One Machine for Heating Cooling & Domestic Hot Water: Multi-Function Heat Pumps to Enable Zero Net Energy Homes

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ABSTRACT

The evolution of heat-pump technology promises a revolution for residential energy efficiency. While traditional residential mechanical design uses multiple systems and fuels to provide thermal services, the emerging generation of heat-pump technologies can provide heating, cooling and domestic hot water with a single appliance. These heat pumps operate over a wider temperature range than their predecessors, offer substantial efficiency improvements, and introduce opportunities for waste heat recovery. The domestic hot water heating market is beginning to experience this change as air-source heat-pump water heaters deliver obvious energy savings over electric-resistance water heaters; and (arguably) also beat condensing gas-fired systems in terms of source energy consumption and greenhouse gas emissions. However, we anticipate that the current introduction of stand-alone heat-pump water heaters is only the first step in a transition toward multi-function heat-pumps that can replace conventional air-conditioners, furnaces, and hot water heaters. The study presented draws from multi-season field measurements of operation and performance for several multi-function heat-pumps. The research assesses the overall efficiency of these systems, and compares the advantages and disadvantages of alternative designs. Our research provides monitored examples of air-source heat pumps, geothermal heat pumps, water-to-water systems, and desuperheaters. We also describe the design of the multi-function heat pump at the core of a zero-net-energy demonstration home designed to generate enough electricity to also power the annual drive cycle of an all-electric sedan. The heat-pump in this home is designed to cover all heating, cooling and domestic hot water needs with no backup.

Introduction

Traditionally, residential mechanical design has relied on separate systems to provide each specific thermal service including space heating, space cooling, and domestic water heating. In California, gas furnaces are generally used for heating, vapor-compression forced-air systems for cooling, and gas-fired storage systems for domestic water heating. Reversible heat pumps offer an opportunity to merge these multiple functions into a single machine. There has been some small but growing application of reversible air-to-air heat pump systems to provide both heating and cooling, and geothermal heat pump systems have enjoyed relatively broad application within niche markets. Broader adoption for these systems will require overcoming a variety of technical and financial challenges. The domestic hot water heating industry has recently made significant advances to commercialize stand-alone electric heat-pump storage hot water heaters. These systems offer obvious benefits compared to electric resistance water heaters, and can (arguably) also be better than condensing gas-fired systems in terms of source energy consumption and carbon emissions. Since heat pumps are all-electric, they offer the possibility of a move away from on-site combustion for thermal services in residences. This aligns well with goals to reduce non-point source emissions of NO_x, and with the budding policy initiatives to advance zero net energy homes as standard practice.

As heat pump systems become more common within the industry, we anticipate a movement toward central multi-function heat pumps that provide heating, cooling, and domestic hot water services in residences. This combination of functions within one machine promises capital cost savings, efficiency improvements, and opportunities for a significant amount of waste heat recovery. This paper explores a variety of heat pump system architectures that provide multiple functions, and reviews some of the advantages and challenges with each. Detailed field measurements of performance were conducted for three homes that employ different multi-function heat pump arrangements. The results of these efforts motivated the design of a more fully integrated multi-function water-to-water heat pump system applied as the core mechanical system in a zero net energy research home recently commissioned in Davis, California. The Davis home is designed to generate enough electricity to offset its annual consumption, plus also cover the annual drive cycle for an all-electric vehicle. Achieving this target drew on a number of innovative features. The mechanical system employs a reversible water-to-water heat pump that provides hot and cold water to hydronic radiant systems for space conditioning, and provides all domestic hot water for the home with no backup. When in cooling mode, the equipment employs a desuperheater to harvest some waste heat for domestic water heating. The heat pump also utilizes an innovative low-cost in-ground heat exchanger that costs a fraction of conventional ground-source approaches, and which recovers heat from greywater.

Technical Overview of Multi-Function Heat Pump Strategies

Multi-function heat pumps employ a reversing valve to allow the indoor (load) heat exchanger and outdoor (source) heat exchanger to swap roles so that the load-side heat exchanger can provide either heating or cooling (see Figure 1). For system architectures that can effectively utilize waste heat for some useful purpose (generally pre-heating for domestic hot water), multi-function heat pumps may include a desuperheater - a heat exchanger located on the discharge side of the compressor before the reversing valve and primary condenser.

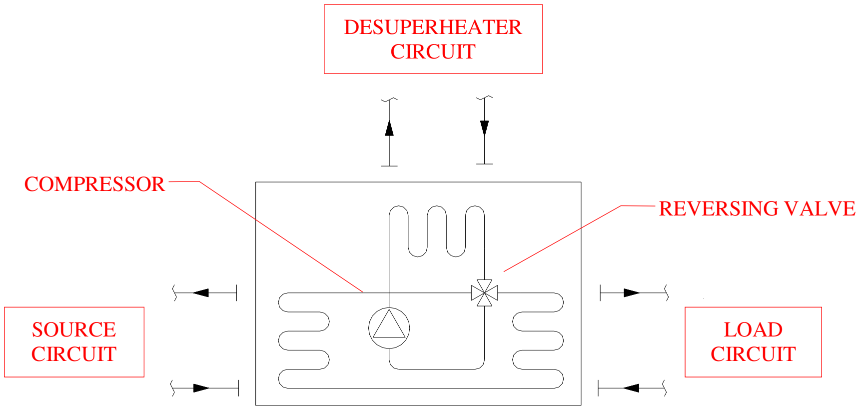

Figure 1. General schematic of a multi-function heat pump with desuperheater.

This reversible refrigerant circuit is central to all multi-function heat pump systems, but it can be applied in a wide variety of ways. Traditionally, residential heat pumps have used a refrigerant-to-air heat exchanger located outdoors and thus use ambient air as the thermal source. Alternatively these systems can use a refrigerant-to-water heat exchanger, where the water subsequently exchanges heat with the ground (or a cooling tower, etc.). Similarly, the load side of this system can exchange heat with either air or water. There are a variety of ways to accomplish both forced-air and hydronic distribution systems. The discussion herein does not cover all options, but reviews the advantages and challenges of some alternatives via explanation of the system architecture for each field evaluation. For example, a hydronic system allows the heat pump to serve as the primary source for domestic water heating, while a forced air approach integrates more easily with traditional residential mechanical designs.

Measured Performance for Multiple Applications

Measured performance from three field evaluations of multi-function heat pump systems are presented here. The first project used a ground-source-heat-pump (GSHP) with an indoor DX coil (refrigerant-to-air heat exchanger) for a forced air heating and cooling system. This approach is also referred to as a water-to-air heat pump (WAHP). In addition to the heating and cooling functions, the WAHP installed in the first project also includes a desuperheater that transfers some heat to the water in a domestic hot water pre-heat tank.

The second two projects used an air-to-water heat pump (AWHP) to deliver radiant heating and cooling, primarily through the floor. In addition, in cooling mode these systems run chilled water through a fan coil to provide some dehumidification. Chilled water is piped first to a small fan coil, which provides some dehumidification and warms the water entering the slab to reduce the risk of condensation on the floor surfaces. Figure 2a shows a schematic of the GSHP system, and Figure 2b shows a combined schematic for the two AWHP systems.

