

Best Practices from the Field: Air-to-Water Heat Pump Combi Systems

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ABSTRACT

Air-to-water heat pump combination systems represent an emerging class of technologies to meet residential and light commercial building decarbonization goals by serving multiple thermal loads - space conditioning and water heating - in one appliance. Research and field experience with these systems have yielded a breadth of lessons learned that will be shared in this paper with the goal of scaling practices to increase heat pump adoption. Combined space conditioning and water heating, or “combi”, systems can serve as an impactful decarbonization strategy for existing homes serviced by conventional fuel-fired equipment, by replacing warm-air furnaces and storage-type water heaters. From a system view, one of the key barriers to market adoption of air-to-water combis is the complexity of a field engineered combi installation, relative to a separate water heater and warm-air furnace or ducted, or direct-expansion type, electric heat pump. A practical breakdown of best practices related to controls, installation practices, and hardware (storage tank, fan coil, etc.) from the authors’ project experience is provided in this paper. Discussion will cover the breadth of air-to-water heat pump systems near commercialization or currently available, including case studies from both electrically-driven and fuel-fired systems. Suggested strategies will be presented to improve a home's delivered efficiency for space and water heating with field-assembled combi systems. Advice for retrofits will be provided to make homes “combi-ready” to both improve a home's delivered efficiency in the short term, while incrementally converting the home to hydronically-coupled forced-air heating. Finally, economic and energy return on investment comparisons from the case studies and technologies will be shared.

Introduction

Opportunities in residential energy efficiency for non-incremental savings (e.g. > 20%) are scarce due to technology limitations of traditional combustion equipment and air-to-air heat pump systems. Residential space conditioning and domestic hot water (DHW) systems in the United States are traditionally discrete systems with separate energy sources. Traditional air-to-air (A2A) heat pumps, including ductless mini-split options, can only provide space heating and cooling, and most of these heat pumps are not designed to have additional capacity to heat water. Common approaches of applying one A2A heat pump for space conditioning and a separate, indoor packaged heat pump water heater can result in negative interactive effects wherein the majority of the heat absorbed by the heat pump water heater is present due to operation of a space heating heat pump, de-rating the total energy savings. In cold climates, the authors have experienced this interaction in very low-load passive house buildings with a small space heating load. In one extreme instance, the DHW heat pump pulling heat from the room adjacent to the water heater closet caused extreme comfort challenges that the A2A minisplit was unable to address. The homeowners resolved the issue by placing a large electric resistance heating mat under an area rug to supplement the A2A heat pump and maintain comfort, an unwelcome situation and unexpected operational expense in their new construction super-insulated home.

Heat pump performance and cost effectiveness can be optimized and overcome many challenges using *combination space and water heating systems* (“combi” systems). By replacing two system components (e.g. furnace and water heater) with one heat pump, the incremental equipment cost and installation costs can be reduced. With greater delivered efficiency, a combi system can shorten long payback periods of upgrading from a condensing natural gas furnace to a heat pump and provide DHW. While additional hydronic components are often necessary, such as circulation pumps and a hydronic air handling unit (AHU), those costs saved by “bundling” equipment and infrastructure upgrades outweigh these incremental system costs.

Hydronic systems also offer advantages especially as it relates to zoning. With a buffer tank and a variable speed fan, a ducted system could be zoned for each individual room without impacting outdoor unit performance. Other advantages include dual and multi fuel configurations, defrost without impacting indoor temperature or needing backup heat in most climates, and integration with other things like solar thermal, waste heat recovery, and other efficiency strategies.

In residential applications, combis are occasionally packaged, but more often they are field engineered systems. Packaged combi systems have been commercially available for many years in residential and multifamily applications, typically with a fuel-fired water heater (tank or tankless) paired with a hydronic AHU. However, due to the need for flexibility when retrofitting buildings, most AWHP combi systems are typically field-assembled rather than installed as a packaged unit in single-family applications. In the past, combi systems have often faced technical barriers including unrealized efficiency gains, as well as market barriers due to unfamiliarity from installing contractors and perceived complexity (Less et al, 2012).

Additional hardware components are often necessary for combi installations, such as circulation pumps, heat exchangers, three-way valves, and a hydronic AHU, which can make installation daunting to unfamiliar contractors. However, costs saved by “bundling” equipment (i.e. space and water heating) and infrastructure upgrades can outweigh these component costs with as-installed system efficiencies of 90% or greater for conventional fuel-fired combi systems (Kingston et al, 2016). While hydronic heating distribution systems (delivering heat via radiators, emitters, etc.) are more common in Europe, most U.S. homes have forced-air heating distribution, 73% of single-family homes with central air conditioning (A/C), and of those with natural gas heating, 88% have central warm-air furnaces (EIA 2022). As a result, the focus of this study is residential combi systems with forced-air distribution.

Air-to-water heat pumps (AWHP) are an emerging class of technologies looking to address many of the historic challenges with combi systems. This highly efficient technology differs from traditional electrically-driven air-to-air heat pumps, also known as direct expansion (DX), in that heat is delivered at useful temperatures into a water-based delivery system instead of into the air. This provides a hydronic-based delivery system and allows for the use of conventional hydronic system components, such as low-temperature radiant emitters and baseboards, as well as the option to deliver heat into a forced-air distribution system using a hydronic AHU. The water-based delivery system of an AWHP uses a heat exchanger to provide heat for domestic water heating applications in a combi application. With enough capacity, an AWHP could also be installed as a “multi-function” system in residential applications to provide pool or spa water heating in addition to AHU and space heating.

