Two Case Studies of Combi Air-to-Water Heat Pumps with Thermal Storage

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ABSTRACT

Prior papers discuss the potential of air-to-water heat pumps with thermal storage (A2WTS). This paper will present case studies of two A2WTS installations in contrasting climates.

For heating electrification, A2WTS offer advantages over non-storage heat pumps. A2WTS can shift electricity consumption off peak and can optimize efficiency while meeting heating demand. In cold climates, A2WTS may reduce backup heating needs and increase electrification cost-effectiveness. Also, A2WTS providing space and water heating may be cheaper than separate systems.

The first case study discusses installation in a small, century-old home in a temperate climate. System components include one 119-gallon storage tank serving space and water heating, the A2WTS controller, and the heat pump, and system operation aligns with a local time-of-use electricity rate. In the second case study, an A2WTS replaces a propane boiler in a larger, 20-year-old home in a cold climate. Components include two heat pumps, two 83-gallon storage tanks, and an A2WTS controller that communicates with the electric utility.

The case studies provide design and installation experience and preliminary system performance data. Both systems were able to meet design performance, maintain comfortable temperatures, and provide adequate hot water. The systems also used thermal storage to shift electricity consumption off peak.

The A2WTS allowed for more energy efficient, grid-friendly decarbonization than possible with non-load shifting electric resistance systems. The system worked well in Site 1's mild climate, though installation in an older, existing home had challenges. Site 2's installation was easier, but cold climate heat pump performance proved challenging.

Introduction

The path to decarbonizing building space heating in the U.S. requires retrofitting more than 73 million homes that have natural gas, fuel oil, or propane heating systems with electric heating, ventilation, and air conditioning (HVAC) systems (EIA 2020, Table CE3.1). Using conservative assumptions for fossil-fuel equipment and heat pump efficiencies, we estimate that residential heat pumps could consume 1.4 quadrillion British thermal units (quads) of electricity to provide the same service as the 3.5 quads of fossil fuel energy currently consumed by residential HVAC.[1] Electricity for residential HVAC in a decarbonized economy could increase total residential electricity consumption by 27%, from 5.2 to 6.6 quads.

The biggest share of this increase in electricity use will be for decarbonizing residential space heating and will be seen during the winter months. A significant challenge with the use of heat pumps for space heating is that as the outdoor air temperature drops, and the demand for space heating rises, heat pump efficiency also drops. Prior research on air source heat pumps without thermal storage has found that in areas that experience intense cold, this compounding

[1] Based on assumptions of 80% efficient fossil-fired HVAC equipment replaced by 200% efficient heat pumps.

effect could mean that electrified residential space heating could contribute to wintertime peak electricity demand (Amero et al. 2022).

Electric storage water heaters, whether heat pump or electric resistance, can have integrated demand flexibility capability and can shift electricity consumption away from times of hot water usage when equipped with the proper controls. Thermostat demand response programs have been used to reduce summer electricity demand peaks from residential air conditioning. In homes with heat pumps or electric resistance space heating, thermostat demand response could also help shift some space heating electricity consumption off-peak. However, most electrically heated homes do not have thermal storage, and the amount of wintertime peak reduction smart thermostats can provide is limited by the need to protect occupant comfort and safety when it is very cold outside.

An air-to-water heat pump with thermal storage (A2WTS) can store energy as hot water by running during off-peak periods and then draw on that stored heat to maintain comfort during peak demand times. Thermal storage can also make heat pumps more efficient by, for example, allowing them to run during the day when ambient temperatures are higher and by storing heat for space heating at night when ambient temperatures drop and heating demand rises. Thermal storage can also be used to maximize solar photovoltaic (PV) generation self-consumption and to lower electricity bills by taking advantage of time-varying rates.

The two case studies of residential combi (combination space heating and hot water) A2WTS presented in this paper are not part of ongoing research or formal experimental installations. In both cases the homeowners are energy efficiency professionals who independently decided to replace fossil-fueled space and/or water heating systems with A2WTS in existing homes. The projects were carried out with the support of local efficiency program incentives and federal tax credits. The two homes are both in heating-dominated climates, but with very different seasonal heating needs and temperature extremes. The early operating experience and preliminary results provide insights into how large numbers of residential heat pumps can be integrated into the electrical grid.

Case Study Sites

Table 1 summarizes the site characteristics for both sites. The first site is located in a temperate climate in the San Francisco Bay Area, with a lower capacity system required to meet heating needs. The second site is a cold climate installation in Vermont, with several additional system components required to meet the larger heating load. Both sites will be discussed in detail in the following sections. We have not provided project cost information because both case studies had extenuating circumstances that made their cost data less useful as predictors for future A2WTS projects. For Site 1, much of the installation labor was provided by the homeowner, and Site 2 is the first installation of the A2WTS as a replacement for a boiler in a residential hydronic heating system in a cold climate. Additionally, we have not provided a full comparison of pre- and post-retrofit utility bill costs; Site 1 was only fully occupied after completion of this project, so pre-project bill costs are not available, and Site 2 does not yet have sufficient data collected to report on operating costs.

Table 1. Summary of case study site characteristics

Parameter	Site 1 – San Francisco Bay Area	Site 2 – Northern Vermont
Climate zone	Warm marine	Cold

Heating degree days	3,000	8,000
Building age (years)	120	20
Heat distribution system	Forced air	Hydronic and forced air
System heating capacity (kBTU/hr)*	12 (constant) 24 (peak, with TES)	52.8 (constant)
Thermal energy storage (TES) capacity	119 gallons	166 gallons
Backup heat type and capacity	None	7 kW tankless water heater, wood stove
Monitoring start date	March 2025	March 2026

*Rated system heating capacity, not actual. At Site 1, the ambient temperature during peak heat demand is warm enough that the capacity of the heat pump is unaffected. At Site 2, the ambient temperature at peak is low enough that heat pump capacity is reduced.

Site 1: San Francisco Bay Area

Site. The first case study site is an approximately 900 square foot (sq. ft.) detached home with low occupancy. In this case, an ongoing site renovation required replacement of obsolete space and water heating systems. The prior space heating system consisted of a natural gas gravity wall furnace with a heating capacity of 38,000 British thermal units per hour (Btu/hr), located in the central part of the home with a dedicated, vertical exhaust vent through the roof. The prior water heater was a 38-gallon natural gas storage unit located in the home's crawl space, where the maximum ceiling height is approximately 55 inches. There was no air conditioning due to the mild climate (see Figure 1).