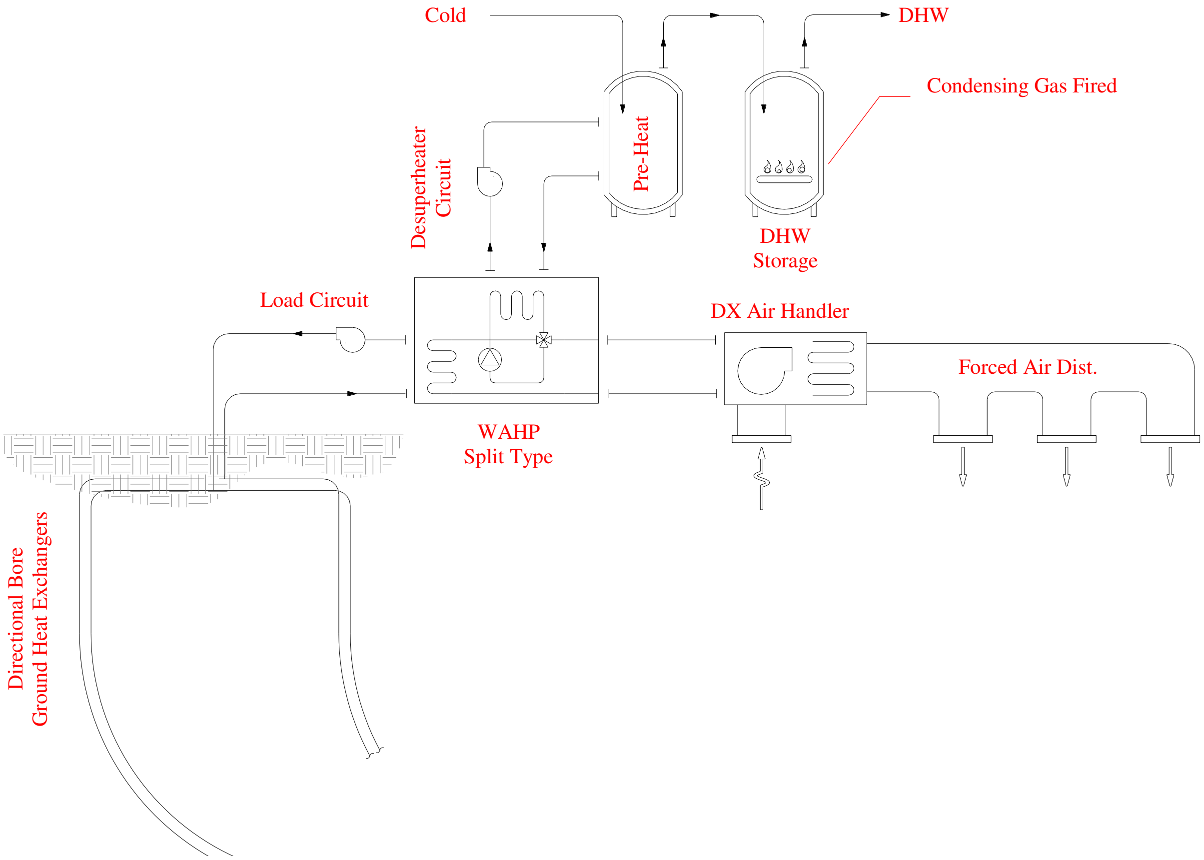

Figure 2a: Schematic of the water-to-air heat pump system at the Sacramento house. The system uses directional bore ground coupled heat exchangers. Desuperheater operates with heating and cooling.

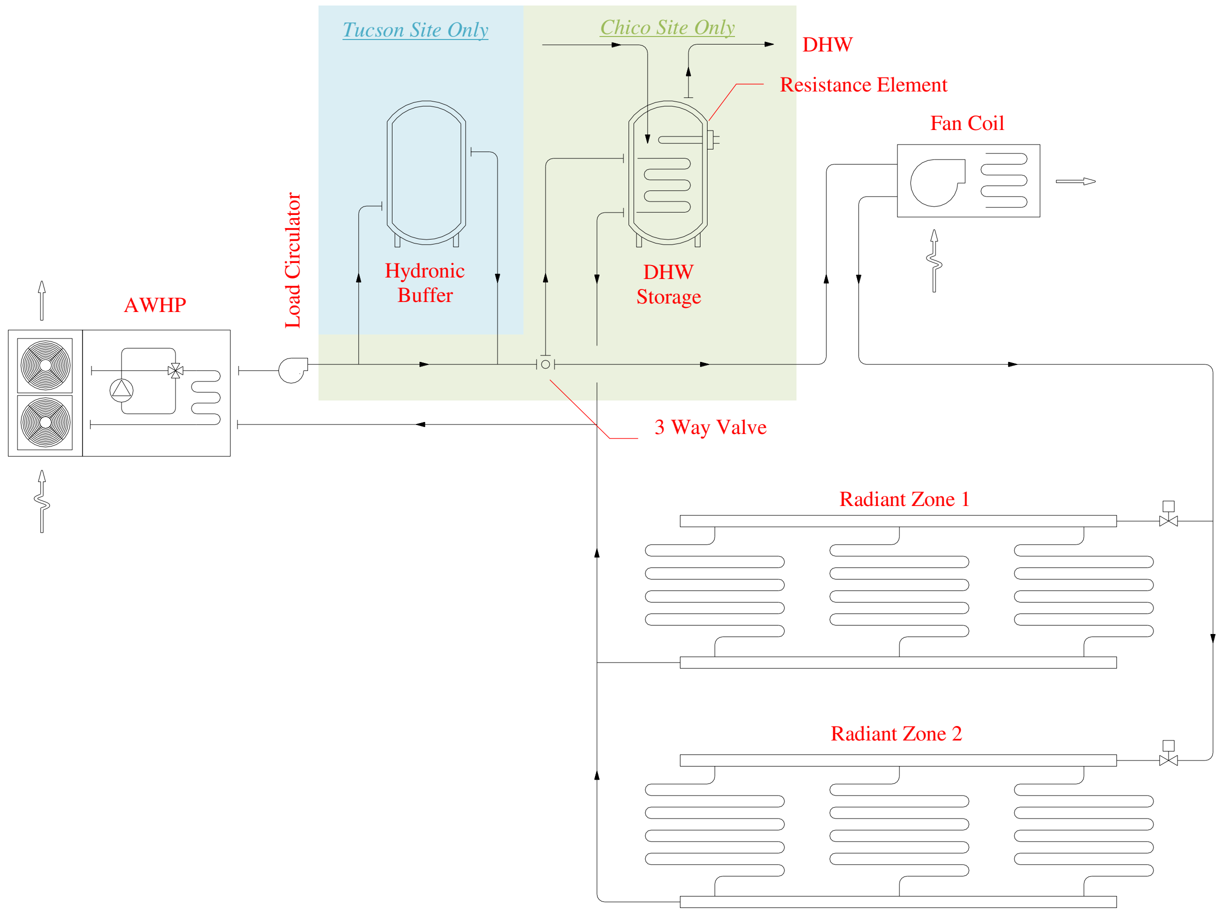

Figure 2b: Schematic of two alternate multi-function AWHP systems. Chico site includes DHW with electric resistance backup and three way valve to isolate hydronic load from DHW storage. Tucson site includes buffer tank in hydronic loop to decouple heat pump capacity from variable internal load.

