimental tests used a 3 kW HP and a 14.5 kWH 8°C PCM TES in the virtual plant

Generalized Control Algorithm.

In the pursuit of standardization and ease of implementation, we also developed a simple generalized control algorithm for heat pump and thermal energy storage systems that leverages the best aspects of both the heuristic and MPC strategies. For a given set of electricity price and load forecasts, it finds a near-optimal operation schedule for the heat pump that guarantees thermal comfort while avoiding the use of electricity during expensive peak hours (it does not account for potential demand charges, as dynamic pricing is expected to replace demand charges in California [Matisoff 2020]). As with MPC, the algorithm is implemented in a closed loop, where the first step of the schedule is implemented at each time step, and the state of the system serves as a feedback.

The operation schedule prescribes the thermal power of the heat pump at each time step over the prediction horizon (time is typically discretized in hours and the horizon is generally set to 24 hours). The schedule is determined through an iterative, forward-moving process. Before the process begins, the heat pump's power is initially set to 0 at each time step. The first hour in which the load cannot be met (i.e., insufficient SOC at that time) is identified. Then, the heat pump's thermal power is increased during the lowest-cost hour(s) before that hour, until the load is satisfied at that hour. The power is increased only if it does not lead to exceeding the storage capacity. Additionally, if increasing the power results in reaching lower cost operating hours in the future, then the power is increased only enough to allow the storage to supply the load until that point. This process is repeated until the load is met at every hour in the prediction horizon.

The generalized control algorithm can be applied to both the series and parallel configurations, and is meant to be applicable to a wide range of configurations. For this reason, this control algorithm is used to determine the operating costs used in the generalized sizing method described in the next section. It assumes that the heating power of the heat pump can be adequately controlled, either directly or indirectly. In this study, we control it indirectly through the setpoint for the heat pump's supply water temperature, assuming that the temperature of the water returning from the PCM is roughly constant for a given state of charge. Direct control would involve modulating compressor speed, a control point which is only accessible to heat pump manufacturers.

The developed algorithm was implemented in Python and used to control a high-fidelity Modelica model of the system in series configuration. Its performance was compared against the heuristic algorithm, which turns off the heat pump during peak hours and evenly distributes the shifted load to the hours before the peak.

Functional Mockup Units (FMUs) for Testing:

The primary method of developing all of the aforementioned controls is co-simulation via Functional Mockup Units (FMUs). Akin to compressing a large collection of files into a .zip file, a functional mockup unit allows for data exchange between a detailed model and a control algorithm without having to compile and run a simulation in the native model compiler program, which often requires a software license and prior knowledge on how to operate the software. Interaction with the FMU is done through publicly available tools that can be leveraged for co-simulation, including PyFMI. For both the series and parallel systems presented earlier, we co-simulated our control strategies with the system model through a hardware-in-the-loop (HIL) approach. The model states such as SOC, water temperatures and system electric demand are fed back to the control algorithm which then decides any change in mode command and setpoints based on the feedback. Figure 2 illustrates this data exchange.