Unlike most A2A heat pump applications, AWHPs can be driven by fuels or electricity. Fuel-fired AWHP are not a new technology, available in North America and abroad (Toppi et al. 2014), and use multiple different thermodynamic cycles described further below.

Combi AWHP are available as prefabricated systems in some markets, containing at minimum space conditioning and water heating systems, and frequently including ventilation and increasingly some power storage or converters. Egerter and Campbell (2020) provide an extensive comparative table with features and various manufacturers for both European and US markets. While more mature in other markets, prefabricated systems are uncommon in North American, with most manufacturers offering field-assembled AWHP combi products. Many of the companies that currently offer ductless A2A heat pumps in North America make AWHP and sell them in Asian and European markets. Some prominent manufacturers are in early stages of bringing their AWHPs to the North American market, including Mitsubishi, Taco, Stiebel Eltron, and others.

AWHPs are a technology category that is newer in North America, but well established in other parts of the world, with extensive installations throughout Asia and Europe. The North American heat pump market exceeded \$600 million in 2020 and is estimated to exceed 270,000 units by 2027 with the market value doubling over that time (North American Air to Water Heat Pump Market Size by Application et al, 2021). A significant majority of the AWHP market potential is in residential applications, but in order to achieve that market growth, technology solutions will need to overcome the relatively small market for residential hydronics in North America.

Technology Overview

AWHPs operate by moving energy from a low ambient air-source and transfer the energy to a fluid, distributed hydronically. AWHPs can be electrically-driven (via vapor compression) or fuel-fired (via absorption or other processes), but the fundamental energy transfer concept is often similar. The units are typically located outside of the building envelope, which for fuel-fired systems eliminates indoor air quality and depressurization concerns, since combustion is then located outdoors. Both electric and fuel-fired systems will typically have packaged refrigerant systems in an outdoor unit, with a heat exchanger to transfer energy to a water/brine loop that circulates into the building and associated end uses which may include emitters, storage tanks, or hydronic AHUs, as shown below in Figure 1. Without a field-charged refrigerant system and associated refrigerant handling certifications, AWHP installation may be achieved by a broader population for those with plumbing skills.

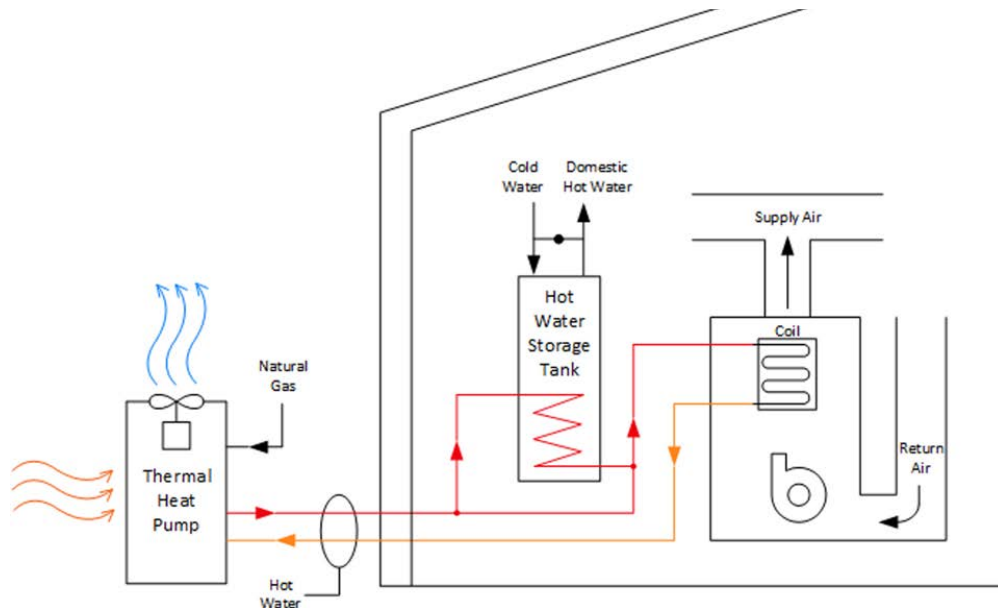


Figure 1: Representative fuel-fired AWP thermal heat pump in "combi" system application with hydronic AHU and DHW storage Source: GTI Energy

The vast majority of conventional electrically-driven AWHPs use a vapor compression cycle in the outdoor packaged AWP unit. At its core, the compression of a refrigerant creates a pressure difference which, in turn, drives the refrigeration effect moving heat from the cold source to the warm/hot sink such that the saturation temperature during phase change favors this direction of heat flow from the evaporator to the condenser. In all AWP systems, this energy is then transferred to a water loop, often a closed loop including anti-freeze additives. Several systems feature variable-speed compressors for output of as low as 30% of their rated capacity. A variable capacity electric AWP supplying a year-round water heating load can typically achieve annual average coefficients of performance (COP) in the range of 2.5 to 4.0, depending on climate and the temperature to which the water loop needs to be heated.

