COLD CLIMATE HOUSING RESEARCH CENTER

CCHRC

Laboratory Study of Integrating an Air Source Heat Pump into a Combined Heating and Ventilation System for Cold Climates

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Introduction

CCHRC and Natural Resources Canada partnered to develop a combined heating and ventilation system for residential buildings that utilizes cost-effective heating appliances. The objective of this project was to test the integration of an air source heat pump (ASHP) into the BrHEAThe System, a combined heating and ventilation system developed by the Cold Climate Housing Research Center (CCHRC) to improve indoor air quality in energy efficient homes. The BrHEAThe system was developed to address poor indoor air quality in rural Alaskan homes. Natural Resources Canada is interested in the BrHEAThe system to help with poor indoor air quality issues they have their northern regions. Adding an ASHP to the BrHEAThe system makes the heating portion of the combined system more feasible in parts of Canada where electric heating is cost effective. This project follows a previous desktop study on the feasibility of the concept.

Background of the BrHEAThe System

The CCHRC BrHEAThe System is an integrated system that combines space heating with heat recovery ventilation. BrHEAThe utilizes a single distribution network to distribute balanced fresh air and space heating for high-performance homes in cold climates. Traditionally, the BrHEAThe System has consisted of an oil, gas, or propane fired boiler-based space heating device integrated with a water-to-air heat exchanger, air filter assembly, and heat recovery ventilator (HRV) to supply comfortable, healthy, and fresh air to the building's occupants.

BrHEAThe was developed to improve ventilation in rural Alaska housing by mitigating the tendency of occupants to turn off ventilation devices. Often ventilation air is considered too cold, so occupants turn off fans to stop the cold air. Additionally, fans use electricity, which is very costly in rural Alaska, so they are turned off to save money on energy costs. The BrHEAThe System delivers warm air and the HRV is now part of the heating system so it is more difficult to turn off. Figure 1 shows a concept schematic of the BrHEAThe system.