Ambient conditions. The site is located in the temperate San Francisco Bay Area in a warm marine climate zone. To ensure that the A2WTS could meet the home's space heating needs, a load calculation was completed according to the Air Conditioning Contractors of America (ACCA) Manual J: Residential Load Calculation, 8th Edition, which revealed a peak design heating load of approximately 18 kBtu/hr. The outdoor design temperature was determined to be 40°F (i.e., 99% of annual hours are above this design temperature), and the typical indoor ambient temperature set point is 69°F. The building is approximately 120 years old with a relatively loose envelope; for example, the home lacks wall insulation and a modern vapor barrier allowing for some natural ventilation through the envelope. The home does feature some upgrades such as dual-paned windows as well as attic air sealing to reduce heat transfer between the unconditioned attic and the conditioned space. The windows were installed before the heating system installation, and the insulation afterwards. All upgrades were considered in the heating system load calculations and reduced the required size of the A2WTS.

During the monitoring period, the site's average annual outdoor air temperature was 57°F, with an annual minimum temperature of 42°F. December was the coldest month of the year, with an average temperature of 52°F, while September was the warmest month, with an average temperature of 63°F. Typically, the coldest hour of the day is from 6 to 7 a.m., with an average temperature of 54°F, and the warmest hour of the day is 3 to 4 p.m., with an average temperature of 61°F. Outdoor air temperatures were relatively stable throughout the monitoring period. Due to this temperature profile, the home requires some space heating in every month of the year. Figure 1 summarizes annual outdoor temperature trends for Site 1 over the course of the monitoring period.

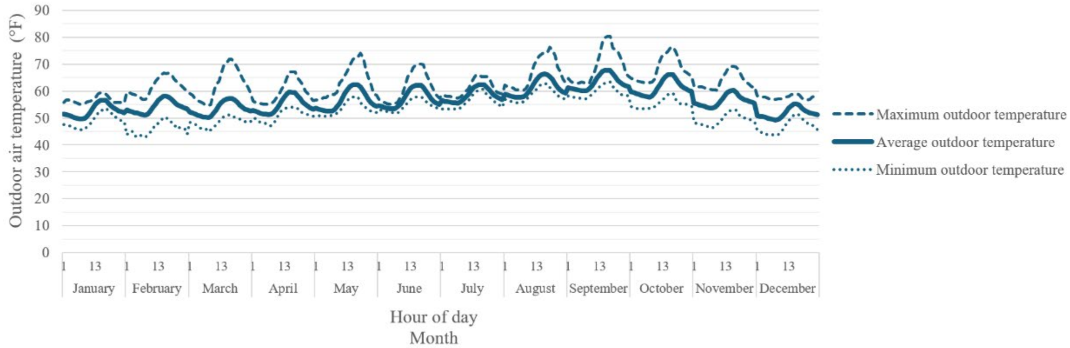

Figure 1. Site 1 outdoor air temperature trends for monitoring period

Considerations in the selection of the A2WTS system. The house is located in an urban environment, where space is at a premium and product footprint and siting are major considerations. Goals for the new system included eliminating onsite fossil fuel consumption, maximizing efficiency and minimizing ongoing operational costs, improving thermal comfort, reclaiming space within the building footprint taken by the legacy system, achieving high reliability and resilience, and minimizing required electrical capacity. Upfront installation cost was also important. The home was only intermittently occupied at the time of the A2WTS installation, therefore installation timeline was not a major consideration.

Because they are relatively novel in the Bay Area, a residential A2WTS system was not immediately an obvious choice to meet Site 1's design considerations. However, the project's flexible installation timeline allowed for careful consideration of various options leading to the choice of this system. Selection considerations included the following:

- *Eliminating onsite fossil fuel use*: The owner wanted to eliminate fossil fuel use for environmental stewardship as well as to eliminate safety concerns and indoor air quality impacts associated with the legacy gas wall furnace and storage water heater.
- *Space constraints*: Due to Site 1's small footprint, the project also aimed to reclaim interior space taken by the wall furnace, giving preference to solutions that could be located outside of the living space – i.e., in the crawl space, attic, or outside. The home's full height attic did have adequate space to support a heating system including ducting, piping, and other required equipment. At the time of installation, the crawl space height of 55" ruled out a unitary heat pump water heater (HPWH) since available products were too tall for the space provided, unitary HPWHs reviewed were not suitable for exterior installation, and interior space was not available. This led to a preference for a water heating system that could be installed outside, where there was adequate space and a temperate climate where freezing temperatures are rare to non-existent. The A2WTS system met the space constraint criteria due to its ability to be installed outside and inside the attic, away from the living space and unhindered by the cramped crawl space.
- *Energy efficiency and load shifting potential*: In the San Francisco Bay Area, the high cost of electricity is a major concern. Residential customers are enrolled, by default, into time-of-use (TOU) rate plans with summer peak period rates that exceed \$0.50 per

kilowatt-hour (kWh).[2] Therefore, the owner strongly preferred efficient options that would minimize electricity bills; for this reason, heat pump technology was preferable to a standard electric water heater. Furthermore, the A2WTS offered the capability to shift usage away from peak periods without compromising thermal comfort and to take advantage of off-peak TOU rates at a savings of about $0.10-0.20 per kWh in the summer and $0.03-0.05 per kWh in the winter.

- *Electrical capacity constraints*: The house is equipped with a 125 Amp electrical panel with limited slots to add new circuits. A unique attraction of this A2WTS is that as a combined system it only requires one 30 Amp breaker in the panel – including a 15 Amp circuit for the condenser and a 15 Amp circuit for the air handler – as opposed to separate large breakers for electric space and water heating systems.
- *Other considerations*: Although the home did not have preexisting ductwork, the owner preferred a ducted system over ductless mini-splits due to the ability to provide balanced temperatures across the entire living space. The owner also chose a larger thermal storage tank to provide resilience benefits and continuous hot water availability during power outages. The selected A2WTS system can be configured to include air conditioning, but the chosen configuration did not include this feature; this was not a concern due to the location's cool summers and shading from nearby buildings that reduces heat gain. Finally, the owner also preferred a "monobloc"[3] heat pump with an enclosed refrigerant cycle to options that would have been more difficult to install and perhaps would have required more maintenance.
- *Upfront cost*: Since both the legacy space and water heating systems needed to be replaced, the cost of the A2WTS system (with applicable tax credits[4]) was comparable to the cost of installing separate, new heat pump space and water heating systems.