The underlying technology for fuel-fired AWHPs predates widespread electrification of buildings in the early 20th century, including sorption cycles for ice production using solar energy in 1878 (Butti, 1980) and using fuel-driven compressors to drive air-conditioning & refrigeration equipment before the U.S. Civil War (Univ. of Fl, 2020). In the most common fuel-fired AWHPs, the energy input from fuel combustion drives a vapor absorption cycle, which absorbs heat from the outside air through an evaporator, providing approximately 40% of the AWP heat output to a hydronic loop. The remaining 60% of heat output is recovered from both the heat of sorption (at the absorber(s)) and waste heat from flue gases. Typically, power is needed to drive an evaporator fan, solution pump, combustion blower, and controls. As a heat pump, the net heating output of a fuel-fired heat pump exceeds the energy input with operating COPs on a fuel-input basis ranging from 1.2 to 1.65 (Winer and Glanville 2020). Fuel-fired heat pumps typically do not require auxiliary/backup heating, as they can function as heat pumps down to -30°C (Fridlyand et al. 2021), which can save on winter peak electrical demand. That being said, with some state energy plans moving away from fossil fuels, broader adoption of fuel-fired heat pump technology may be limited.

An exhaustive comparison of electrically-driven and thermally-driven AWHPs is beyond the scope of this paper, but a list of attributes for qualitative comparison is provided below.

Table 1. Qualitative comparisons of residential AWHP combi heat pumps

AWHP type:	Electrically-driven	Fuel-fired (sorption-type)
Thermodynamic cycle	Vapor compression	Vapor absorption
Common working fluids	R-134a, R-410a, R-32	NH ₃ (R-717)/ H ₂ O
Global warming potential of the common working fluids	1320 GWP, 2088 GWP, 771 GWP*	0 GWP*
Energy requirements	240 volt alternating current (VAC) power	Delivered Fuel (natural gas, propane, renewable natural gas, hydrogen), 120 VAC
Backup/auxiliary heating	Typically electric resistance	None or combustion-based
Residential market players (partial list)	Arctic Heat Pumps, Aermec, Chiltrix, Enertech, Nordic, SpacePak, Unico	Anesi, Robur, Thermolift, Vicot
Site energy COP (electric or gas basis) at 17°F	2.2 – 2.8	1.2-1.9

* Global Warming Potential (GWP) indicates GHG impact relative to CO₂

Packaged refrigerant system types will be the focus for this paper, although at least one electrically-driven AWHP system studied had the refrigerant split to a unit located indoors and can perform heat recovery for DHW preheating. In cold climates, installing AWHPs in a combi system is frequently done to absorb useful heat from outside the thermal envelope for the DHW, avoiding issues of undesired interactive effects between multiple heat pumps in cold climates.

Conventional Combination Space and Water Heating

Field assembled conventional combi systems are well understood, with some of the major issues concerning these conventional combi systems listed below:

- Proper controls and fan coil sizing are needed to make sure most on-cycle events have a sufficient cool return water temperature to promote “condensing efficiency” for water heaters/boilers with 90%+ rated efficiency (Kingston et al, 2016).
- DHW priority must be assured to minimize the impact of loss of comfort (e.g. “cold water sandwich”) when meeting overlaid and/or simultaneous loads.
- Safe handling of Legionella formation by the system operation must be assured for potable water systems, though this doesn’t directly affect AWHPs installed with closed heating loops.

While these issues and others are well understood, the dynamics of a AWHP combi system are much different and the lessons learned, control strategies, and installation best practices of conventional furnace/water heater combi systems do not often apply. Some important considerations for AWHP combi versus conventional 80% efficient gas water heater/boiler-based combi systems are:

- **Increased system thermal mass:** In comparison to A2A heat pumps or fuel-fired furnaces, AWHPs have more in common with boilers than other heating systems, due to an increased thermal mass. Particularly for heat pump-based systems, bringing the unit, the heating loop,

and other components (AHU, etc.) up to temperature and starting the ‘heat pumping’ process can take several minutes, and the system controls must account for this to limit short cycling and maximize inter-cycle heat recovery.

- **Modulating / Variable Speed capabilities:** Electric AWHP systems may be variable capacity and/or inverter-driven to help match capacity and load. Fuel-fired AWHPs may be limited to dual-stage or even 4:1 turndown, unlike the 20:1 turndown common for conventional tankless water heater-based combi systems. As a result, and to meet the refrigerant-to-potable water heating code requirement of a “double wall” for heat exchange, an indirect storage tank is required for the majority of AWHP combi systems. The management of this thermal storage and the dynamics of shifting from space heating to DHW recovery require a different strategy than conventional combi systems.
- **Influence of Operating Conditions:** As an air-source heat pump, the operating efficiency and capacity are influenced by both ambient *and* heating loop temperatures. This influences the use of setback curves, overall performance, and hardware sizing.
- **Using split media:** In some cases, the heat pumps are more akin to a DX system. Space heating and DHW are provided by separate media (refrigerant/water-glycol respectively) and considerations for combi system best practices are affected accordingly. Additionally, there may be increased capital and operating costs associated with installing and operating these components (e.g., circulation pumps).
- **Engineered systems:** Considering these operating characteristics, it is possible a unique engineered system (tank, coil, heat pump, buffer tank) is required as is used with “all-in-one” multifunction electric heat pumps.

Best practices for Scaling AWHP-based Combi System Design

As most residences in North America have forced air space heating, it is important when retrofitting AWHPs into these homes to provide hydronic AHUs. Combi systems in forced-air heating applications are generally deployed in one of two manners, using potable open arrangements, and non-potable closed arrangements. When using an AWHP, combi systems are typically used as a non-potable (closed loop) central heating plant, directly tied to the hydronic AHU. These non-potable central heating plants have advantages over open systems including reduced system complexity, reduced likelihood for system short-cycling in space heating modes, increased ability to operate with higher space heating temperatures (generally up to 180°F/82.2°C), increased acceptance by building codes, and reduced concerns with water quality and bacteria. Generally, in this arrangement the AWHP will be tied to an indirect storage tank in parallel to the AHU to provide potable DHW. This buffer storage can eliminate temporary loss of DHW heat commonly experienced with tankless water heater-based combi systems caused by system cycling/adjustments (“cold water sandwich” or “cold slug”).