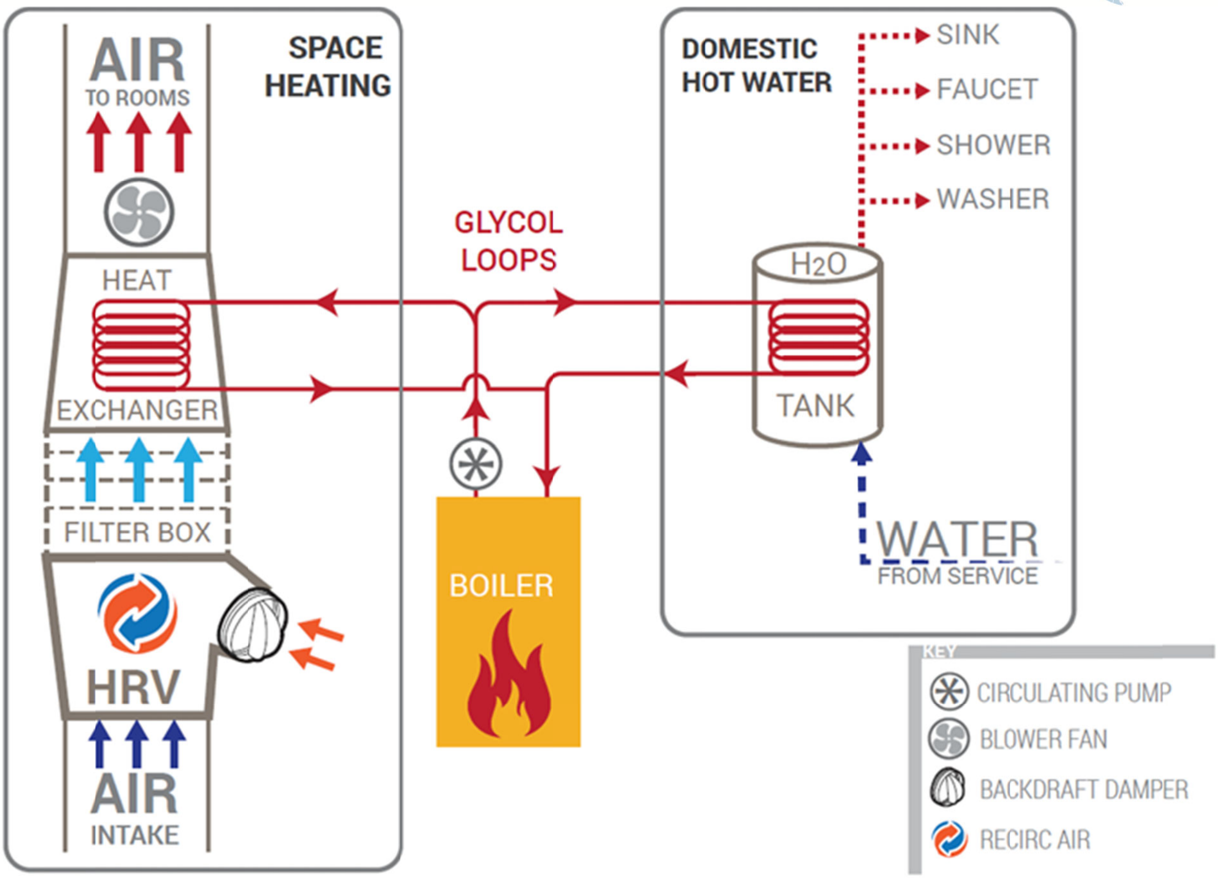

Figure 1. Existing BrHEAThe System. Adding an air source heat pump to this system will change the configuration slightly.

Concept Development

CCHRC worked with CANMET Energy of Ottawa to develop the initial expansion of the BrHEAThe system to include an air source heat pump. This concept report is available on CCHRC's website: http://www.cchrc.org/sites/default/files/docs/Feasibility_Study_of_Integrating_ASHP_in_Cold_Climates_for_NRCan.pdf. Figure 2 shows the original conceptual design. The ASHP needed to meet the following requirements:

- a manufacturer-rated design temperature that is appropriate for cold climates
- a low-flow heat delivery to enable small ducting for the distribution of heated air in the home
- the ability to meet a design combined space and water heating demand of 25,000 BTU/hour in a cold climate
- availability in Alaska and Canada with a track record of use.

The Sanden GS3-45HPA was selected as it met these requirements at a reasonable cost and in addition uses CO_2, a HFC free refrigerant.