Equipment. The A2WTS system selected includes a monobloc air-to-water heat pump that uses CO_2 refrigerant, one 119-gallon thermal storage (hot water) tank, a proprietary controller to manage system operation and water flows, and an air handler unit with heat exchanger to send heated air through ductwork to the conditioned space. In this configuration cooling and dehumidification were not provided, but a supply ventilator was included to bring in outside air. The system has a variable heating capacity of approximately 12 kBtu/hr when using the heat pump only or a peak capacity of approximately 24 kBtu/hr when taking advantage of the fully charged thermal storage tank (for up to 4 hours). Since the Site 1 home is small and in a moderate climate, this heating capacity easily meets the anticipated heating demand. The thermal energy storage allows the heat pump to cover 24 hours of heating load while prioritizing operation in the afternoon, when ambient temperatures are higher, and California electricity prices and greenhouse gas emissions are lower due to the state's abundance of solar energy.

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[2] Pacific Gas and Electric, "Residential rate plan pricing," March 2026, https://www.pge.com/assets/pge/docs/account/rate-plans/residential-electric-rate-plan-pricing.pdf

[3] Monobloc heat pumps have a single enclosure housing the compressor, evaporator and heat exchangers. This allows them to use a smaller refrigerant charge than other types of heat pumps. Rather than circulating heated or chilled refrigerant to the point of use, monoblocs usually circulate hot or cold water.

[4] For example, at the time of installation available tax credits included the Energy Efficient Home Improvement Credit (26 U.S. Code § 25C) that allowed homeowners to claim 30% of the cost of qualifying heat pump installations, up to $2,000, or the Residential Clean Energy Credit (26 U.S. Code § 25D) that allowed homeowners to claim 30% of the cost of battery storage technology with a capacity of at least 3 kWh.

Then, the system draws on stored energy during the TOU peak periods, avoiding operation during these expensive times.

Installation.

Water heating. As noted above, site conditions required removal of the existing gas water heater from a cramped crawl space and installation of the A2WTS storage tank on the building's exterior. Significant prep work included the construction of a level platform and weatherproof steel enclosure on a tight exterior slope and new envelope penetrations to connect to the existing domestic hot water distribution system. The monobloc heat pump was sited next to the tank and connected to an existing, dedicated electric circuit. Significant insulation and weatherproofing were installed around the tank and all exterior copper piping to minimize heat loss and protect the material from weather, animals, or other potential sources of damage.

Space heating and controls. The owner removed the gravity wall furnace from the center of the home and installed the new air handler and fan coil in the building's attic. This also required relocating the attic entry to allow for easier access and building an insulated platform for some system components. Because the home did not have preexisting ducting, new rigid metal ducts were installed, sealed, and connected to the new air handler. New water piping was installed from the exterior storage tank to the air handler heat exchanger. Finally, the system controller was installed in the building crawl space and plumbed to the space and water heating components. Communication wiring also connected the controller to the tank, heat pump, and air handler. A third-party low-voltage smart thermostat was then installed for system control and monitoring.

Installation timeline and experience. Determining the location of the combi A2WTS system components and site preparation were by far the most time intensive aspects of the installation, requiring trade work outside the normal skillsets of plumbing and/or HVAC contractors, including carpentry for attic preparation and metal work to create the exterior tank enclosure. Site preparation took several days to complete before the A2WTS system components could be installed.

System installation included both traditional HVAC and plumbing trade work as well as tasks outside of those trades. HVAC work included the installation of rigid metal ducting and installation of new supply registers. Plumbing work included new piping and connection to system components. Other work outside of traditional HVAC and plumbing included communications wiring between the controller, heat pump, tank, and air handler. Once site preparation and component siting was complete, the installation of the core A2WTS system components (controller, plumbing, communications wiring) was relatively quick – a two-day job, followed by a short commissioning process.

Lessons learned from the Bay Area project. The A2WTS fit all design goals, but many challenges were encountered during installation. Key lessons learned from this project included:

- *Multi-system replacement can reduce upfront costs*. Residential A2WTS can achieve many design benefits, and system costs can be similar to comparable separate space and water heating heat pumps if all system components can be replaced within the same project and if tax credits and/or program incentives are available.

- *Temperate climates offer flexibility*. Due to the relatively low heating load in the Bay Area and lack of need for air conditioning, a small A2WTS can manage all space conditioning and water heating demands.
- *Tradeoffs exist between installation flexibility and system footprint*. Residential A2WTS offer flexibility in terms of their ability to be installed in a variety of locations. However, the footprint of thermal storage tanks must be considered.
- *Site preparation requirements can impact project timeline and labor costs*. Site 1 faced many challenges that were primarily due to the age of the home, the limited space available for an A2WTS installation, and the need to move space and water heating systems to new locations. For retrofit projects, depending on the pre-existing systems, site preparation may be costly and time-consuming, and it may require significant labor outside of the installation of the core A2WTS system components. These costs should be considered in scoping the project, if applicable. Site preparation would likely be easier and cheaper in a newer home with existing ductwork.
- *A2WTS installation may require coordination of multiple trades.* This project required carpentry for site preparation, electrical to supply required power, plumbing to install piping and tanks, and HVAC to install ducting and air handling equipment. Coordination between the trades can add time or cost to an A2WTS installation. As these systems become more common, full-service installers may offer such coordination.