The first project, called "Sacramento house", is a three-bedroom, 2,200 ft^2 two story custom home located in a suburban Sacramento neighborhood. This home uses the 3-ton Water Furnace 5 Series, a two-function WAHP with a heat recovery package to provide heating, cooling, and a portion of the domestic hot water. This system uses an additional storage tank to pre-heat water before it reaches the primary domestic hot water heater.

The second project, called "Tucson house", is a 1,935 ft^2, single-story spec home located in the hot-dry climate of Tucson, Arizona. The Tucson house uses an Aqua Products RCC for space heating and cooling only. The RCC packages a conventional Ruud 13 SEER heat pump with an off-the-shelf refrigerant-to-water heat exchanger. Since the Aqua Products unit does not have variable capacity capability, a 30 gallon buffer tank was installed on the return side of the load circuit to prevent heat pump short cycling when load is low.

The third test home, called "Chico house", is a three-bedroom, 3,270 ft^2 straw-bale house located in the hot-dry Northern California climate of rural Chico. The Chico house uses the Daikin Altherma inverter-driven three-function AWHP for space heating and cooling as well as domestic water heating. As shown in the schematic, a 3-way valve is installed to divert hot water to the DHW storage tank when there is a DHW call. The Chico house also incorporates a nighttime ventilation cooling system to reduce the amount of heat pump cooling required.

Water-to-Air Heat Pump (Ground Source) with Desuperheater (Sacramento House)

Figure 3 plots five values for each day of monitored operation at the Sacramento installation. The daily minimum and maximum ambient temperatures are recorded, along with the minimum, maximum, and average temperatures in the source circuit (the ground loop). For the cooling season, the minimum source temperature is the source return water temperature (i.e. from the ground); while for heating it is the source supply temperature (i.e. to the ground). Temperatures recorded for each day are not from a particular time, but rather map the temperature range experienced for the ground loop each day. The typical temperature split was 5°F, and periods of prolonged heat pump operation caused operating temperatures to drift throughout the day.

Figure 4 shows the daily thermal energy output from the heat pump (delivered to the load circuit) during both the heating and cooling seasons. Figure 5 plots the thermal energy input for domestic water heating from the desuperheater, and from the primary gas fired water heater. The desuperheater for this installation operates both during heating and cooling. For the eight-week shoulder season between Sep 13 and Nov 6 the desuperheater does not contribute to domestic hot water heating because the heat pump does not operate for heating, nor for cooling.

In heat-pump heating mode, the desuperheater reduces space heating capacity. The optimal use of the heat pump for water heating during the heating season needs to consider the impacts of added fan electricity consumption (running longer to offset lower capacity) relative to reduced natural gas consumption for domestic water heating. Over the course of the period studied (Jul – Jan), the desuperheater contributed 36% of the thermal energy for hot water.

Figure 6 plots the average “Combined-Service EER" for the WAHP in each mode of operation as a function of the average temperature in the ground loop. Each point represents the average of all observations that were made within the corresponding temperature bin. The metric includes all compressor energy, pump energy, and fan energy for the system. It also includes all useful thermal energy generated by the system in each mode. For a portion of time, the first stage of both heating and cooling achieved EERs of nearly 20. However, a time weighted analysis of performance results in an average EER = 15.74 (COP = 4.61) for Heating Stage 1, EER = 12.2 (COP = 3.58) for Heating Stage 2, EER = 14.8 (COP = 4.34) for Cooling Stage 1, and EER = 11.6 (COP = 3.4) for Cooling Stage 2.

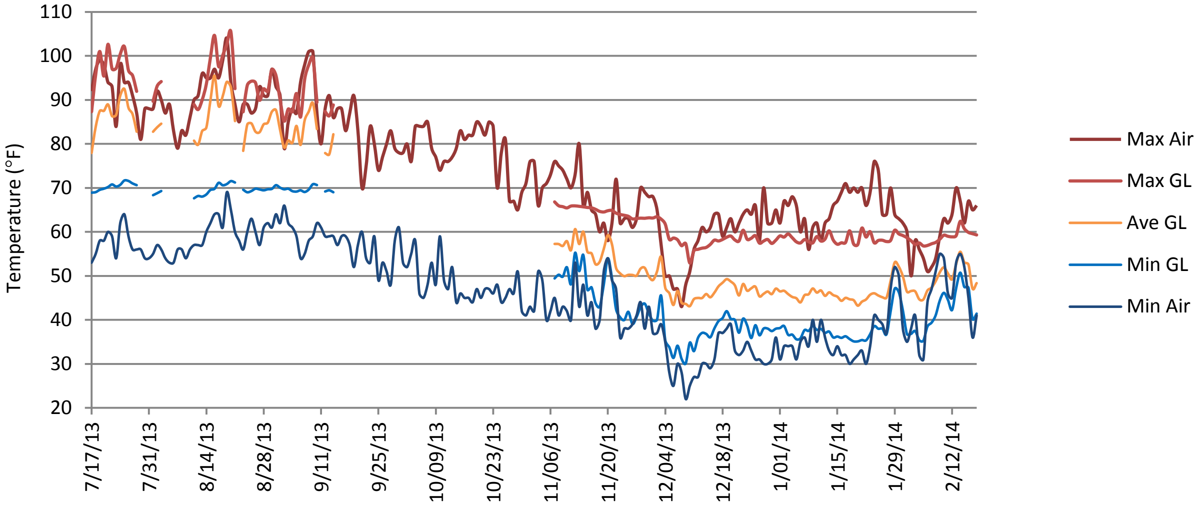

Figure 3. Daily minimum, maximum, and average air temperatures and source circuit water temperatures.