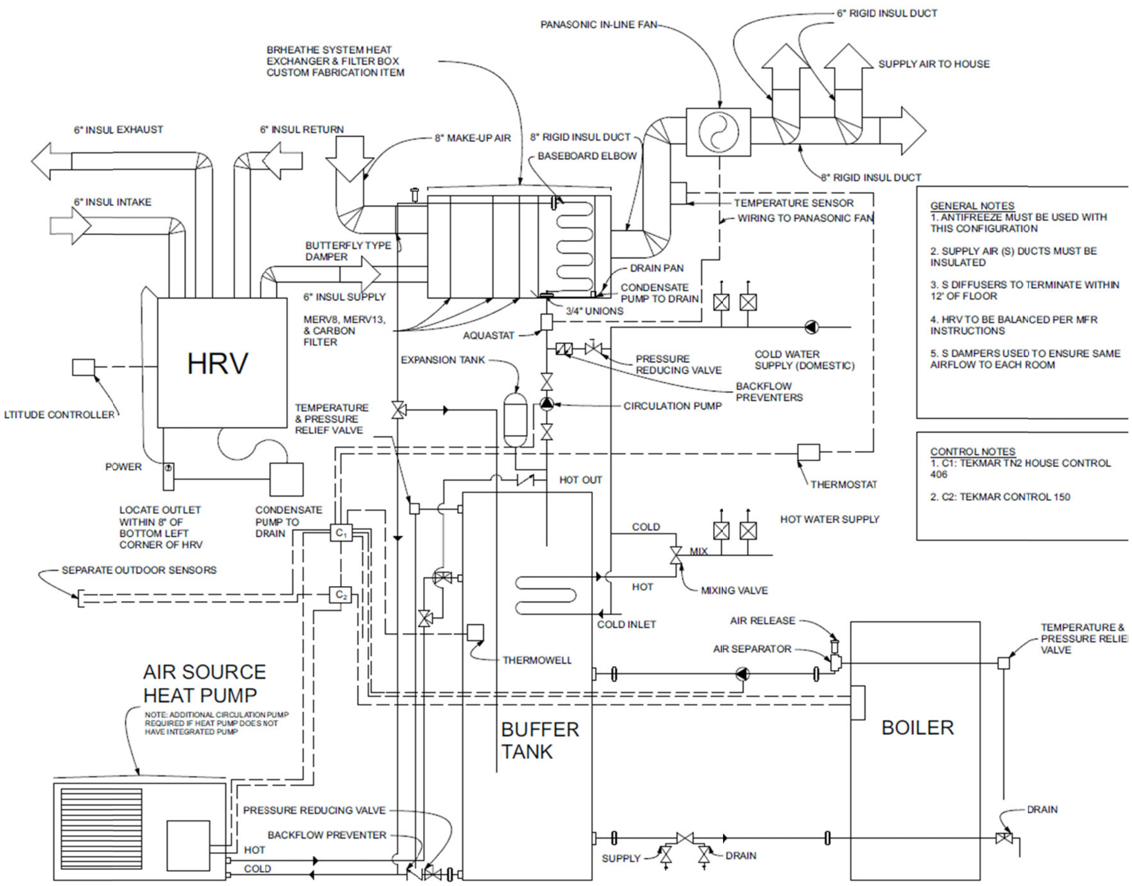

Figure 2.The concept BrHEAThe System with an ASHP. The boiler may not be needed in all climates.

Laboratory Testing

The initial concept development was encouraging enough to move on to a laboratory test of the combined system. CCHRC began building a test bed in February 2018 to test and improve upon the conceptual design. There were several design modifications that were made as the project moved forward, detailed by Table 1. The full system was commissioned on March 23, 2017. Figures 3 and 4 show the ASHP installed at the Cold Climate Housing Research Center. There are more installation photos in Appendix A.

Figure 3.The Sanden GS3-45HPA heat pump. The ice removal tray is not pictured.

Figure 4. Completed installation of combined heating and ventilation system with integrated boiler and air-source heat pump.

Table 1.Laboratory Testing Timeline

Timeline	Action
Winter 2017	Final equipment selected and ordered.
Winter/Spring 2018	Equipment arrived at CCHRC in February. System was installed and commissioned by the end of March (see Figure 5). Data collection systems were troubleshot and calibrated for testing. Data collection began in March until the end of the heating season in April.
Summer 2018	First reconfiguration of the system's plumbing occurs in May (see Figure 6). Domestic hot water (DHW) draw plan developed with NRCan by the end of August.
Fall 2018	Data collection begins for 2018-2019 heating season in September. Controls and pumps were reconfigured in October. After operation, the internal pump for the Sanden developed a crack in its casing. This led to the ordering of a new heat transfer fluid, Dynalene, to decrease viscosity and increase heat transfer.
Winter 2019	Data collection occurs throughout the heating season after the arrival of the Dynalene. DHW load added into the system in January. During the month of February, the ASHP began displaying a variety of errors codes. A new wire harness was delivered by Sanden to resolve the issue.