With advantages and disadvantages between potable and non-potable based combi systems, depending on specifics of the home and retrofit versus new construction scenarios, combi systems are an emerging solution to improve the energy efficiency of residential space and water heating systems. While manufacturers continue to improve cost-effectiveness and efficiency, these improvements are generally incremental in nature. For these applications, AWHP combi systems may offer significant energy savings for delivered space and water heating over baseline and conventional efficiency options, up to 45% gas savings over baseline

natural gas equipment (Garra-brant and Keinath 2020), and similar non-incremental savings seen for electric based products (Eklund and Banks 2017).

We have identified a number of best practices below that are based on the authors' installation experiences from leading several pilot demonstrations of AWHP combi systems. This list is not exhaustive and builds on experience gained in both electrically-driven and fuel-fired AWHP combi systems. The best practices are intentionally both non-proprietary and at a high-level to respect individual manufacturers.



Figure 2: Fuel-fired AWHP cold climate demonstrations Source: GTI Energy

1. Use larger indirect storage tanks, with larger internal heat exchangers, to limit short DHW-recovery cycles

Early field demonstrations of a fuel-fired AWHP combi system used a small 45-gallon indirect storage tank (IST), which has an estimated 11 ft² internal surface area (Glanville et al 2018). When operating in DHW-only mode and space heating was not called, the AWHP combi system short-cycled significantly, with on-cycles averaging only 12 minutes. As the indirect loop and the heat pump itself require time to ramp up to reach DHW recovery supply temperatures, the overall combi system cannot reach peak steady state efficiency for DHW cycles, particularly as the tank heats up quickly, rapidly changing the loop return temperature. We suggest incorporating additional water (and its associated thermal mass) into the system. A larger 80-gallon tank replacement with an estimated 18 ft² internal surface area, can double the DHW recovery cycle times and, in turn, increased overall cycle efficiency significantly. This can be seen in the chart below, where coefficient of performance (COP) for a fuel-fired AWHP are approximately doubled.

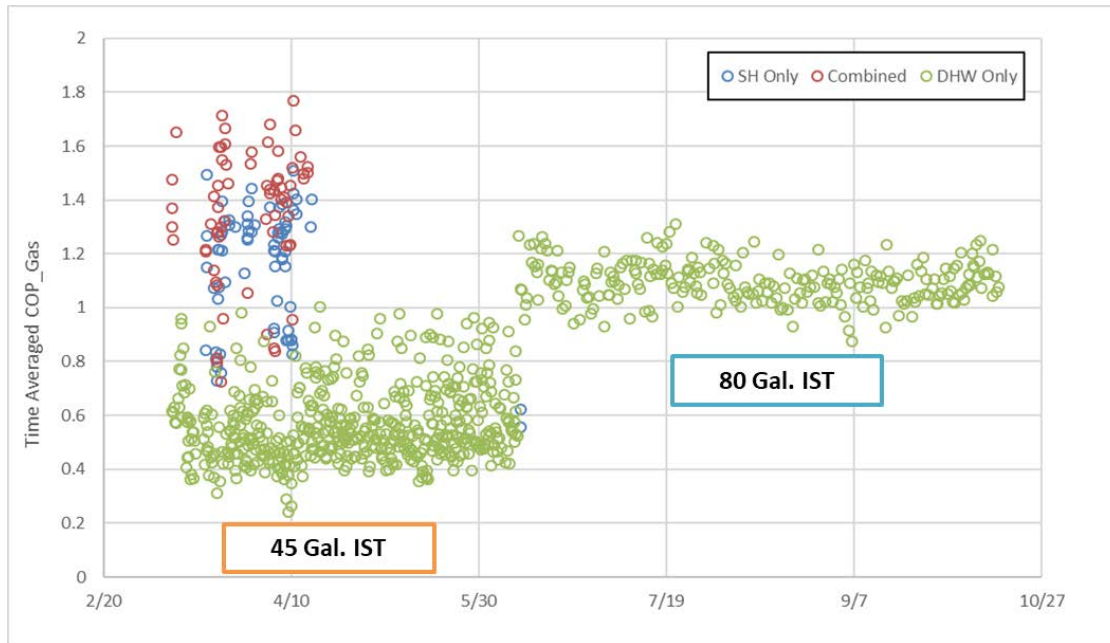


Figure 3: Impact of two IST tank sizes on COP for a fuel-fired AWHP combi. Source: GTI Energy

2) Employ outdoor temperature reset curves

Outdoor temperature reset curves, commonly used by boilers serving space heating loads, adjust the target supply temperature as a function of outdoor ambient temperatures, with peak temperatures during the coldest conditions. Fuel-fired AWHPs typically employ such a strategy, which like boilers, seeks to limit the system losses while maintaining occupant thermal comfort. Special consideration is needed when serving DHW loads however, as while reducing the IST tank temperature as the outdoor temperature increases allows the heat pump to operate at higher COP, this control strategy decreases the DHW temperature, particularly in shoulder seasons.