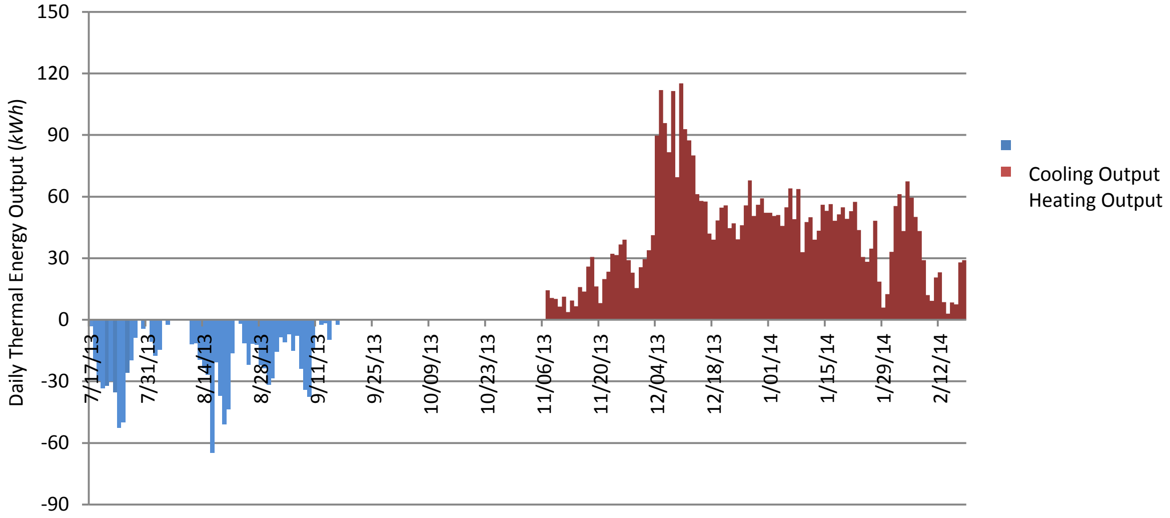

Figure 4. Daily thermal energy output (to the load circuit) for heat pump in heating and cooling.

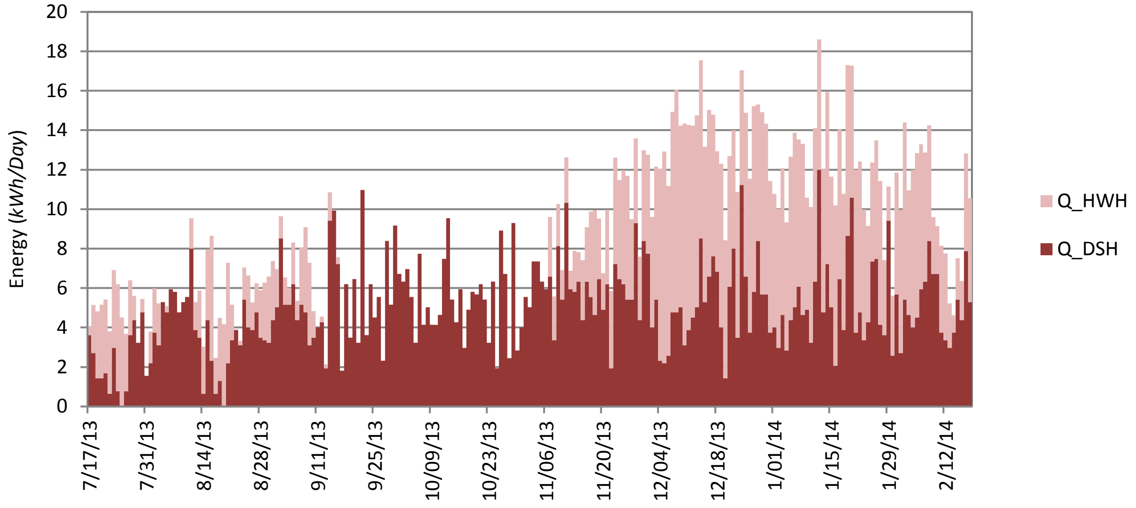

Figure 5. Daily thermal energy input for domestic hot water heating (bars are stacked).

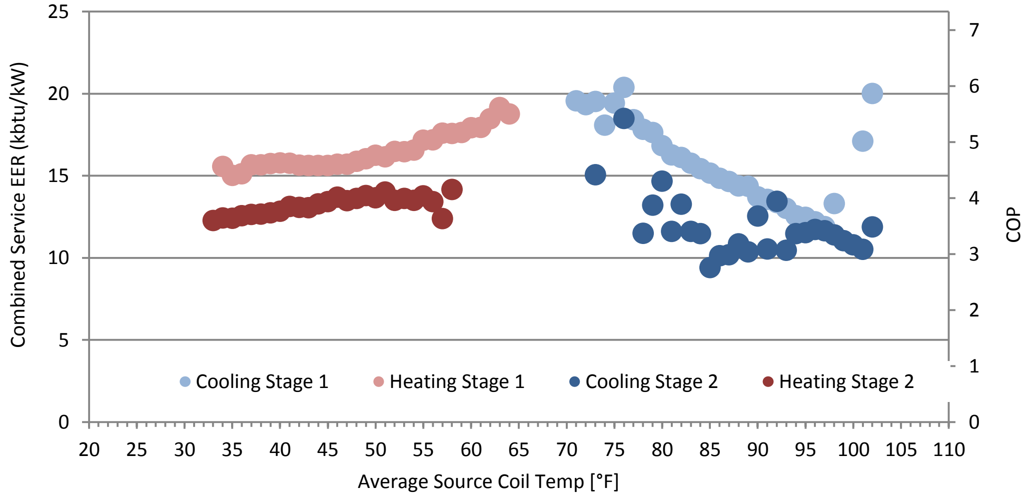

Figure 6. Average "Combined Service EER" for each mode of operation, as a function of the average source side temperature. $T_{SOURCE\ AVG} = T_{GROUND\ AVG} = (\ T_{GROUND\ IN} + 1/2\ (T_{GROUND\ IN} - T_{GROUND\ OUT}))$.

Two-Function Air-to-Water Heat Pump with Radiant Delivery (Tucson House)

Heating performance. Figure 7a charts the full load heating COP of the heat pump system (outdoor unit + circulation pump) at the Tucson house as a function of outside air temperature (OAT). Figure 7b charts the same data as a function of entering water temperature (EWT) on the load circuit. Average seasonal COP over the 2011–2012 heating season was 3.26 (EER = 11.12). There is substantial variation in the observed data for AWHP performance. It appears that this is mostly because of variation in water temperature for the supply loop, caused by the dynamics of zoning (there are three zones), and by other factors that cause variation in load.

For comparison, manufacturer published engineering data for the standard (air-to-air) Ruud heat pump is plotted alongside our measured data. Since the manufacturer's data is for an air-to-air system, Figure 7b plots rated performance a function of entering air temperature (EAT) instead of EWT. Although it is not directly comparable, Figure 7a plots rated performance for an entering indoor air temperature of 74°F.