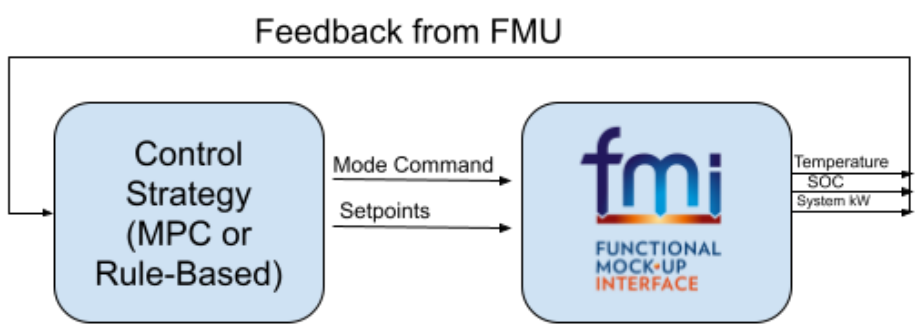


Figure 2. Data exchange between control strategy and the modeled HP+TES plant

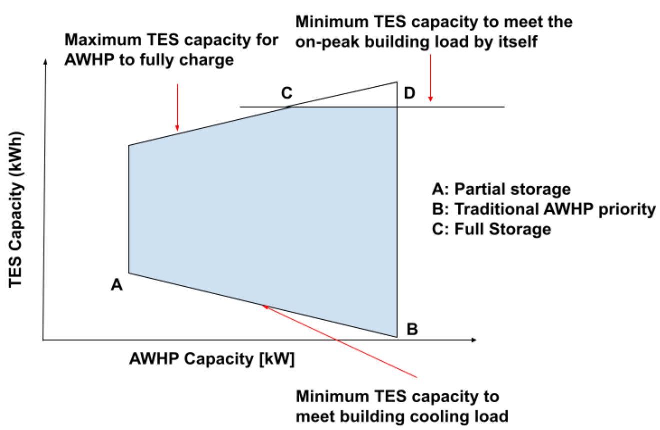
Equipment Sizing & Cost Analysis

Recommended Equipment Sizing.

Selecting the right storage and heat pump capacity is critical in order to bring down the costs of such systems. While increasing the capacity of the equipment generally yields lower operating costs, it also comes with higher investments for capital cost. (Zheng, Ma and Wang 2015) In the series integrated system, the HP is insulated from the hourly changes in zone load and only serves to charge the TES. However, the TES needs to be able to serve the load for the entirety of the high price periods or demand response events to provide demand flexibility. The HP must also be large enough to charge the TES in an adequate time period in order to avoid the

TES falling below a minimum SOC. The parallel integrated system can also only serve the load either through the heat pump or TES, and therefore has an equivalent sizing strategy.

The sizing strategy for these systems is based on a method established by Hao et al. (2021) and was conducted using time series data from the peak cooling day within the observation period (August to October 2021). Using the peak day ensures that the system will be capable of meeting the highest cooling demands we can reasonably expect for the site. In order to create the sizing map, we assumed an 8-hour charging window while the discharge period is assumed to cover 4 hours during high price periods. The resulting sizing map for this case study is shown in Figure 3. This case study represents system sizing at the intersection of the blue line and orange line, which denotes the minimum heat pump capacity needed to serve the peak thermal load at the plant sizing determined. This is equivalent to point A as seen in Figure 3. There are several assumptions made in this case study. First is that the charge and discharge efficiencies of the PCM are treated as 100% and that the PCM is not charge rate limited. This means that it can charge using whatever load the HP can provide, and discharge at the rate required by the site. Specified off-peak times were used as the charging window and on-peak times as the discharging window. The length of time the PCM is allowed to charge or required to discharge affects the maximum recommended capacity, shown in red and orange on Figure 3. These assumptions were useful in this case study, but there is room for future improvement. The charge and discharge windows could be optimized, taking the control strategies into account, and the efficiency and power constraints of the PCM could be considered.



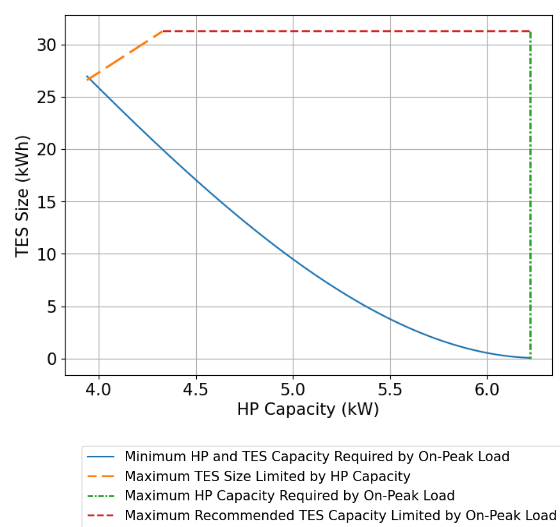


Figure 3. Sizing map that identifies the relationship between TES and AWHP capacity for (A) partial storage, (B) traditional AWHP priority, and (C) full storage scenarios, reproduced from (Hao et al. 2022) [left]. Sizing diagram for generated using field data [right]

Cost Analysis for Sizing.

By estimating both the annualized capital expenditures (CAPEX) and the operating expenditures (OPEX) of HP + TES systems, we define a generalized cost-based sizing approach which simply consists in selecting the equipment sizes (HP thermal power and TES capacity) that yield the lowest overall costs over the lifetime of the equipment.

In this study, we assume that the cost of installing the equipment is not significantly affected by equipment size, and that no panel upgrades are required as a result of installing the heat pump. Therefore, the capital expenditures are the costs from purchasing the equipment only. The capital expenditures are expressed as $/year by dividing these costs by the lifetime of the equipment (typically assumed to be 20 years). Prices for different HP and TES sizes are obtained by scaling from reference prices using a polynomial fit, as shown in Figure 4. The operating costs are estimated from a yearly simulation (with past weather, load, and electricity price data) in which the system is controlled using the generalized control algorithm described in the previous section. When available in simulation, we recommend using the control algorithm that will be used in the physical system to improve the cost estimation.