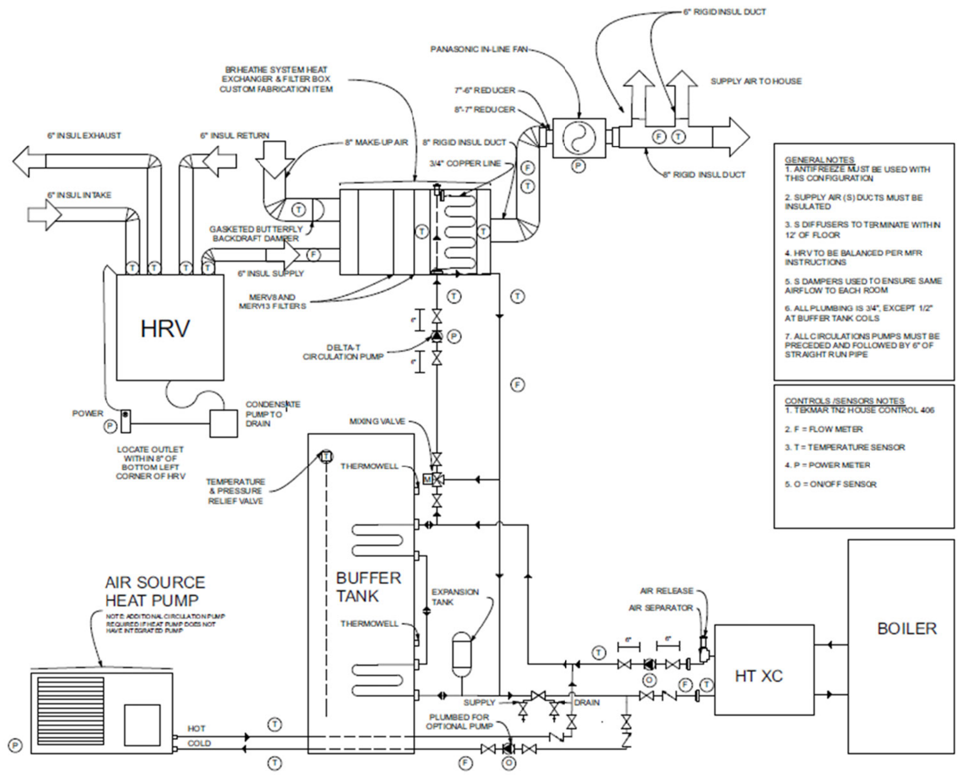

Figure 5. As-built configuration of **t**he BrHEAThe System with the Sanden ASHP as installed in the spring of 2018 with an existing boiler system at CCHRC's laboratory with incorporated design changes.

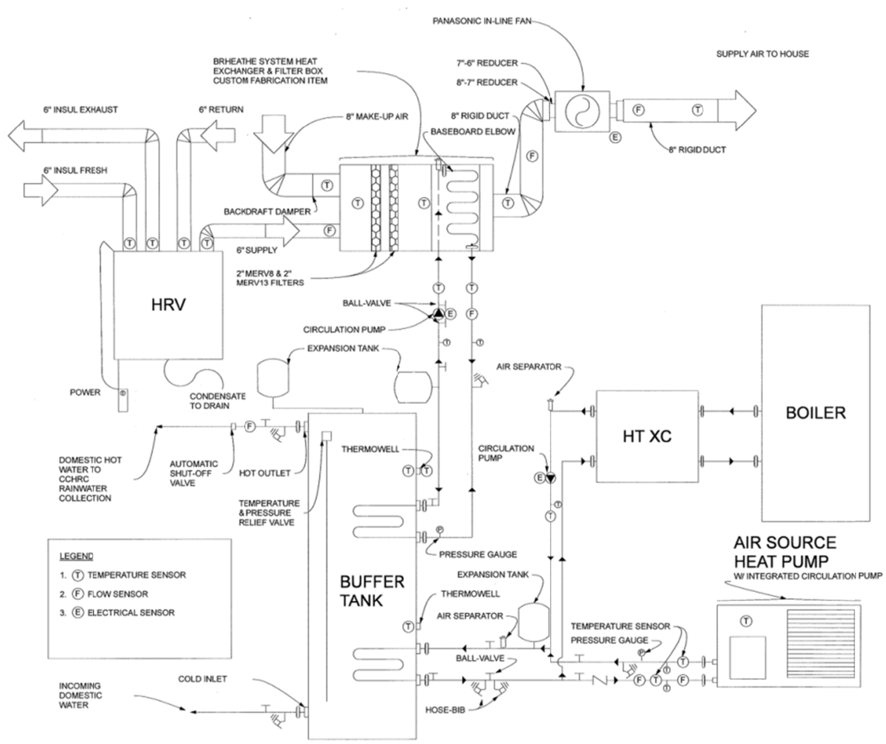

Figure 6. As-built configuration of the BrHEAThe System with the Sanden ASHP as installed in the winter of 2018 with an existing boiler system at CCHRC's laboratory in the final reconfiguration.

Table 2 lists some of the challenges that led to design modifications during the building process.

Table 2. Design and building challenges

Challenge	Result
Filling the buffer tank with glycol as originally planned presented an uncommon plumbing practice and expense.	Design was modified to accommodate glycol through the tank coils and the tank was filled with water.
Fluid flow through the integrated system	The flow through the tank coils was too restricted and the majority of the fluid was flowing to the heating coil where resistance was lesser. A zone valve was added to shut off flow to the coil when there was no space heating call. In the first configuration the pump for the coil was overwhelming the ASHP pump and running too much flow through the heat pump.
Sanden GS3-45HPA	The Sanden had repeated error codes. The main circuit board had to be replaced in Spring 2018. The internal pump has been problematic in delivering the required amount of flow for the system to work properly. The internal circulation pump arrived at CCHRC in a cracked condition that led to its immediate replacement. In the next heating season, the internal circulation pump cracked. The working fluid of propylene glycol was replaced with a lower viscosity fluid, Dynalene, to alleviate viscosity issues for the pump.
Closed heating loop	The closed loop did not allow the return temperatures to the Sanden to get as low as they should have been for the CO_2 driven heat pump. The heat pump efficiency is dependent on a large temperature difference between the return to the supply.
Chiltrix 80 gallon dual coil heat exchanger tank	The buffer tank's coils seem to be too restrictive to attain the desired maximum temperature in the tank.
Tekmar Controls	The Tekmar system was too restrictive on the set up of the system and was unable to communicate properly with the AHSP or to keep the heating tank at temperature without a call for heat. The ASHP was removed from the controller and put on an outdoor thermostat.