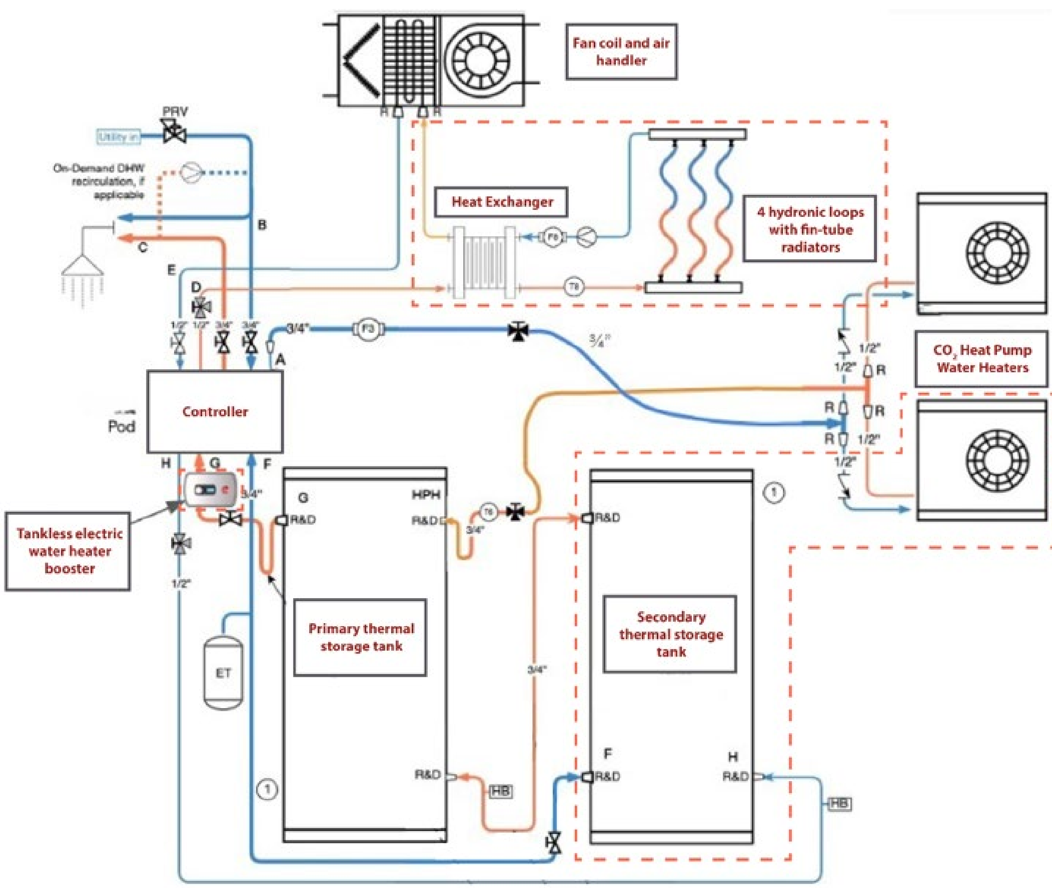

Figure 2. A2WTS system schematic

Summary of A2WTS systems. Figure 2 shows the components and connections in the A2WTS systems installed at Site 1 and Site 2. Components inside the red dashed outline are not part of Site 1 and are only in the Site 2 system, specifically:

- Hydronic heating loops with fin-tube radiators
- A flat plate heat exchanger to separate potable hot water from the water in the hydronic heating loops
- A second monobloc air-to-water heat pump and storage tank
- A back-up tankless electric resistance water heater

Site 2: Northern Vermont

Site. The Site 2 A2WTS installation is in a three-story, single-family detached home built in 2005 with 3,000 sq. ft. of conditioned space located in a rural area near Burlington, Vermont. Space heating was originally provided by a propane-fired, modulating condensing boiler rated at 63 kBtu/hr with four zones of hydronic heating distribution for space heat and one for water heat. Additional heating is provided by a wood stove with external air feed rated at a maximum output of 55 kBtu/hr. A solar thermal hot water system provided about half of annual water heating energy. Historical annual space and water heating energy consumption in this configuration was 77 MMBtu/year, evenly split between propane and wood. In 2022, the Site 2 owners installed a 15 kBtu/hr ductless mini-split heat pump with a low-temperature cut off at 5°F to 15°F that is used for heating for nine months of the year and cooling during the summer.

Ambient conditions. The climate at Site 2 is humid continental and experiences 8,000 heating degree days annually with temperatures ranging from a high of 94°F in the summer to a low of -20°F in the winter, as shown in Figure 3. Daily temperature swings are often greater than 20°F and can be as large as 40°F. At design temperatures of -12°F exterior and 68°F interior, ACCA Manual J compliant software estimated a maximum heating load of 44,354 Btu/hr.

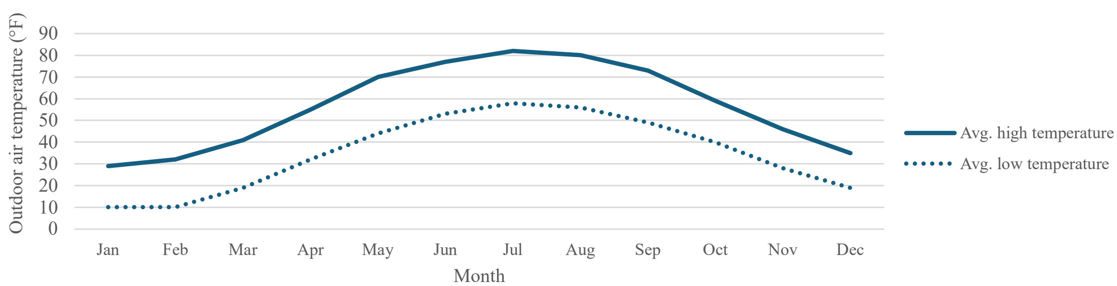

Figure 3. Site 2 average outdoor monthly high and low temperatures

Considerations in the selection of the A2WTS system. Site 2 had ample exterior space for the installation of two monobloc air-to-water heat pumps along the west wall of the house, directly adjacent to the basement mechanical room where the legacy propane boiler and water heater tank were located. This allowed a short exterior piping run from the monoblocs into the house. After removal of the legacy equipment, there was ample space in the mechanical room to accommodate the two 83-gallon hot water storage tanks, air handler, fan coil, and control module. Site preparation consisted of building a wooden frame to lift the air-to-water heat pump units above seasonal snow drifts. Other selection considerations included the following:

- *Eliminating onsite fossil fuel use*: The owners wanted to eliminate their last fossil fuel appliance, the propane boiler, to shrink their carbon footprint and because of a negative experience with propane leakage into the home.
- *Reducing onsite wood fuel use*: The owners use a wood stove for supplemental heating when temperatures fall below 40°F and wanted to decrease their wood use. Reflecting the expected continued use of the wood stove, the Site 2 A2WTS was designed to maintain an indoor temperature of 50°F when there is an outdoor temperature of -12°F, or a heat output of 34 kBtu/hour. This approach reduces the size and cost of the A2WTS while ensuring that if there is no one home to operate the wood stove when the outdoor temperature drops to -12°F, the indoor temperature will not fall low enough to damage the home or contents.
- *Energy efficiency and load shifting potential*: Site 2 is served by energy efficiency utility Efficiency Vermont and electric utility Green Mountain Power. Both provided incentives for the A2WTS installation as part of a pilot program to explore its demand response benefits. There was no TOU rate available for Site 2 that would be appropriate for use with the A2WTS system, but the residential electricity rate[5] is significantly lower than at Site 1. However, past prices for both propane and cord wood suggest that operating cost savings from the switch to an electric A2WTS are likely to be small.
- *Demonstrating an A2WTS system as a drop-in replacement for a residential boiler*: Given the state-of-the-art of available air-to-water heat pumps, designing a combi A2WTS system to be the sole source of heat in the Vermont climate would have meant changes to the heat distribution system, such as new radiators or additional ducting. Instead, the Vermont A2WTS was designed to maintain a minimum indoor temperature of 50°F at the outdoor design temperature of -12°F, with the objective of protecting the contents of the house if the owners were away during a cold snap. When the owners are home, they augment the A2WTS with the wood stove when necessary.
- *Maximizing the use of solar generated electricity*: Site 2 has a ground-mounted PV array that generates 20,000 kWh per year and increasing electricity used for space heating will allow a more optimal use of this resource.
- *Maximizing benefits of battery storage*: Site 2 also has 26 kWh of behind-the-meter battery storage as well as level 2 electric vehicle (EV) supply equipment that serves a battery EV and a plug-in hybrid EV, with a combined storage capacity of about 80 kWh.
- *Resiliency*: The North American Ice Storm of January 1998 knocked out electricity in northern Vermont for one to two weeks during the coldest time of the year. Site 2 is also 200 meters from the Winooski River, which experienced catastrophic floods during Tropical Storm Irene in 2011. Site 2's electricity generation and storage systems and multiple overlapping heating systems improve resiliency.

Equipment. As shown in Figure 2, the Site 2 A2WTS uses similar components from the same vendor as Site 1, but the Vermont system is larger and more complex than the one in the Bay Area. Site 2 uses the same proprietary controller as Site 1 that directs hot water to the different system components and that communicates with the air handler and fan coil integrated into the

[5] At the time, the Green Mountain Power Residential Service Rate 1 was $0.215/kWh throughout the year.

mechanical ventilation system. The system also has two monobloc, CO_2 refrigerant heat pumps rated at 15.4 kBtu/hr output each, two 83-gallon hot water storage tanks, and a 7 kW tankless electric resistance backup water heater for a maximum rated system heat output of 52.8 kBtu/hr. However, the actual heat output of the A2WTS system at Site 2 is limited by the hybrid hydronic/forced air distribution system (see Lessons Learned below).

Installation. The biggest challenge in installing the Site 2 A2WTS was finding a local contractor who was willing to take on the job. Air-source heat pumps and fossil fuel-fired hydronic heating systems are common in the area, but A2WTS for hydronic systems are new. The installation took longer than expected due to the contractor's lack of familiarity with the equipment and the A2WTS provider's lack of experience with residential hydronic heating systems. Integrating the air handler and existing heat recovery ventilation system was particularly challenging.

Lessons learned from the Vermont project. The Site 2 A2WTS installation had different challenges than Site 1. Key lessons learned from navigating the Site 2 project were:

- *Installer experience with hydronic heating systems is helpful but not alone sufficient for a successful A2WTS installation*. A critical factor in the success of both projects was the ongoing, intensive involvement of the A2WTS equipment provider who was on call to the contractor and owner during the installation.
- *The installed A2WTS system is not a drop-in replacement for legacy residential hydronic systems in the Northern Vermont climate*. In hydronic heating systems with fin-tube emitters, circulating water temperature drives heat transfer because they depend upon convection for heat transfer. The hotter the circulating water temperature, the greater the convective airflow across the fin-tube and the more heat is transferred. The heat pump used at Site 2 has a maximum output water temperature of 150°F, which is lower than the legacy propane boiler (maximum 180°F), therefore heat transfer is also lower. At the outdoor design temperature, the heat pumps produce enough heat to meet Site 2's heating load but the legacy hydronic loops[6] cannot distribute the heat rapidly enough to maintain the design temperature of 65°F across the four heating zones. The low heat transfer rate also means that the circulating water temperature drop across each loop is small, which degrades the efficiency of the heat pumps.

  The solution to both the heat transfer and circulating water temperature drop problems at Site 2 was to run the water returning from the heating zones through a fan coil unit before sending it back to be reheated. This transfers additional heat from the hydronic loops to the ventilation air, lowering the return water temperature. This solution was feasible because although Site 2 has hydronic heating, it also has a mechanical ventilation system that terminated in the mechanical room where the A2WTS was installed. The fan coil unit both improved heat transfer to the conditioned space and reduced the return water temperature to the heat pumps, which improved the coefficient of performance (COP). Additional work is planned to increase airflow through the fan coil unit to further improve COP. A similar pilot project underway in Milinocket, Maine with funding from Efficiency Maine uses cascading heat pumps to generate hotter water

[6] Four zones with fin-tube convective baseboard radiators.

for the hydronic loops and does not need to use a fan coil. European experience suggests this may also be possible with a single-stage AWHP with R-29 refrigerant.