Finally, the total expenditures (TOTEX) are obtained in $/year by summing the capital expenditures and the operating costs. With this metric, it is possible to compare the costs associated with different combinations of equipment sizes and select the most cost-effective solution, via a parametric sweep of simulations. It is important to note that the results obtained with this method are case specific, as they strongly depend on the available electricity prices and typical heating loads expected in the building.

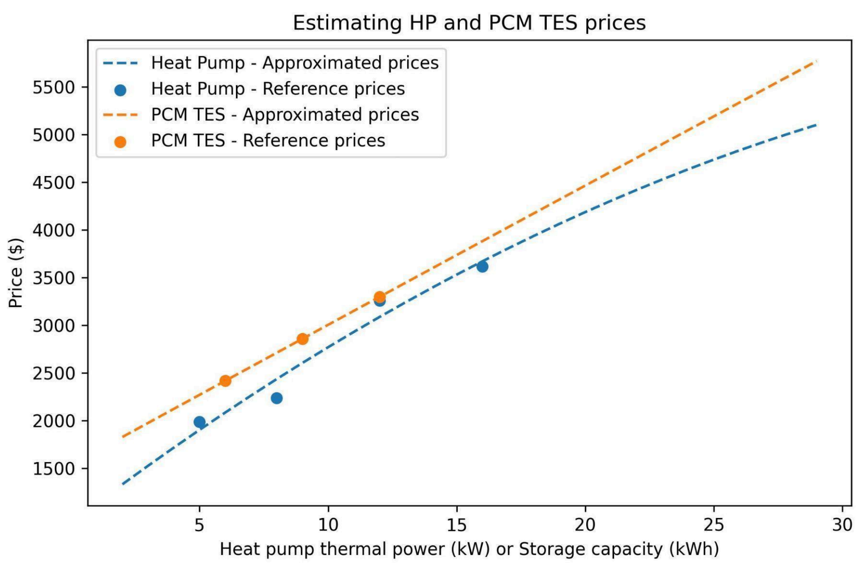


Figure 4. Estimating CAPEX costs for different sizes of HP and PCM TES, based on reference prices

Note: Reference prices were obtained from online sources (Midsummer, 2024) for the Samsung Gen 6 R32 Monobloc Heat Pump and from SunaAmp thermal batteries.

Results

Control Strategies Testing

Parallel system performance with heuristic vs MPC control algorithms.
Figure 5 shows the power profile for the heuristic control and MPC strategies. The MPC algorithm demonstrated the capability to predict thermal loads and strategically discharge the

TES, thereby shifting the building load from the morning high-price period to the lower-price period at night. The lower TES SOCat the end of the day meant a more substantial overnight thermal demand as the HP charged the TES in preparation for the next day. Despite the high evening peak, the overall demand is lower for the MPC. The MPC algorithm demonstrated its ability to anticipate thermal loads, unlike the heuristic controller, which initiated TES discharge well before the high-priced period, per the set schedules that could not capture the highly dynamic price signal.