3) For variable capacity systems, matching with modulating or variable-speed AHUs is advantageous and can improve comfort

Some AWHPs are variable capacity systems that provide some degree of modulation. Based on field demonstrations, it is advised to employ multi-stage or modulating AHUs paired with these heat pumps, and carefully designed controls. These were qualitatively found to improve occupant comfort, with no perceptions of “cold blow” noted in occupant surveys (Garrabrant and Keinath 2020). Just as important, the ability to control AHU air flow is an additional system control point to maintain a desired return temperature to the AWHP and to lengthen on-cycles. For “high-mass” systems, mitigating short-cycling is critical to system reliability and operating efficiency alike.

4) Minimizing the loop volume is key to reducing system losses

Each time an AWHP on-cycles, it is important to maximize the system runtime through modulation and effectively switching between space heating and DHW modes. However, there will always be system losses that eat away at the installed system’s steady state performance. This is not unique to AWHPs; all cycling equipment will waste heat via cycling losses, however AWHP combi systems and other hydronically-driven forced-air systems have higher losses due

to the thermal mass of the heat pump and hydronic loop. These losses are estimated to be ~25%, meaning that only 75% of the total AWHP's system output is typically captured as useful space heat and/or hot water during each complete on-cycle. When cycled, AWHPs warm up and gradually reach steady performance for a given loop temperature (condenser/absorber), ambient temperature (evaporator), and heat the closed loop to the desired temperature, which can take 5-10 minutes depending on the loop volume. In turn, the loop heats the AHU and/or IST and, once the load is met, heat recovery is employed. A fraction of heat output will always remain 'locked' in the loop below useful heating temperatures, a sort of "cycling tax". Keeping loop runs short, direct, and well insulated will help minimize these losses and associated penalties.

The impact of reducing loop volume during early GTI Energy demonstrations for DHW recoveries is shown in the figure below. For an estimated actual loop volume of 10 gallons, the modeled impact of a 33% and 50% reduction in loop volumes (shorter runs and/or smaller diameter) are shown, where a near proportional improvement in delivered efficiency is seen with these volume reductions. This impact is more pronounced with longer standby periods between on-cycles, where more loop heat is lost to the mechanical room (Glanville et al. 2018).

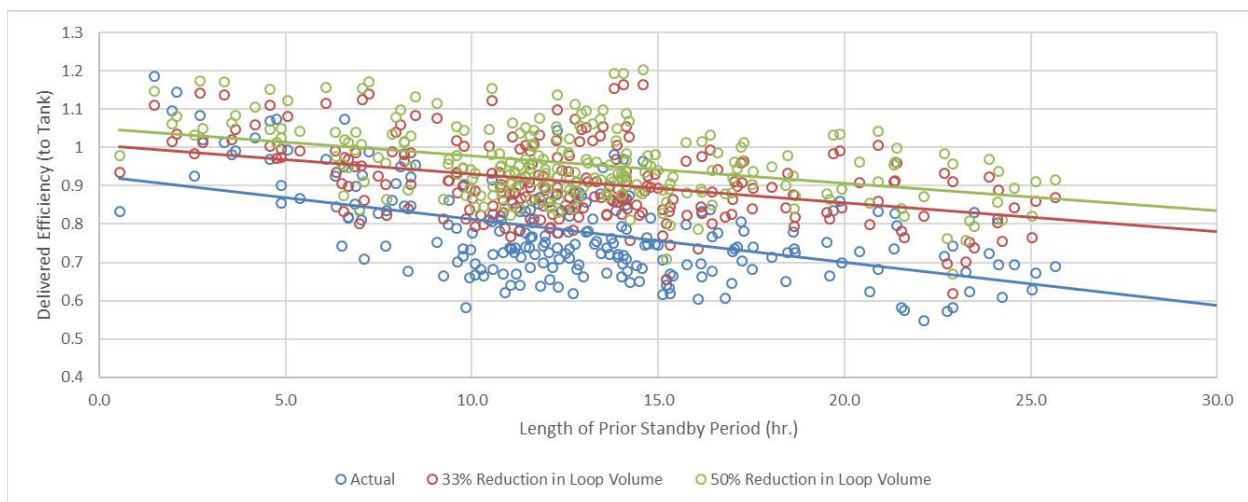


Figure 4: Calculated delivered efficiency to storage tank for actual and reduced loop volumes. *Source: GTI*

5) Standby losses can be further mitigated with avoided thermosyphons

As an AWHP cycles off, particularly in the winter heating season, the standby loss heat rate between the indoor and outdoor components is non-uniform. As heat losses accelerate for the heat pump and outdoor hydronic components, this can create adverse thermosyphons where even slight elevation changes are possible. This will often be the case where the outdoor AWHP was at a higher elevation than the indoor AHU and IST components, typically installed in a conditioned basement. As the indoor components will generally be warmer, this keeps this portion of the loop warmer, which via buoyancy migrates to the outdoor loop and heat pump, where accelerated heat losses rapidly cool the fluid to sink back to the lower elevation indoor section. A thermosyphon forms and this unsteady, uncontrolled flow accelerates system heat loss. Check valves should be employed (spring-loaded preferred) to assure no adverse thermosyphons continue, which can be placed at the AWHP or indoors. These will prevent both reverse thermosiphon between the buffer tank and heat pumps, as well as forward thermosiphoning from the buffer through distribution piping.

6) Assure the glycol/water mixture is properly controlling corrosion in indoor components and, if possible, employ auto-fill assemblies

While closed heating loops are common for boiler-based hydronic systems, using glycol/water mixtures for outdoor-installed AWHPs requires additional care for corrosion control. Depending on the system design, the glycol/water mixture may come into contact with the AHU, IST, heat pump, and a wide array of plumbing fittings and pipe runs. At one Wisconsin-area site, corrosion at the AHU was observed during replacement, leading to selection of a better optimized corrosion-inhibited glycol for the remainder of the test period (Glanville et al. 2019). Other than completely avoiding ferrous components, a dirt and magnetic particle separator on the flow inlet to the AWHP can help limit impacts of corrosion and debris on the heat exchanger.