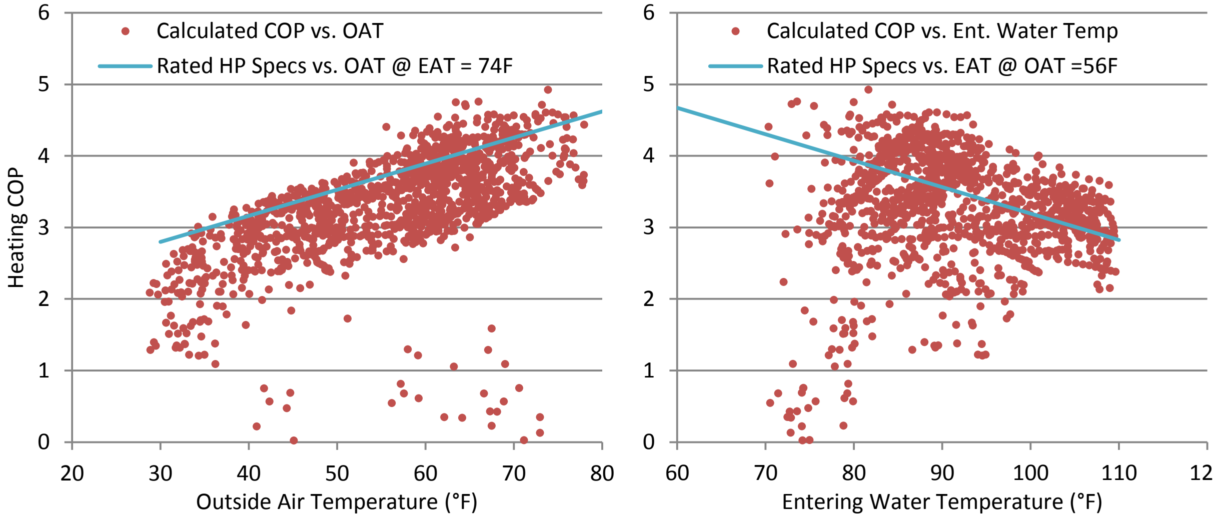

Figure 7. Measured COP for ASHP at Tucson house in space heating (a) versus outdoor air temperature (OAT) and (b) as a function of entering water temperature (EWT). Manufacturer-rated performance is also charted. (n=1,241 15-minute intervals).

Cooling performance. Efficiency for cooling was evaluated as the ratio of water-side cooling capacity to total electricity input (outdoor unit + circulation pump). Figure 8a plots EER for full-load cooling at the Tucson house as a function of OAT. Figure 8b plots the same data as a function of EWT. Similar to the figure for heating-season performance, manufacturer rated performance for an air-to-air heat pump is also plotted for comparison. The manufacturer rated data in **Error! Reference source not found.**a uses an indoor-coil inlet condition of 78°F dry-bulb and 60°F wet-bulb, which may or may not be directly comparable the conditions seen by the refrigerant in this hydronic application.

The Tucson house data illustrates a strong correlation between cooling efficiency and OAT. Performance is not as dependent on load-side conditions return water temperature (EWT) does have some impact. During cooling events, supply water temperatures from the heat pump were observed to decline continuously, while temperature split across the hydronic load did not increase as substantially. For prolonged periods of cooling operation, this resulted in reduced system efficiency. Additionally, latent cooling effects from the fan coil were delayed until supply water temperature declined below the indoor dew point. In contrast to the heating season system characteristics, **Error! Reference source not found.**b indicates that there is not a strong relationship between cooling efficiency and EWT. This is explained by the fact that outside air temperature effects dominate the efficiency, and that EWT is not well correlated with outdoor temperature.

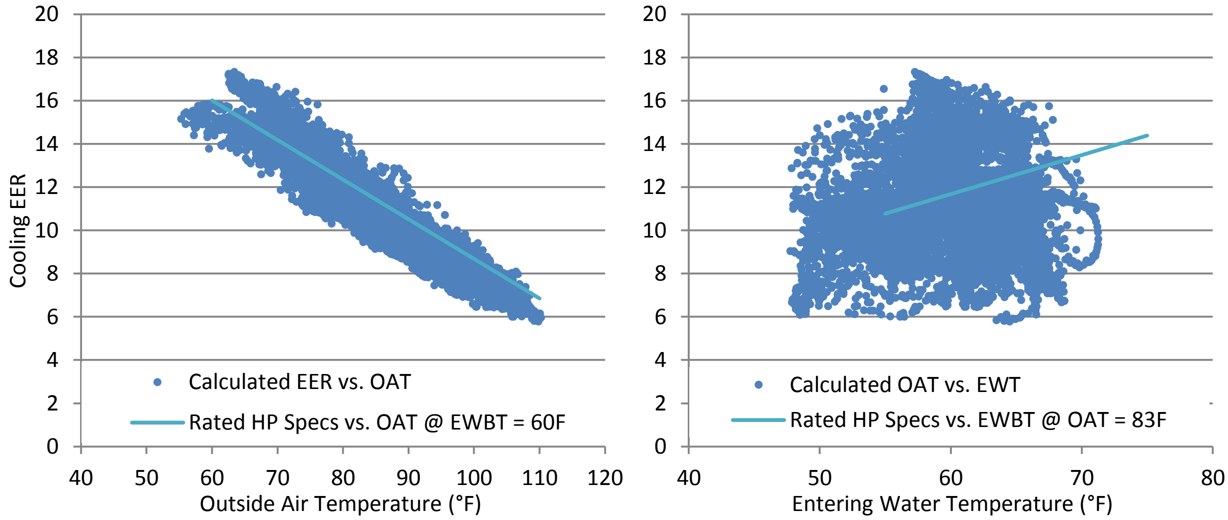

Figure 8. Measured cooling EER for ASHP at Tucson house as a function of (a) outside air temperature, and (b) entering water temperature. (n = 8,208 15-minute intervals) Manufacturer rated performance is also presented.

Three-Function Air-to-Water Heat Pump with Radiant Delivery (Chico House)

Heating performance. Figure 9 plots the observed heating COP for the Daikin Altherma at the Chico house for periods of continuous operation during each monitoring interval. Figure 9a plots performance as a function of outdoor air temperature, and Figure 9b plots the same data as a function of leaving water temperature (LWT). The plots also include manufacturer-stated performance for the Altherma across a range of operating conditions.

Measured performance as a function of outside air temperature tracks closely with manufacturer-stated data. The comparison as a function of load conditions is less clear. This is mostly because efficiency is not as sensitive to leaving water temperature as it is to outside air temperature, and because there is a strong relationship between outside air temperature and leaving water temperature in the data observed (leaving water temperature is lower when outside temperature is lower). The trend for manufacturer-stated performance provides the predicted efficiency across a range of LWT at a fixed outside air condition (44°F). For data that corresponds to operation at that outside air condition, our field observations align closely with manufacturer-stated performance. Some of the differences between manufacturer-stated performance and observations are also likely due to part-load operation. The Altherma specifications are only published for full-speed operation. The Altherma system uses an inverter-driven compressor and adjusts compressor speed to match output capacity to the load. If the supply water temperature overshoots a set point the compressor will throttle down, and if temperature falls short of the set point it will ramp up. This capability is especially valuable for reducing temperature lift and reducing the cycling that would usually be required to serve variable loads with a fixed-capacity machine.