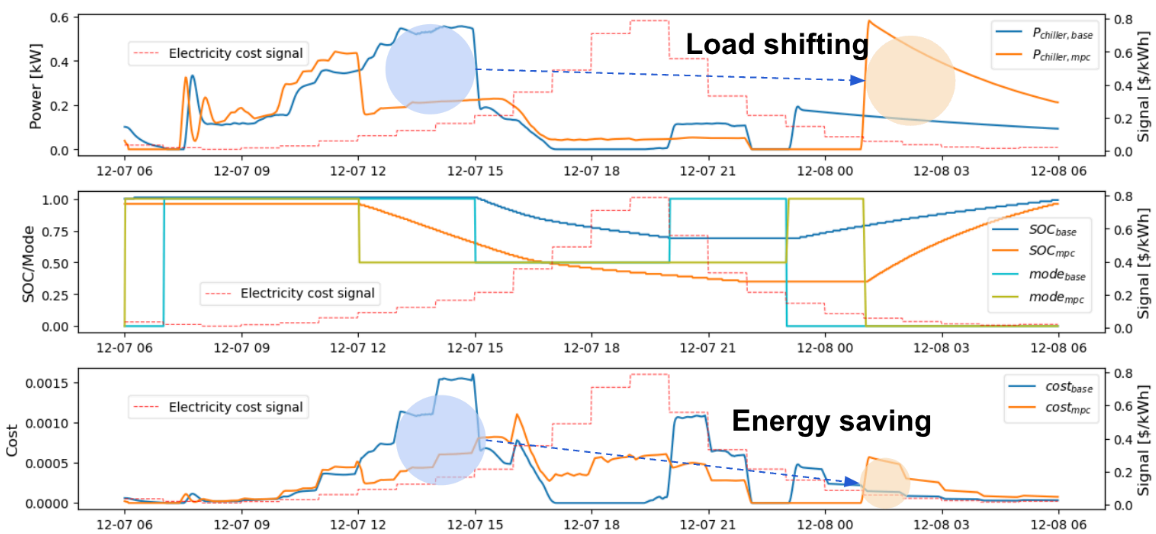


Figure 5. Power profiles, averaged across testing days, for the baseline scenario and the MPC scenario for FLEXLAB HIL test.

Successful MPC prediction allowed for the effective shift of thermal loads to periods with lower prices, resulting in a 10% reduction in HVAC energy use and a 24% reduction in total electricity costs compared to baseline operations with heuristic control. Results are summarized in Table 2.

Table 2. Summary of results for FLEXLAB

Test	Heuristic (Baseline) Total	MPC Building Total (% Reduction)	Heuristic (Baseline) HVAC Total	MPC HVAC Total (% Reduction)
Average daily energy consumption (kWh)	12.4 kWh	11.9 kWh (-4%)	3.23 kWh	2.91 kWh (-10%)
Average daily cost ($)	$2.60	$2.00 (-24%)	$0.39	$0.30 (-23%)

Series system performance with heuristic vs generalized control algorithm.

FMUs were designed to assess the performance of the generalized control algorithm on the parallel and series system configurations. As a reminder, the generalized control algorithm outputs a schedule of thermal power at which the heat pump should operate for every hour in the prediction horizon.

In the series system, the heat pump can only serve the PCM, and the temperature returning from the PCM is assumed to be roughly constant. Therefore, the thermal power of the heat pump can be controlled using the setpoint for the supply water temperature (the heat pump's mass flow rate is assumed to be a function of the supply water temperature, as is typical of commercially available heat pumps).

In the parallel system, the heat pump can either serve the PCM or the Zone, or both simultaneously. In this implementation, the hour is split into two sections: the heat pump first serves the zone directly until the zone's heating load is satisfied, and then switches to charging the PCM for the remainder of the hour. In both modes, the heat pump operates at the same thermal power, modulated by the supply water temperature setpoint. When the HP is serving the zone, the setpoint is dynamically adjusted as a function of the measured return water temperature. When the HP is serving the PCM, we use the same assumption as with the series system in which we consider the return water temperature to be a function of the state of charge.

Figure 6 shows an example of a 24-hour simulation with the FMU of the series system controlled with the generalized control algorithm (solid blue line) and the baseline algorithm (dashed blue line). The heat pump power was indirectly controlled by dynamically adjusting the supply water temperature setpoint and assuming that the water returning from the PCM can be calculated from its state of charge. When the blue line is above the red line, the heat pump is supplying more heat than required by the zone, and this excess energy is charging the storage. The performance is satisfactory, and peak hours (indicated by the higher electricity prices) are successfully avoided by both algorithms. Given the small storage size used in this simulation (10.3 kWh) and large heating loads, both algorithms are only capable of discharging for 2 consecutive hours at a time. The main difference between the two stands on how the charging is distributed across the hours. The generic algorithm makes the most out of the least expensive hours of the day (12 to 14), whereas the baseline charges equally in all hours before a price peak, regardless of the electricity price.