Additionally, auto-fill assemblies are advised to assure the hydronic loop is primed and pressurized, ensure peak performance, and avoid pump cavitation. These are an increasingly popular solution to automatically “top off” the loop, preferably from a premixed glycol/water mixture if in freezing climates. This can be helpful during the first few months of operation as microbubbles are worked out of the system by air separators. This also replaces the need for potable make-up water connection in the hydronic loop, which could dilute the antifreeze protection, save potential back flow contamination, and inspire less curiosity from code officials.

7) Balance space conditioning and domestic hot water demands in combi systems

Whenever an AWHP combi is providing cooling, simultaneous calls must set a priority. DHW is usually given priority over heating or cooling, as a DHW load will likely be satisfied quickly and failure to meet delivered DHW demand is more easily perceived. Once the IST has met the temperature limit, the system can resume the space conditioning call. During the space heating season, the system will continue to operate seamlessly. For a system that also provides cooling, after the DHW load is met, AWHPs may have a delay of 5 minutes or greater to allow for refrigerant pressures to equalize before resuming cooling mode operation. Oversized buffer tanks can help mitigate this. A similar time delay on the AHU blower when transitioning from DHW cycle to chilled water cooling will help prevent a hot water “slug” through the AHU cooling coil.

8) Leverage buffer tank heat recovery to ensure longer on-cycles

Optimizing and debugging system controls can be a time-consuming activity for installers. One recommendation is to use the buffer heat storage of the IST more effectively. Early prototype systems would switch from space heating to DHW recovery mode purely as a function of thermostat/aquastat input, with limited constraints placed (e.g. timer delays). Advanced heat recovery was used to “top off” the IST with heat in between space heating cycles, independent of DHW demand, to assure the heat pump wouldn’t cycle off between thermostat calls. More refined control strategies may incorporate variable speed / modulation control and the ability to strategically employ “overshoot” of space heat/DHW output to extend system runtime.

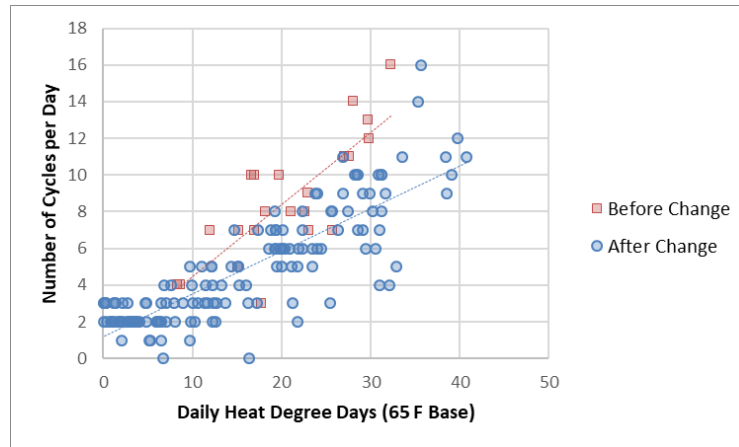


Figure 5: Impact on Controls Change at AWHP Site on Cycling Rate Source: GTI Energy

9) Systems should avoid short-cycling and excessively long on-cycles

In some fuel-fired demonstrations, heat recovery controls coupled with periods of moderate/mild winter temperatures, were *too successful* in ensuring extended runtime, leading to operating cycles lasting more than 24 hours at a time. These excessively long runtimes were the result of the fuel-fired AWHP combi “load-following” the home’s space heating load, operating at a low modulation point, and observed to both result in lower overall cycle efficiencies with enhanced system heat loss and placing additional “wear and tear” on the AWHPs with longer runtimes per heating load served. Later, enforced off-cycling was employed at cycling periods of 8+ hours, though optimizing this duration is an area for further research.

10) Use pre-fabricated installation kits to improve the efficiency and cost of AWHP combi installations

We explored the benefits of pre-engineered/pre-assembling plumbing components for AWHP installations to reduce the complexity, time, and cost of system installation. While the number of components was exacerbated by research instrumentation needs of the sites, the figure below highlights original field-assembled components vs. an improved approach.



Figure 6: Manual plumbing assembly at early site (Left) and pre-fabricated/assembled fittings for later site (Right) Source: GTI Energy

Contractor unfamiliarity with hydronics is a key barrier that manufacturers are working to solve. Pre-engineered kits are available from some AWHP manufacturers, as well as solution providers from some hydronic component manufacturers, such as Caleffi. Some manufacturers such as Anesi have integrated many hydronic components such as three-way valves, expansion tank in empty space within their hydronic AHU; Enertech and Taco have taken similar approaches with an indoor controller box. Pre-assembled kits create a more “plug and play” experience for installers replacing a conventional natural gas furnace and easing the integration of hydronics into HVAC installer workflows and saving hours on the installation time.

Design practices summary

The ten design recommendations discussed above for AWHP combis help position an installed system for success, optimal efficiency, and reliable long-term operation. However, the hardware-intensive approach and unfamiliarity with hydronic aspects of AWHP systems will present challenges for many HVAC installers and will likely remain a niche approach without significant market transformation efforts.

Case Studies

Two case studies on AWHP combi systems will now be presented to pull concepts together. In the first, an electric AWHP is discussed, used with permission from a colleague, and in the second a fuel-fired AWHP system demonstrated by the authors will be presented.