- *Low ambient temperatures pose specific challenges*. The Site 2 A2WTS uses potable water as the heat transfer and storage medium. The space heating zones are in a closed loop separated from the heat pumps and storage tanks by a flat-plate heat exchanger. There is no antifreeze in the water that flows outside to the heat pumps, which improves COP but requires freeze protection on the short pipe runs between the exterior wall of the home and the monobloc air-to-water heat pumps. In winter, Site 2 can experience extended stretches below 0°F, so the freeze protection system must be powerful enough to protect the system but sophisticated enough to only operate when needed.
- *Incentives are helpful to achieve cost parity*. The total cost of the Site 2 A2WTS installation significantly exceeded the cost of installation for a high efficiency propane boiler and unitary HPWH. The high cost was due both to the cost of the equipment and the fact that this was the first installation as a residential boiler replacement with hydronic distribution system. The Site 2 project received incentives from Efficiency Vermont and Green Mountain Power and federal tax credits, which lowered the cost of the A2WTS to be comparable with a boiler and HPWH.

Results

Site 1

Monitoring for the San Francisco Bay Area site began in March of 2025 and continued through May of 2026. This paper presents results for this period about potential benefits and occupant experience for residential retrofit A2WTS systems in moderate climates.

Monitoring data and methodology. Several sources provide data that underlies the analysis for Site 1. These sources include the following:

- Manufacturer-provided A2WTS system controller data: The onsite A2WTS controller monitors component energy consumption, heat delivery, and water flows through the system and transmits these data points to the cloud via an Internet connection. Data on product energy consumption and heat delivery were collected from this source and used to calculate product efficiency and other metrics.
- Thermostat data: The system uses a third-party smart thermostat, and data collected from this product provided information about indoor and outdoor air temperature and humidity, temperature set points, and heating and ventilation runtime.
- Utility meter data: Utility meter data provides information about system electricity costs based on the home's TOU rate plan.

Results. Results for Site 1 include energy impacts, demand and load shifting performance, energy cost information, and impressions of occupant experience with the system. The analysis is based on a monitoring period from March 2025 to May 2026, which includes shoulder, summer, and winter operation.

Table 2. Energy impacts for Site 1

		Outdoor air temperature (°F)		Average daily energy metrics by month (kWh)				Coefficient of performance	
Year	Month	Min.	Average daily	Heat pump usage	System usage**	Heat delivered (DHW)	Heat delivered (heating)	Heat pump	System**
2025	March	44.9	53.4	10.1	10.9	5.7	27.8	3.3	3.1
	April	47.1	54.8	4.8	5.3	3.7	12.1	3.3	2.9
	May	50.5	56.7	4.4	4.9	7.1	8.6	3.6	3.2
	June	52.0	57.2	4.3	4.8	5.1	9.8	3.5	3.1
	July*	53.2	58.4	2.6	3.0	5.3	4.2	3.7	3.2
	August	55.6	61.2	1.5	1.9	4.7	0.7	3.6	2.8
	September	57.1	63.2	1.1	1.5	3.0	0.5	3.3	2.4
	October	53.3	61.3	2.5	3.0	5.6	4.0	3.8	3.2
	November	46.3	51.7	4.1	4.6	4.7	10.4	3.7	3.3
	December	43.5	56.4	10.8	11.6	4.8	33.2	3.5	3.3
2026	January	45.5	52.7	8.6	9.3	5.6	25.2	3.6	3.3
	February	42.8	54.2	6.9	7.6	7.5	17.3	3.6	3.3
	March	50.2	59.2	2.5	2.9	7.1	2.9	4.0	3.4
	April	51.2	57.1	3.7	4.2	7.5	6.2	3.7	3.2
	May	50.3	57.2	3.7	4.2	7.8	6.4	3.8	3.4

* Site attic installation was installed in July 2025, altering home heat requirements.
** Includes heat pump, fans, and controls

Energy impacts. Table 2 shows energy impacts for Site 1. Average outdoor air temperatures for this monitoring period were relatively stable, with about 10°F of difference throughout the year. Average daily heat pump energy use ranged from about 10 kWh in the winter to a low of 1 kWh in September, which was the warmest month in the monitoring period. Heat pump efficiency ranged from a COP of 3.3 to 4.0. System COP, including fan and controller energy use, was slightly lower. Attic insulation installed in July 2025 significantly reduced heating requirements – June and July had similar outdoor air temperature conditions and occupancy, but July average heat pump energy use was about 60% of usage in June. Heat delivery varies by end use – domestic hot water (DHW) delivery is fairly consistent, ranging from an average of about 4-7 kWh per day, but heating delivered for space heating ranges from 0 kWh in the summer to 30 kWh in the winter. Total annual electricity use for the system was approximately 1,800 kWh, measured in a one-year period following installation (April 2025 to March 2026). This value represents about 33% of the site's total annual electricity use; the site is all-electric. Future annual electricity use is expected to be less than this value due to the enduring efficiency impact of the attic insulation. This aligns with prior research that has shown that combining retrofits such as roof insulation with heat pump installation improves thermal comfort and can significantly decrease building energy requirements (Rodriguez et al. 2026).

Demand impacts. Figure 4 shows demand results for Site 1, including load profiles for heat pump (left) and fan (right) average demand during the entire monitoring period, for the month in the monitoring period with the highest heating load (December) and for the month in the monitoring period with the lowest heating load (September). The profiles also show the TOU rate peak period from 4-9 p.m.

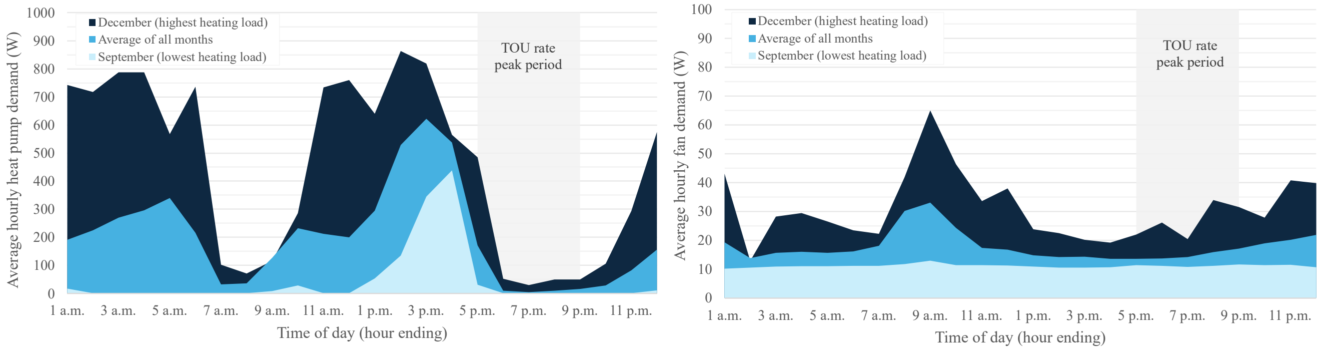

Figure 4. Average daily demand profiles for Site 1 heat pump (left) and fan (right)