Components

The installation of the integrated system consists of CCHRC's existing Viessman boiler, existing Lennox HRV2-300DDP, Sanden 43 Gen 3 CO2 ASHP water heater, Chiltrix 80 gallon dual coil heat exchanger tank, the BrHEAThe system filter and coil box, various plumbing components, and various forced air components. Table 2 provides an outline of the cost of components, installation labor, and shipping costs to CCHRC. Labor rates are set at $150 per hour in accordance with current local pricing in Fairbanks, Alaska. The boiler and HRV were previously installed systems, so pricing reflects the most recent BrHEAThe system material costs from September 2017 to demonstrate total cost of the integrated system. See Appendix B for specifications on the plumbing and ventilation components.

Table 3. System costs

Component	Material	Shipping	Labor	Total
Ventilation Coil Box & Ducting	$867.15	$159.80	$600.00	$1,926.95
HRV	$1,088.21	--	--	$1,088.21
Plumbing	$2,746.87	--	$3,750.00	$6,472.47
Heat Pump and Tank	$4,274.40	$1,096.45	--	$5,370.85
Boiler	$2,705.00	--	--	$2,705.00
Controls	$2,277.00	--	$1,600.00	$3,877.00
Electric	$63.78	--	$380.00	$443.78
Total	$13,998.01	$1,256.25	$6,630.00	$21,608.66

Data System

A data collection system was set up to determine the following:

1. What is the maximum space heating capacity of the BrHEAThe system based on outside temperature? What is the contribution from the boiler and the ASHP individually?
2. What is the heat pump Coefficient of Performance (COP) based on outside temperature?
3. Does the defrost cycle on the ASHP affect COP?
4. What is the DHW capacity of the system?

A single datalogger was used to keep track of the energy flows around the system for the heating and heat pump parts of the project. A separate datalogger was used to meter and to control the domestic hot water flow. All of the data points measured during the project are listed in Appendix C.

Air Source Heat Pump Data

Data for the heat pump was collected in 10-second, 1-minute, 5-minute, and hourly averages. The averages were developed only during the running time of the heat pump. The overall electrical power draw of the heat pump was metered in order to compare it to the heat energy delivered by the heat pump. The efficiency of the heat pump can be determined by dividing the amount of heat energy delivered by the electrical energy used to deliver that amount of energy.

Power used is computed internally in the CR1000 data logger using outputs from a voltage transformer and a current transducer. The heat energy from the heat pump to the buffer tank is calculated post data collection from the fluid flow and the difference in temperature to and from the ASHP. The density and specific heat for 60% propylene glycol were used (1046 kg/m^3 and 3371 J/kg·K respectively). When the glycol was switched for Dynalene, the density used was 1018 kg/m^3 and the specific heat was 3809 J/kg·K.

$$Q=m\cdot c_p(t_{hot}-t_{cold})=V\cdot ro\cdot c_p(t_{hot}-t_{cold})$$
m=mass flow=V·ro=volumetric flow·density
c_p=specific heat capacity
t_{hot}=temperature of the fluid from the ASHP
t_{cold}=temperature of the fluid returning to the ASHP from the buffer tank

$$COP=Q/E$$
Q=heat delivered by the heat pump
E=electricity used by the heat pump

Additionally, the temperature on the outside fins of the ASHP was monitored in an effort to determine the defrost cycles of the ASHP and to correlate that with electrical energy use.

BrHEAThe Energy Flow Data

In order to analyze the energy flows through the BrHEAThe coil, both the energy from the liquid side and the air side were metered.