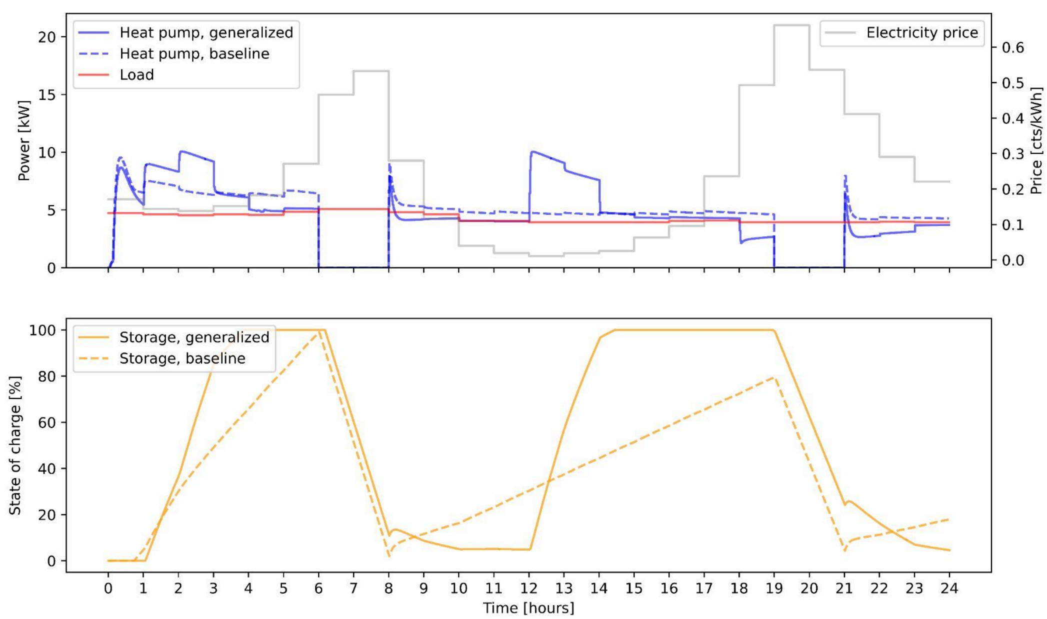


Figure 6. 24-hour simulation of the series system on the corresponding FMU, where the thermal power of the HP is indirectly controlled through the supply water temperature setpoint

Similarly to the MPC developed for the parallel system configuration, the performance of the generalized algorithm was compared to a baseline algorithm. The baseline would turn off the heat pump during pre-designated peak hours (2 hours in the morning peak, 2 in the evening peak) if the storage could provide the load during those hours, and evenly distribute the shifted load to the hours before the peaks. Table 3 summarizes the results obtained with both algorithms when simulating the series system configuration used to heat a house from January to April (included), using past weather and load data. For these simulations, the system was sized according to the strategy described in the 'Recommended Equipment Sizing' subsection, which recommended a 10.35 kW heat pump with 10.3 kWh thermal energy storage.

Table 3. Summary of results for simulating the series system using past load and weather data

Test	Heuristic HVAC Total (Baseline)	Generalized HVAC Total (% Reduction)
Average daily energy consumption (kWh)	47.3 kWh	47.3 kWh
Average daily cost ($)	$9.02	$7.61 (-16%)

These results show that, in this specific scenario, the generalized algorithm was able to save about 34% on electricity costs through load shifting, which is roughly 16% more than what the baseline algorithm was capable of achieving. Both these algorithms use the storage to displace heating loads over time, which explains why the amount of energy remains the same.

Equipment Sizing Simulations

While the results above demonstrate the benefits of different control strategies for operating costs, we would also like to explore the effects of varying HP + TES sizes on total costs. Here, we apply the Cost Analysis for Sizing to determine the most cost-effective combination of heat pump thermal power and thermal storage capacity. The electricity prices used in the simulation are the highly dynamic CalFlexHub (LBNL, 2024) seasonal electricity prices. The operating costs are estimated using the generalized control algorithm, which is independent of the energy system configuration (parallel or series).

Figure 7 provides sample results for a single-family residence in a cold climate, where the total annual costs are estimated for a range of equipment sizes through a parametric sweep. From the plots, we can see that, at first, the additional expenses for purchasing larger equipment are compensated by the reduced operating costs resulting from the ability to shift heating loads to hours in which electricity prices are low. However, above a certain size, the total costs increase as these additional expenses are no longer outweighed by the operational cost benefits.

The red dot on Figure 7 shows the point at which the total costs are minimized, which is a compromise between large equipment for low operating costs (OPEX) and small equipment for low capital costs (CAPEX). To reiterate, the optimal sizing of the equipment will depend on the control algorithm, weather, load and electricity prices associated with the area and building in which the system is installed. In this case, the cold climate, high heating demand, and very dynamic prices used in the simulation recommend large equipment (22 kW HP and 48 kWh TES). In many use cases, this will lead to additional costs such as panel upgrades which could change the recommended equipment size. Given the currently available thermal battery sizes, some options might also not be feasible as of today.