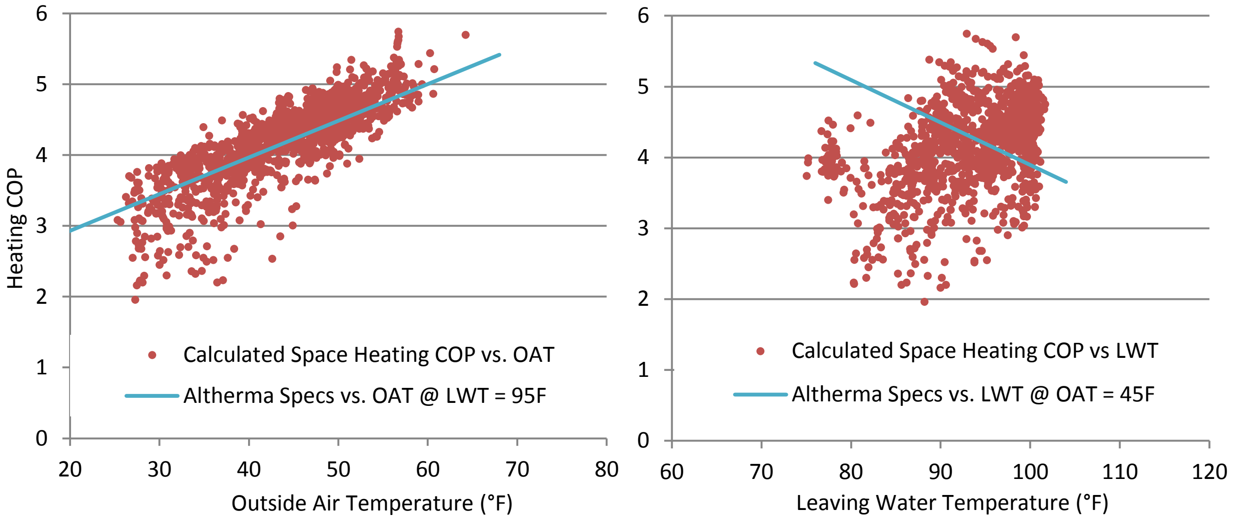

Figure 1. Measured COP of the Chico house AWHP in heating mode as a function of (a) outside temperature and (b) leaving water temperature. Manufacturer rated performance is also presented. (n = 1,383 15-minute intervals).

Cooling performance. Figure 10 plots the observed cooling EER at the Chico house for periods of steady-state operation. Similar to earlier results, Figure 10a plots the data as a function of outside air temperature, while Figure 10b plots the data against leaving water temperature. As Chico has cooler evenings and the house uses a nighttime ventilation cooling strategy, the number of cooling hours for this installation were much fewer than the Tucson house. With the small sample size, it is tough to compare the measured results with engineering specifications, however on average the measured performance is close to rated values.

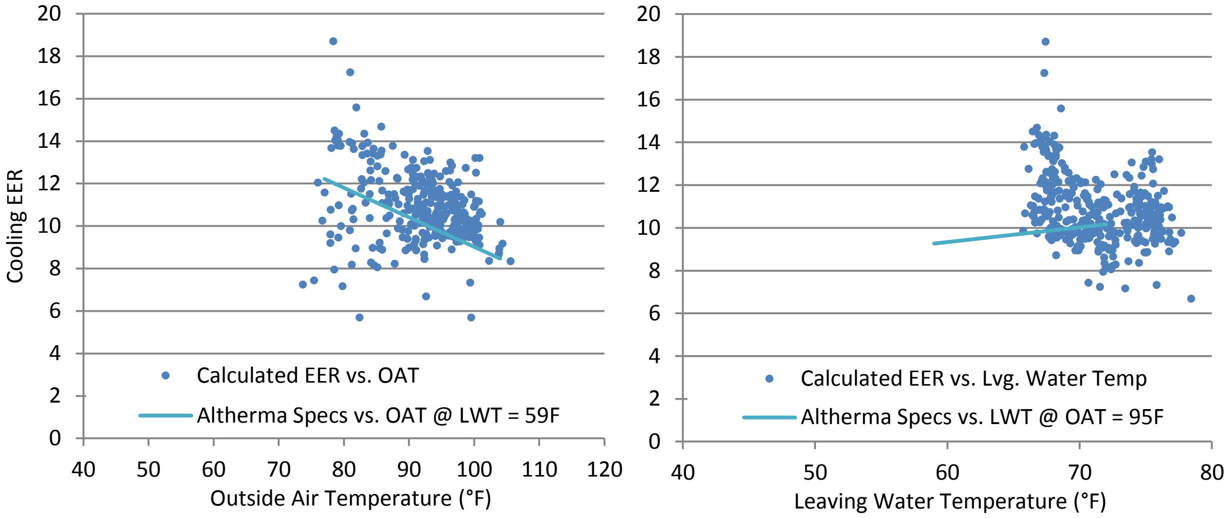

Figure 10. Cooling EER for the Chico house AWHP as a function of (a) outside air temperature, and (b) leaving water temperature. Manufacturer stated performance is also plotted. (n = 337 15-mminute intervals).

Domestic hot water performance. Figure 11 plots the observed system efficiency at the Chico house for periods where the AWHP provides domestic water heating. Note that this installation does not include a desuperheater, and therefore operates in heating-only, cooling-only, or DHW-only modes. Performance ranges widely from COP =1.0 – 3.0, which is well below manufacturer specifications. While full load performance in the laboratory could likely match manufacturer stated ratings, we believe the low performance observed in the field is caused by a combination of component sizing, control sequence, and temperature set points for domestic water heating.

For a large portion of the operating time in this mode, the temperature differential in the load circuit was only 2°F. The Altherma automatically adjusts compressor speed to match a supply water temperature set point. Figure 11b clearly shows that the system consistently supplies water between 125–130°F. While the compressor speed modulates, the load-circuit circulating pump does not. Measured data indicates that the average flow rate through the storage tank was 9.8 *gpm*. This flow and the small temperature differential equate to 9.8 *kBtu/h* heating capacity. The Altherma rated heating capacity is 48 *kBtu/h*, but the system mostly operated at partial speed to output roughly 20% capacity in order to keep the supply water temperature set point between 125–130°F. During partial-capacity operation the compressor power decreases substantially, but since the pump speed did not modulate, pumping power becomes a larger fraction of the energy use and overall efficiency suffers, as illustrated by the results in Figure 11.

The heat pump was generally not able to meet the storage tank set point of 130°F, and the auxiliary electric resistance heat was regularly activated to satisfy water heating demand. It appears that this may be because the tank set point temperature was very close (if not higher) than the supply water temperature set point. Over the 13 month monitoring period the heat pump supplied 76% of the energy to the DHW tank. For a lower tank set point, we expect the heat pump could deliver a larger fraction of the DHW annually. The seasonal combined total system COP between November 2011 – October 2012 was 1.05. This low value was a result of electric resistance heat operation, excessive pump power, and storage losses.