The energy from the liquid side is calculated just like the energy from the AHSP:

$$Q=m\cdot c_p(t_{hot}-t_{cold})=V\cdot ro\cdot c_p(t_{hot}-t_{cold})$$
m=mass flow=V·ro=volumetric flow·density
c_p=specific heat capacity
t_{hot}=temperature of the fluid from the buffer tank
t_{cold}=temperature of the fluid returning to the buffer tank from the coil

The energy added to the air from the coil is a little more difficult to calculate. The flow of air in ducts is highly variable and getting precise measurements at the low flows used in this design was not possible. Air flow measurements were recorded by Nailor differential pressure sensors. In an effort to calibrate the sensors, air flow was measured via an Energy Conservatory TrueFlow meter and a DG-700 digital manometer for the Nailor sensors at the coil box. The flow metering plate was inserted into the filter slot of the coil box and differential pressures were measured with the DG-700.The Nailor sensors at the coil box were confirmed to be taking accurate measurements.

The energy equation is the same:

$$Q=m\cdot c_p(t_{hot}-t_{cold})=V\cdot ro\cdot c_p(t_{hot}-t_{cold})$$
m=mass flow=V·ro=volumetric flow·density (1 kg/m^3 for air)
c_p=specific heat capacity (1010 J/kg k for air)
t_{hot}=temperature of the air leaving the coil
t_{cold}=temperature of the air entering the coil

In addition to the heat energy flows, the electrical use of the three pumps, booster fan, and HRV were recorded to gain an understanding of the overall energy use of the BrHEAThe system.

Domestic Hot Water Data

In an effort to evaluate domestic hot water use, a typical water use profile was created (Edwards, Beausoliel-Morrison, &Laperriere, 2015). The schedule of hot water use is presented in Table 5.

Incoming and outgoing domestic water temperatures were monitored as was the total flow on 1-, 5-, and 60-minute intervals. The domestic hot water flow was controlled by the datalogger which roughly met the hot water draw in liters. This aspect of the project was not run during the whole project but off and on for a week at a time for four different weeks.

Water Utility	Time	Approximate Duration	Hot Water Draw (L)	Hot Water Draw (gal)
Master bedroom shower	6:50	10.2 min	36	9.5
Kitchen tap	7:45	3.0 min	13	3.4
Kitchen tap	11:00	3.0 min	11	2.9
Kitchen tap	12:30	6.0 min	13	3.4
Dishwasher (1st)	18:30	6 min	27	7.1
Main bathroom bath	21:05	5 min	41	10.8
Master bedroom shower	22:30	15 min	55	14.5
		Total	**160**	**52**

Results

Initial Set up – spring 2018

In the initial set up the system was based on the early conceptual work. Due to the start of the project in early spring the data collection window was limited to a few weeks. This initial data was used to inform changes to the system that took place over the summer.

BrHEAThe heat delivered

The low temperature supplied from the buffer tank to the air-heating coil led to much lower heat output than anticipated. The system was planned to deliver about 6 kW (20,000 Btu/hr). Under the first set up only 1.7kW (6,000 Btu/hr) was delivered at its maximum. The buffer tank supply temperature never rose above 47°C, which was well below the design temperature of 71°C.

ASHP Performance

Initial data show the ASHP was not performing as efficiently as expected. A 2013 lab study of the heat pump found the COP at -8.3°C to be 2.1 (Larson, 2013). For the brief time the system ran in the spring the hourly COP did not get above 2 regardless of outside temperature. The heat pump was configured to its highest setting delivering 80°C fluid. The set point was lowered to 71°C for the second set up. Figure 7 shows the COP vs. outside temperature for the first set up.