Heat pump operation peaks overnight, from midnight to 6 a.m., and again in the afternoon between 1 and 4 p.m. In the cold months, the heat pump operates in multiple periods throughout the day, while in the warmest months, heat pump operation generally only occurs in the afternoon. Average cold season heat pump demand nears 800-900 watts in many periods, with a peak demand value around 1,500 watts, while average warm season maximum demand is around 400 watts, occasionally reaching a peak value of approximately 800 watts. Fan energy consumption is an order of magnitude less than heat pump consumption, ranging from 10 to 40 watts on average, and fan operation peaks in the morning start up period of 7 to 9 a.m. Fan energy consumption patterns differ from heat pump operation, demonstrating the value of TES to decouple heat pump operation from real-time user demand. The demand profiles also show little-to-no heat pump demand during the highlighted TOU peak period. This demonstrates the value of TES to shift load off peak while still meeting occupant comfort needs.

Occupant comfort. Figure 5 summarizes occupant comfort metrics for the system. For the time period of March 2025 to May 2026, the average outdoor air temperature was 57°F, ranging from 52°F in the coldest months to 63°F in the warmest month. The average heating set point was 68°F, and average indoor temperature was 70°F, ranging from 67 to 72°F.

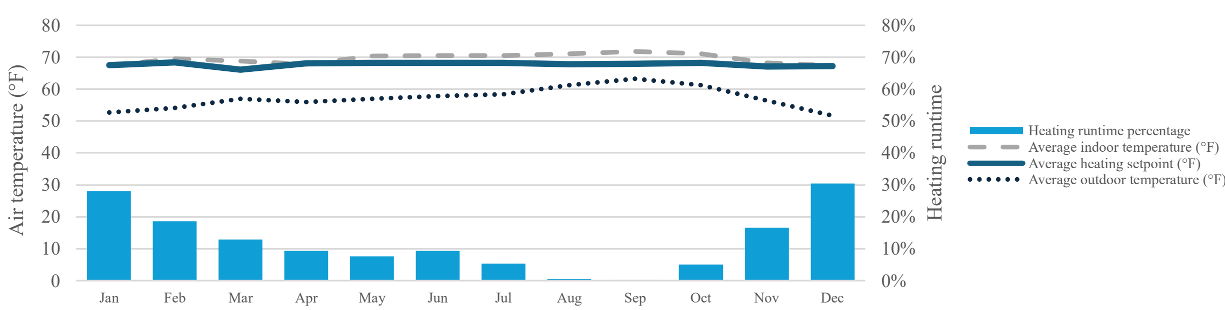

Figure 5. Site 1 occupant comfort metrics

These results demonstrate that the system maintained stable interior thermal comfort throughout the year. The figure also shows the heating runtime percentage throughout the year. The warmest months barely required heating, though they did include a small amount, and the heating system ran about 30% of the time in the winter. The system did not commonly experience strained periods where longer runtimes were required. In general, the system performed well in terms of occupant experience, and no significant operational issues have occurred.

Load shifting impacts. Figure 6 shows the site's TOU rate period for each hour of the day as well as the average percentage of heat pump energy use within that hour. These results show that 95% of heat pump energy use occurs within the TOU rate off-peak period; this load shifting is made possible by the A2WTS system's smart controller and the TES tank that allows energy to be stored off peak for use during the peak period. The site's TOU rate had an incremental energy cost of about $0.03-0.05 per kWh for peak period winter usage (total winter peak rate was about $0.50 per kWh) and an incremental energy cost of $0.10-0.20 per kWh for peak period summer usage (total summer peak rate was about $0.63 per kWh).

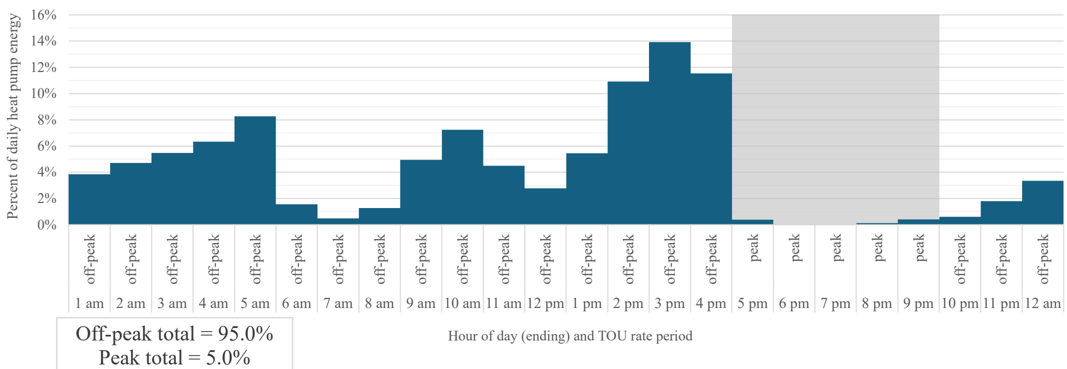

Figure 6. Average hourly heat pump energy use for Site 1 by TOU rate period

Maintenance and operating costs. Maintenance costs for the A2WTS at Site 1 are expected to be comparable to those for the pre-retrofit space and water heating systems since the system does not require differing, specific ongoing maintenance tasks. As for ongoing costs, as noted above, pre-retrofit utility bill costs are not available because the site was not permanently occupied prior to system installation. In the year following installation, from April 2025 through March 2026, the electricity cost paid for space and water heating totaled about $700 (based on the period's average electricity rate of $0.40 per kWh). Comparatively, assuming the same amount of heat delivered and accounting for the average measured heat pump COP (about 3.5), the efficiency of the pre-retrofit natural gas gravity wall furnace for space heating (70%), the efficiency of the pre-retrofit natural gas storage water heater (60%), the per-therm gas rate at the time of monitoring (approximately $2.50 per therm),[7] we estimate that providing the same amount of space and water heating using the pre-retrofit system would cost approximately $695. This value is almost exactly equivalent to the monitoring period operating cost of the A2WTS. Though operating costs are equivalent, the A2WTS offers additional, non-energy benefits such as safety and air quality benefits from decommissioning the home's gas infrastructure, resilience benefits due to increased hot water storage compared to the prior systems, reclamation of space within the home's interior, and improved thermal comfort.