New York Electric AWHP Combi Retrofit

A single-family detached home constructed in the 1980’s in upstate New York was built with a 300-gallon underground propane tank, in a unique arrangement where the tank was owned by a propane supplier with exclusive filling rights. This supplied propane-fired equipment mainly including a furnace, water heater, and range. Approximately 90% of the propane usage was estimated for space and water heating. At the time of the project start (spring 2021) propane was \$3.62 per gallon, which comes out to about \$44 per MMBtu delivered (assuming a 89% combustion efficiency). Annualized propane costs approached \$4,000 by early 2021 for this household.

An Enertech AWHP combi system was installed in June 2021 to provide space heating, chilled water cooling and close to 100% of domestic hot water, with electric resistance making up the difference in peak conditions. The heating and cooling was supplied through existing forced air distribution system, and a 9 kW electric resistance system was included for backup heat. To future-proof the installation, a hydronic manifold station was installed to allow for future panel radiators or addition of radiant floor heating. The unsubsidized installed AWHP system cost was approximately \$23,000 and conservative measurements estimate the annual COP at 2.5. The average cost of thermal energy provided by the pump in this installation based on electric rate of \$0.125/kwh (or \$14.65 / MMBtu delivered) resulted in an annual estimated savings of \$2,400 per year compared to the prior propane-based heating systems. The savings resulted in less than a 10-year payback without accounting for the additional rise in propane fuel costs (Siegenthaler 2022).

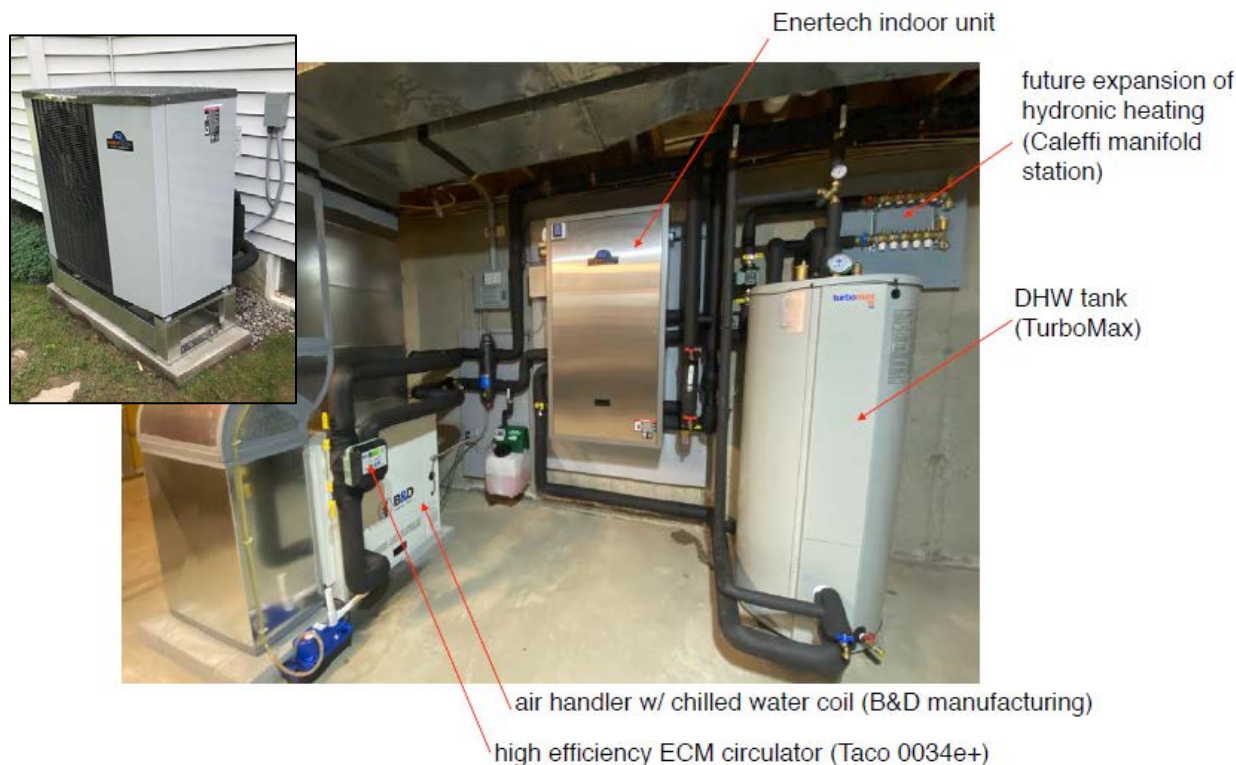


Figure 7: Outdoor and indoor components of Enertech AWHP combi in New York. *Source:* John Siegenthaler

Illinois AWHP Combi Retrofit

A consortium of North American natural gas utilities supported a field demonstration of multiple fuel-fired AWHPs from 2019-2020 manufactured by Stone Mountain Technologies Incorporated, now marketed under the Anesi heat pump brand. The Anesi heat pump is an AWHP system that GTI has performed laboratory evaluations on and confirmed 140% Annual Fuel Utilization Efficiency (AFUE) performance¹. These AWHP installations were retrofit combis providing all space heat and water heat. One single-family detached home constructed in the 1960s in suburban Chicago was the only U.S. host site with extended operation. The demonstration unit was a pilot unit in this case and received some technology improvements after the first heating season to prepare for commercial product launch. The AWHP replaced a 0.67 Uniform Efficiency Factor 40-gallon storage water heater and 92% AFUE.