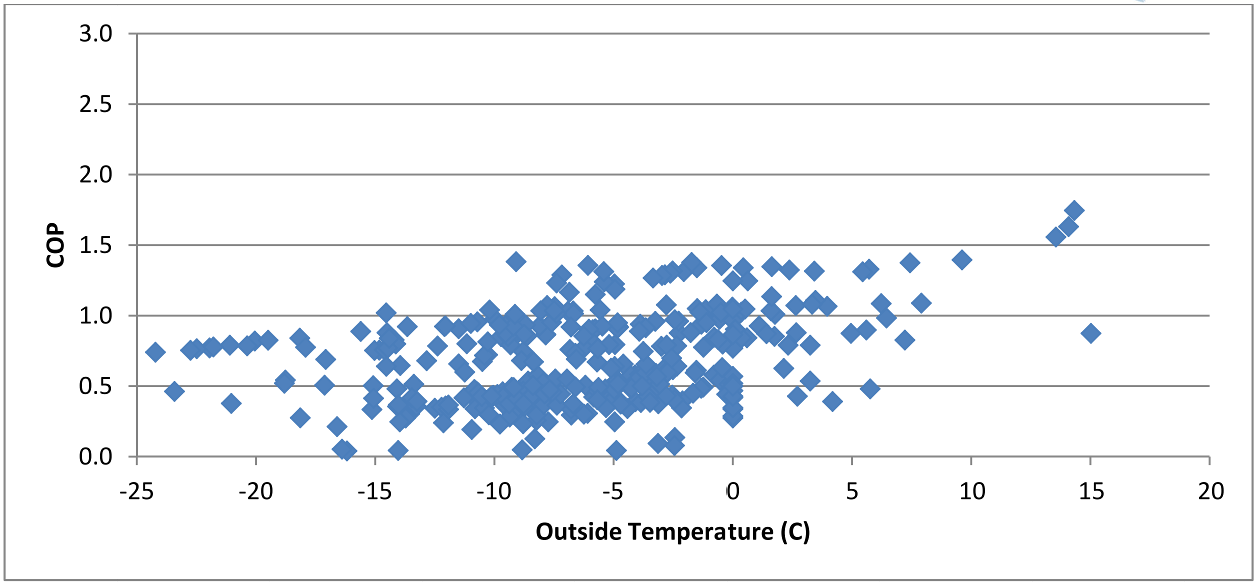

Figure 7. Hourly COP and outside temperature. There is potentially a small correlation between outside temperature and COP.

There are other factors affecting the COP of the Sanden besides the outside and delivery temperature. Since it is designed to heat domestic hot water directly, it requires a high temperature difference in the fluid across the heat pump. The COP does track with the temperature difference better than with the outside temperature. Temperature differences above 20 C° give a higher COP (see Figure 8). It is expected that as the unit approaches the delta T it is designed for (around 55°C) it could approach the COP in its specifications.

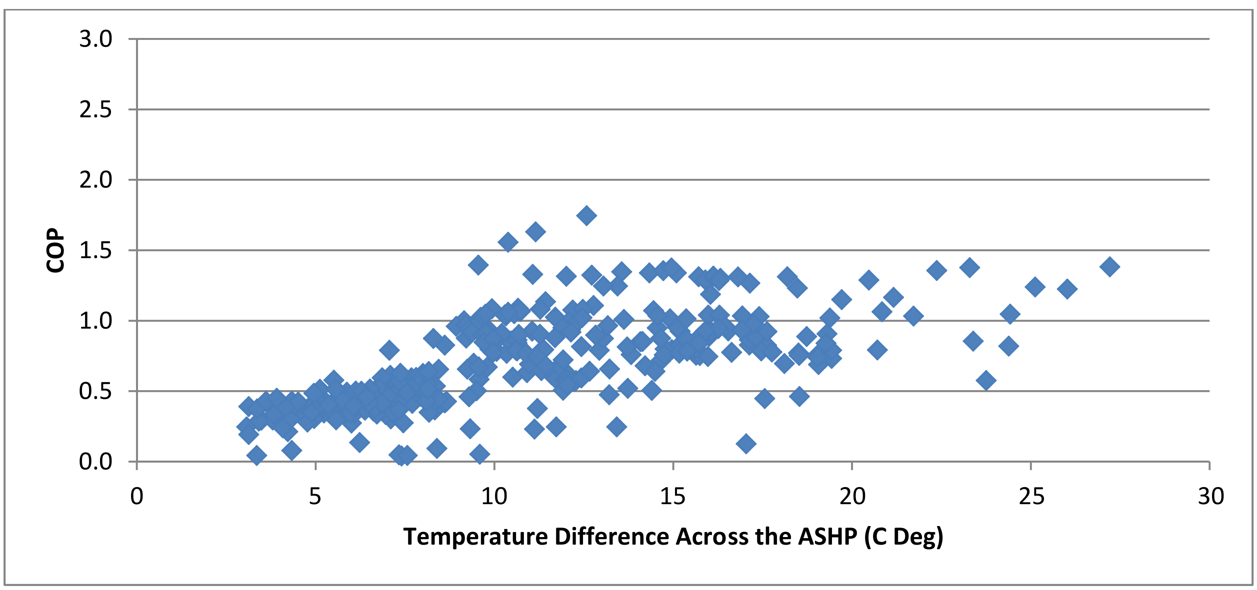

Figure 8. COP and temperature difference across the heat pump. The heat pump is designed to have a high temperature difference; these low differences most likely caused the poor performance of the heat pump.