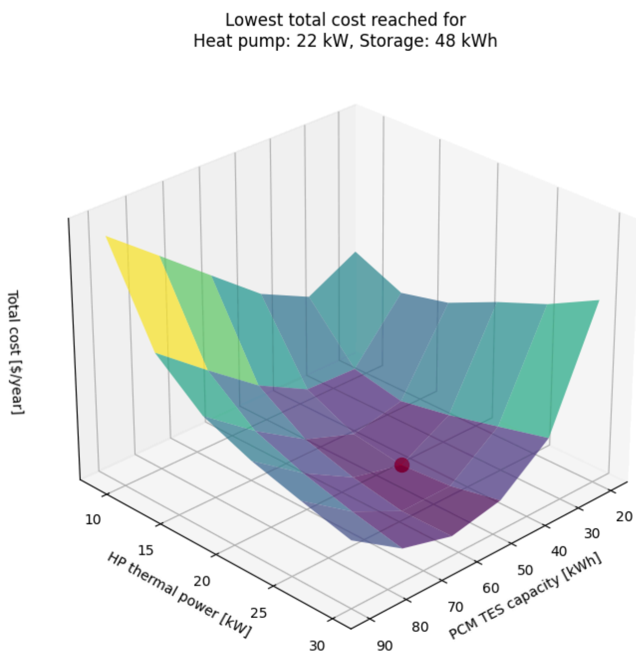


Figure 7. Plot showing the total yearly price (TOTEX = CAPEX + OPEX) of a HP and PCM thermal energy storage system for different equipment sizes. The red dot represents the optimal combination of equipment capacities for this particular example.

Note: The operating cost analysis used to generate Figure 7 considered a yearly weather and heating load data from a 2,200 square foot house in Western Massachusetts with a maximum hourly cumulative heating requirement of 8.4 kWh. With similar load data for any other building, an alternate TOTEX surface map could be generated to identify optimal sizes for the HP + TES.

Discussion

This paper presented three different control approaches for integrated HP + TES systems. The presented MPC for the parallel system reduced building costs for the designed case by 24% but is customized to a specific situation and requires tuning prior to deployment. The simple price-responsive algorithm is intuitive and performs close to the equivalent optimization problem at 16% reduction, but could be challenging to set up depending on the system configuration and available control inputs (controlling the HP's thermal power is generally not directly possible). The two approaches have different, viable paths to market. MPC could be viable in products that are designed/tuned once and sold repeatedly, akin to the smart controls in a Nest thermostat, e.g. a prefabricated, plug-and-play HP + TES system with pre-installed controls. The simple price-responsive algorithm is designed to avoid the tuning required by MPC, which makes it more viable for installations designed in the field or for startup companies that want a control algorithm to leverage with low development budgets.

While the technical potential of integrated HP + TES systems is tremendous, market adoption has been slow due in large part to the challenges of 1) each site requiring customized design without supporting tools, and 2) limited applicable control algorithms. The sizing tools presented here can create a foundation for design tools that support industrial practitioners identifying a high-performing, minimal cost system, while leveraging model-based design strategies enables rapid integration of data describing the specific sites where the system will be installed. This enables designs of systems which are right-sized for specific buildings, reducing both the CAPEX and OPEX of the installed system.

The simple price-responsive algorithm presented here was designed for AWHP + TES systems, but fundamentally operates by identifying the lowest cost times to operate equipment. It could be expanded to other situations where a) building needs, b) operating costs, and c) equipment capabilities are known. Ongoing conversations include collaboration with industry to determine the optimal times to charge/discharge PCM, leveraging the algorithm to identify the optimal times to send load shifting control signals to end-uses. The sizing methods presented here should work just as well for other TES-integrated systems such as in-duct PCM and would likely need only minimal modification to also include other end uses such as heat pump water heaters.

Conclusion

In this study we explored more effective ways of sizing and controlling heat pump systems when integrated with TES. Our cost analysis calculates the total cost of all sizing combinations to determine optimal sizing based on minimized cost. These methods will be needed to scale the deployment of these systems, further equipping manufacturers, engineers, and contractors with tools to consider the interactions between heat pump and TES sizing, controls and total costs. Ultimately, the future to keep in mind is one where adopters of this technology can easily size, purchase and reap the benefits of these innovative system designs.
In future work, a sizing tool that takes into account regional differences in utility rate structures and thermal load could further provide value to the aforementioned stakeholders.

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