An Anesi heat pump with maximum output of 120,000 BTU and 4:1 turn down ratio was an adequate size to replace the existing furnace and provide domestic hot water at this home. The combi system design included the outdoor AWHP unit, a hydronic AHU, 80-gallon IST, and a control board – a similar setup to the Enertech system setup described above.

Detailed instrumentation was installed to monitor all aspects of the combi system performance and delivered energy. This was compared against a performance-based model for the baseline furnace using an input-output correlations for condensing and non-condensing furnaces from prior GTI laboratory evaluations and the gas capacities of the furnaces from each site calibrated with utility billing analysis from the site. The installed performance achieved 30%

¹ Tested to ANSI Z21.40 rating conditions for fuel-fired heat pumps

reduction in natural gas savings on an annualized basis. The heat pump system fully provided all space heat and DHW for the home, with no need for electric resistance backup heat. Space heat was delivered through existing ductwork that had previously received Aeroseal duct sealing prior to baseline monitoring.

As this was a pilot demonstration with extra research instrumentation, actual costs are not reflective of commercialized costs, so we instead use EIA estimates for total installed cost of residential natural gas heat pumps of \$14,700². The average cost of thermal energy provided by the AWHP gas heat pump in this installation resulted in 30% reduction of natural gas consumption. While not a significant economic benefit due to the low price of natural gas, the CO₂e benefits of the fuel-fired AWHP system compared to other options was impressive. We followed the approach Fridlyand et al (2020) laid out comparing marginal electricity grid emissions, since increased or decreased demand for electricity in buildings is managed on the margin (EPA 2021), which for the foreseeable future will be dominated by fuel-fired power plants. When applied to this site's performance, emissions savings were modeled at saving 8.2 tons of GHGs versus the baseline system. This is demonstrated in the figure below, which also shows scenarios of "Better Gas" (condensing furnace with tank water heater), and "Best Gas" (condensing furnace with tankless water heater), as well as with an all-electric scenario of a cold climate air source heat pump along with an electric heat pump water heater.

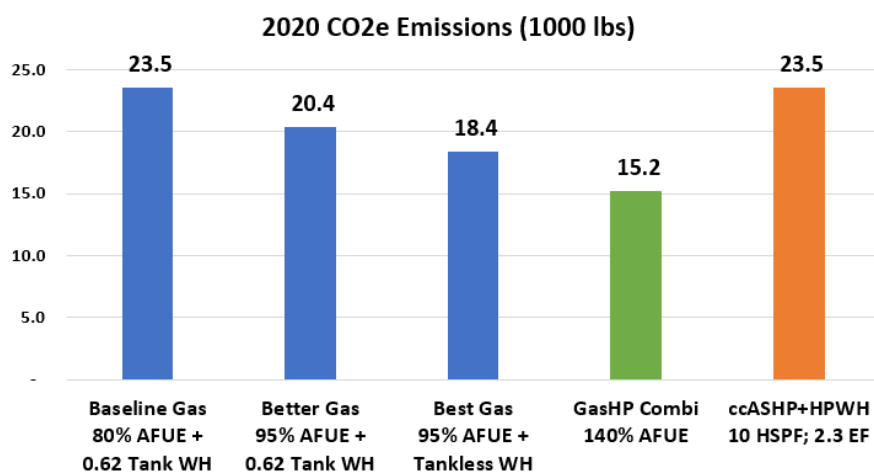


Figure 8: Comparison of AWHP "GasHP Combi" with other options in Chicago (left); GasHP Combi at -5F ambient temperature (right). *Source: GTI Energy*

Summary

By combining modern air-to-water heat pump technology with residential space conditioning and water heating systems, designers can achieve benefits not possible with separate heat pump systems. These include superior comfort, minimally invasive installation, the ability to heat domestic water, integrate with a wide range of other loads and energy sources, and a long service life. The cost of an AWHP system lands somewhere between that of a ductless minisplit and a water-to-water geothermal heat pump system, but can deliver a combi approach for space conditioning and domestic hot water. Additionally, AWHP combi systems avoid the

² Source: <https://www.eia.gov/analysis/studies/buildings/equipcosts/pdf/full.pdf>

issue of upgrading electrical panels to accommodate two 240V breakers (one for space heat and one for water heating), and take up less space outside.

Using national averages for electricity generation, the GHG emissions reductions are comparable in both electrically-driven and fuel-fired applications of AWHPs; both are better than the baseline scenarios they are compared against. As with many emerging technologies, cost effectively decarbonizing a home with AWHPs is difficult to do through an economic lens only, apart from offsetting relatively expensive fuels such as propane or fuel oil. If renewables are included on a site or a location happens to be in area with significantly low-carbon electricity compared to the national average, an electrically-driven AWHP will have superior decarbonization characteristics. From a source energy carbon standpoint, in applications where onsite renewable energy generation is not possible, a fuel-fired AWHP may be more attractive to reduce GHGs immediately. If in the future the electricity grid is decarbonized, fuel-fired AWHPs may be less beneficial than electric AWHPs and the hydronic infrastructure can be repurposed.

There are clear decarbonization benefits to installing AWHP systems in a combi application to provide both space conditioning and water heating. The concepts and details presented in this paper serve as building blocks for successful integration of electrically-driven or fuel-fired AWHP systems that provide all space conditioning and water heating for residential applications. With the majority of AWHP combi systems being field engineered, the lessons shared in this paper will help scale adoption of this important building decarbonization strategy.

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