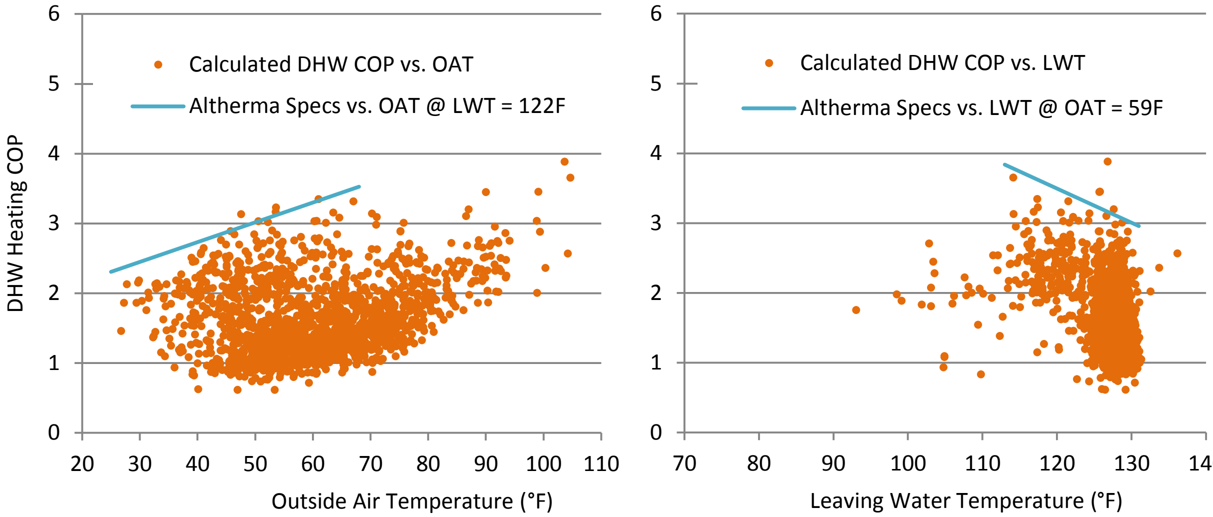

Figure 11. COP for the Chico AWHP in DHW mode as a function of (a) outside air temperature and (b) leaving water temperature. Manufacturer rated specifications are also plotted for each. (n = 1,607 15 minute intervals).

Three-Function Water-to-Water Heat Pump (Ground Source) with Desuperheater and Radiant Delivery (Davis House)

Following on the performance observations and lessons learned from these three projects, the authors have developed and recently commissioned installation of a multi-function heat pump architecture that allows a single heat pump to provide all heating, cooling, and domestic hot water for a home with no backup.

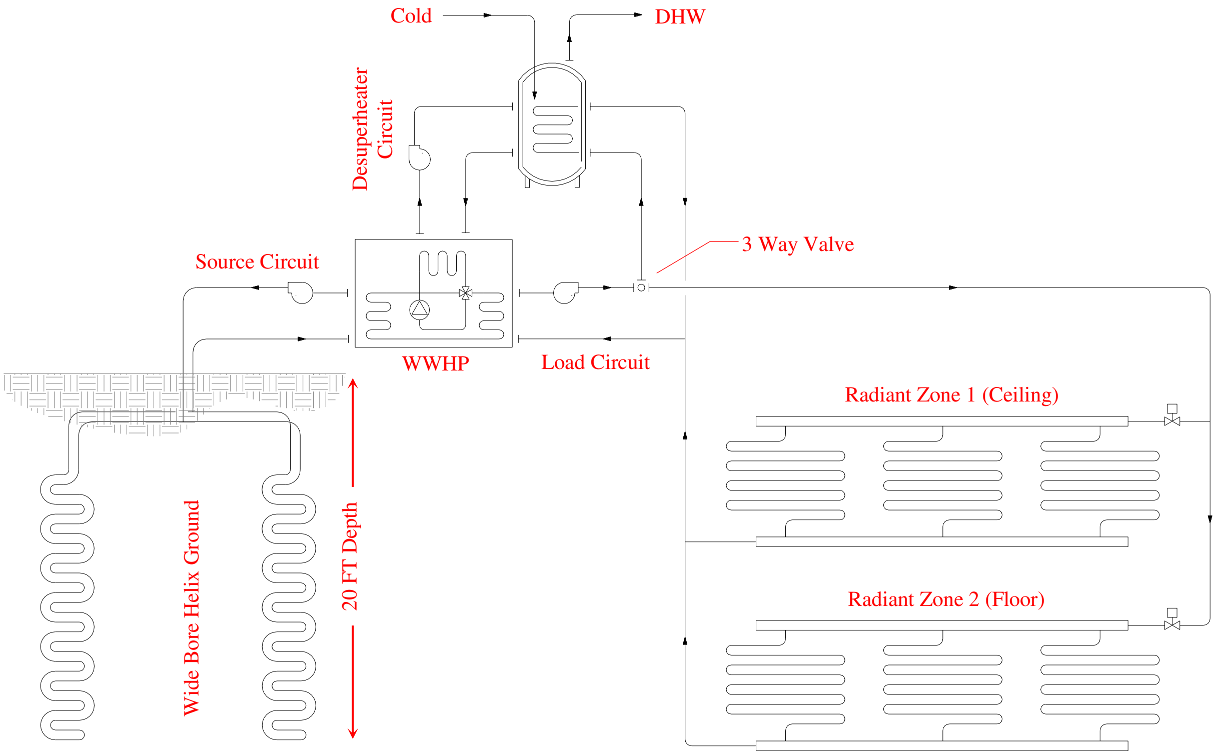

Figure 12. Schematic for multi-function heat pump system in Davis home.

This system utilizes a lower-cost ground source heat exchanger design that uses greywater to augment the performance of the heat pump. The design consists of parallel helix coils constructed of ½" ID HDPE tubing, set into 20' deep 24" diameter bores. Grey water from the home flows around the outside of these heat exchangers, increasing thermal conductivity year round, and augmenting the effective ground temperature in the winter. This heat exchanger approach installs for roughly 25% the cost of conventional ground coupled systems.

The multi-function heat pump for the Davis home delivers heating and cooling to the home via radiant floors and ceilings. Supply water temperature in cooling mode is controlled to avoid cooling surfaces below the dew point, and there is no active dehumidification for the home. The system utilizes a desuperheater when in cooling mode. However, different from the Sacramento home, the Davis home uses an actively stratified domestic hot water storage tank to avoid the need for an additional pre-heat storage tank. This allows the system to use a portion of the waste heat from the cooling process to offset domestic water heating load.

The heat pump for the Davis home also serves as the single source for domestic hot water heating. Since the heat pump has a relatively low heating capacity (when compared against conventional domestic hot water heaters) the design achieves acceptable first-hour delivery performance by utilizing a large storage capacity (80-gallons). Since a single heat pump serves both space conditioning and domestic water heating, one service must be given priority when there is a call for multiple services. In this application, since the heating and cooling is delivered through a high-mass system with a long time constant, domestic hot water heating is always given priority. The general strategy for thermal control in the home relies on first minimizing external loads and air infiltration, and then maintaining a steady indoor thermal environment. The heating and cooling system cannot ramp up or set back quickly. When domestic hot water requires heating, the heat pump switches to heating, and flow through the load heat exchanger is directed into the working fluid section of the domestic hot water storage. The heat pump will drive the 80-gallon storage temperature to the domestic hot water set point, and then switch back to heating or cooling for the space. Observations thus far suggest that this prioritization has very little impact on the ability to control indoor comfort.