[7] Pacific Gas and Electric, "Residential Non-CARE and CARE Gas Tariff Rates – January 1, 2024, to December 31, 2025," January 2026, https://www.pge.com/assets/rates/tariffs/Res_240101-251231.xlsx

Site 2

Monitoring for the Northern Vermont site began in March of 2026 and is ongoing. This paper presents only preliminary results for Site 2. Monitoring methodology and data collection is similar to Site 1.

Table 3. Energy impacts for Site 2*

	Outdoor air temperature (°F)		Average daily energy metrics by month (kWh)			Coefficient of performance	
Month	Minimum	Average Daily	Heat pump usage	System usage	Heat delivered	Heat pump only	System
April	17	47.9	19.4	20.4	40.4	2.5	2.0
May	35	54.5	9.3	10.0	22.6	3.0	2.3
June	47	66.5	2.5	2.8	7.2	4.0	2.6

* Monitoring period is March 29, 2026, to April 28, 2026.

Table 3 shows performance of the Site 2 A2WTS with no supplemental wood heating in April and very limited wood use in May and June. During the monitoring period, the A2WTS maintained set point temperatures in the four hydronic zones (typically 68°F) with only 0.1% of heating energy provided by the booster water heater and no supplemental heat from the wood stove or ductless mini-split heat pump.

The system COP for Site 2 was significantly lower than for Site 1. Although the average daily temperature for Site 2 during the month of April was only slightly below the average for April for Site 1, that masks the relatively large diurnal temperature swings at Site 2, as evidenced by the minimum temperature of 17°F for the month. The Site 2 COP was also constrained by the heat distribution system as discussed above. As in Site 1, the A2WTS at Site 2 improves COP by running the heat pump when it is warmer and storing the heat, which allows it to avoid running when ambient air temperatures are relatively low (6-9 a.m.).

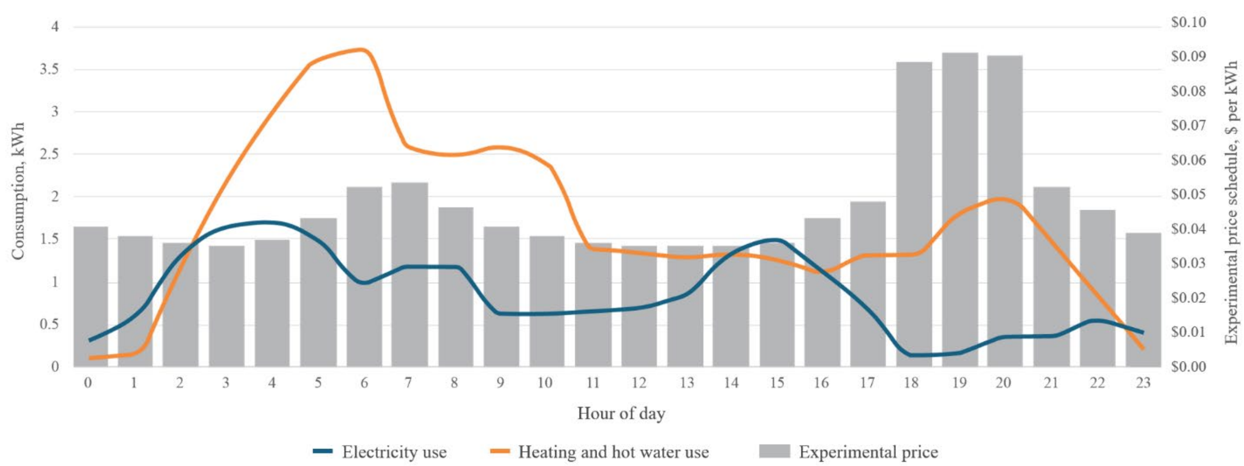

Figure 7. Hourly electricity use and space and water heating consumption for Site 2 A2WTS with Vermont grid prices

Demand impacts. Figure 7 plots Site 2 A2WTS electricity consumption (blue line) and site heating and hot water usage (orange line) over 24 hours and against an experimental electricity pricing schedule (grey bars) for the month of April 2026. The A2WTS stores heat in the early afternoon and then coasts through the time of relatively high electricity cost with low consumption despite increased demand for heat.

Occupant comfort. The Site 2 A2WTS maintained stable interior temperatures on all three floors of the house during the three months shown in Table 2. The coldest ambient temperatures of the year usually occur in January, and a more comprehensive assessment of the system's ability to maintain comfort will take place during the winter of 2026 to 2027.

Discussion and Conclusions

A commercially available residential A2WTS system was able to decarbonize residential space and water heating, meet design comfort requirements, and provide significant demand flexibility benefits over an entire year when installed in an existing home located in the San Francisco Bay Area. Electricity consumption for both space and water heating was shifted almost entirely out of the peak demand period as defined by the local utility's TOU rate, and operating costs were comparable to pre-retrofit systems. A similar but more complex A2WTS system installed in an existing home in Northern Vermont was able to meet space and water heating needs and provide demand flexibility benefits during shoulder months, based on a few months of operating data.

This research demonstrates that A2WTS can be successfully installed in retrofit applications in existing homes. Thermal storage may be a critical factor allowing the electrification of residential space heating because it can minimize grid impacts and provide demand flexibility services which, if monetized, could reduce residential heat pump operating costs. Residential A2WTS is still an emerging technology in the U.S. – performance should improve and installation costs should decrease as it matures.

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