Cooling for this home also relies on nighttime ventilation cooling, which can reduce mechanical cooling loads by more than 50%. For this home, we expect that nighttime ventilation cooling will reduce mechanical cooling requirements by 80%.

Discussion Conclusions and Recommendations

Advantages of Multifunction Heat Pumps. Multi-function heat pumps offer many potential advantages over conventional residential mechanical design strategies. Variations of the technology can be applied in new homes or as retrofits. Most importantly, they serve multiple purposes and therefore eliminate the need for separate mechanical systems, which should reduce equipment costs and system maintenance.

Multi-function heat pumps promise substantial energy performance advantages. In particular, they enable the application of more efficient distribution and delivery strategies such as fan coils, and radiant heating or cooling. These approaches eliminate the leakage and thermal losses associated with ductwork, and eliminate the fan power required in forced air systems. In general, pump power should be much smaller than fan power. Although there are options to make forced air systems more efficient, such as moving ductwork into the conditioned envelope, it could be simpler to use hydronic systems. Hydronic systems can even be installed for existing homes in the case of deep retrofits. When the slab is used for radiant heating and cooling, hydronic distribution can integrate seamlessly into the architecture. As discussed, these systems can operate as air source or ground source – the latter promises significant efficiency improvements, especially in colder climates.

Additionally, we note that there can be significant advantages with respect to maintenance and reliability by including all refrigerant systems into a hermetically-sealed factory-charged circuit (not unlike a refrigerator). Multi-function heat pumps can definitely serve heating and cooling via forced air, but given the broad prevalence of water systems outside of residential construction, we believe that a move to hydronic systems should not be an insurmountable leap for residential contractors.

Challenges to Broader Application. Despite the range of advantages available from multi-function heat pump systems, there are a number of significant challenges to broader adoption in the marketplace.

First, the incremental cost for this type of heat pump is currently very high. The equipment is not common, and there are not many manufacturer options. Given the low volume and low competition market with mostly boutique applications, these systems currently fetch a premium price. However, these machines are actually smaller and simpler than the conventional alternatives. Given that price for high-volume manufacturing is tied to material costs and system complexity, we expect that multi-function heat pumps could be manufactured for sale at a more competitive price point.

Additionally, while the systems can be fairly simple, they still require skilled design, installation and maintenance. These resources are currently not widely available in the industry. From the design perspective, it is much more important for hydronic and multi-function systems that heat pumps be sized correctly. Oversizing a conventional residential air conditioner may result in some waste, but oversizing a single stage heat pump for a hydronic system may cause it to fault repeatedly and fail to operate reliably. Contractors are also not familiar with these systems, and there are structural impediments within the industry that make a transition toward hydronic multi-function heat pump systems difficult.

From the point of view of the trades, plumbers know domestic water distribution, hot water heaters, and sanitary drains, while HVAC contractors know ducts, furnaces, and air conditioners. The systems described here fall somewhere in no-man's-land. For example, for the Davis home, the preferred HVAC contractor installed air-side components such as the whole-house fan and exhaust ventilation ductwork, but they would not install the water-to-water heat pump, the geothermal system, or the hydronic portions of the system. The plumber installed all pipes and valves, including the geothermal system, but their lack of familiarity with HVAC systems meant that they could not commission the heat pump. None of the contractors would commission controls; this was left to a custom controls integrator. We installed a radiant ceiling, but that required the sheetrock installers to install PEX tubing. Similarly, installation of radiant tubing in the slab required close cooperation between the plumber and concrete contractor.

Compartmentalization of construction responsibilities along the lines of traditional residential design has allowed for intense cost competitiveness in conventional construction, but has reduced flexibility. In a new design paradigm with multi-function units, it is no longer clear where one trade ends and another begins; subsequently, cost and construction timeline both suffer. There are few contractors with the range of appropriate skills to install and control this type of design. Not surprisingly, their work usually fetches a premium price in the niche market.

On the technical side, multi-function heat pump systems do face some significant challenges. When integrating a desuperheater, it is best to have a low-temperature storage tank for pre-heating water before it flows to the DHW storage tank, because the desuperheater cannot deliver much useful heat to a domestic hot water storage tank that is already hot. The space required for this tank, and added plumbing are a small but significant complication that hinder uptake of the strategy. Furthermore, heat pump manufacturers typically recommend use of a buffer tank, especially for cooling, in order to avoid a mismatch between heat pump capacity, and hydronic distribution capacity, or thermal load. One hydronic homes described herein does use a buffer tank. Another uses an inverter driven compressor that can operate at part load. The Davis house does not use a buffer tank, but instead directs chilled water through the radiant slab, which has adequate thermal mass to decouple instantaneous heat pump capacity from load.

Currently, the specific deployment of every system is left up to the designer and installer, in which case every project becomes a custom application. Much could be gained from streamlining standard equipment packages and installation strategies. Equipment for the recently constructed home in Davis was sourced from a variety of distributors. The design relied on some common components, but specified others that were more difficult to acquire. This all amounted to a complicated project management process for the plumber, in addition to the custom physical work that was required. We believe that multi-function heat pump arrangements could be much more plug-and-play. We see opportunities to package all of the necessary components into unitary products, or product groups that can streamline application. The ideal technical potential could be a product with two water ports for connection to a ground source loop, two connections to a hydronic distribution system, one port for domestic cold water makeup, and another for domestic hot water output. Manufacturers such as Daikin have made significant strides in moving in this direction with the Altherma product monitored at the Chico house. However, our observations show that despite its variable capacity, this product still has some control challenges to address. Finally, every manufacturer appears to be approaching these problems in different ways, which adds further complexity and training needs for the trades. This is a departure from traditional residential mechanical systems which have enjoyed uncanny similarity and standardization across a wide range of manufacturers.

Recommendations. This paper has touched upon many of the advantages and challenges associated with applying multi-function heat pumps in single-family residences. The Department of Energy *Water Heating Technologies Roadmap* calls for the broad demonstration, evaluation, and commercialization of combined-function heat pump systems in the 2014-2019 timeline. Some technologies to suit this application are available, but systems and controls have not been optimized for combined function, and very few people are familiar with proper application.

Going forward, we recommend that utility pilots and other research explore this technology opportunity in more depth, and clearly evaluate the energy and demand savings compared to code minimum strategies. This should occur in parallel with further research, and in collaboration with industry to support advancing technology capabilities, efficiency, and product offerings. It is clear that the specifics of design and controls strategies can have significant impacts on energy efficiency. These technical challenges need to be identified and addressed.

Most importantly, all corners of the market place will need to become more familiar with the technology. We recommend that continued public research should occur in parallel with programs that immediately introduce available products strategically to early adopters.

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