Final Set up – Winter 2018-2019

Changes to buffer tank's configuration over Summer 2018 were intended to improve the system's function. The overall system heat delivery did not change much with the new configuration, nor did the efficiency of the heat pump. The technical specifications for the heat pump state the "systems are designed to be able to lift water temperatures over 100°F [38°C] quickly and efficiently, having a heat exchanger in the storage tank and a closed loop type system will significantly reduce performance and efficiency." This project proves this caveat very well with low COP and heat delivered.

BrHEAThe Heat Delivered

The maximum delivery temperature from the buffer tank was still 47°C in the new configuration and the maximum heat delivered was 1.8 kW (6,100 Btu/hr).

The buffer tank was bypassed for a short 5-day test in an effort to get higher delivery temperature and determine if the coil could deliver the required heat load. The higher temperatures, up to 72°C, did improve the heat delivered by the coil. However, the flow remained lower than the typical 11 l/min (3 gpm) expected in an actual BrHEAThe install, the maximum was 4 l/min. Several data points were taken at three different flows and the averaged heat delivered was used to create a linear estimate of heat delivered based upon flow that can be extrapolated to higher flows (Figure 9). The linearity of the relationship is not known but the extrapolated point is near the specified data for this coil.

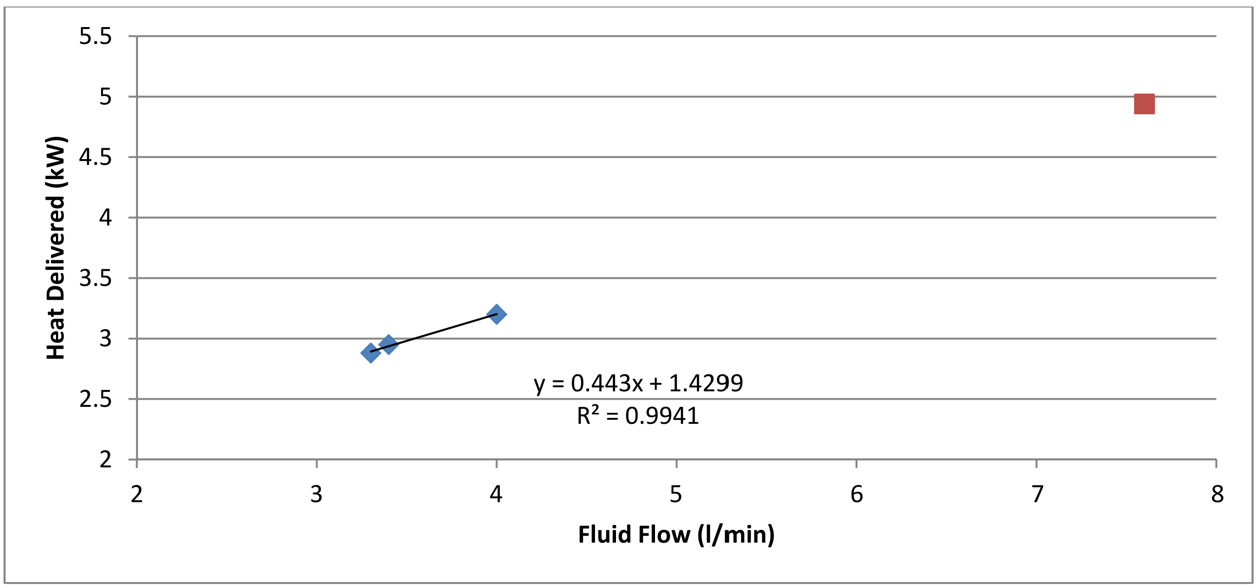

Figure 9. Average heat delivered by the heating coil based on fluid flow. The red dot is the extrapolated heat delivery at the design flow of 7.6 l/min.

The heat pump is rated to have a heating capacity of 4.5 kW (15,400 Btu/hr) at temperatures above -15°C. Below the -15°C the capacity is reduced and dependent on outside temperature. The heat pump did not ever reach 4.5 kW (see Figure 10). The boiler's contribution to the system did not happen in conjunction with the heat pump as the control scheme to do that was not possible. When the boiler ran, it delivered from 2 to 7 kW to the buffer tank (depending on the outdoor set point of the boiler).

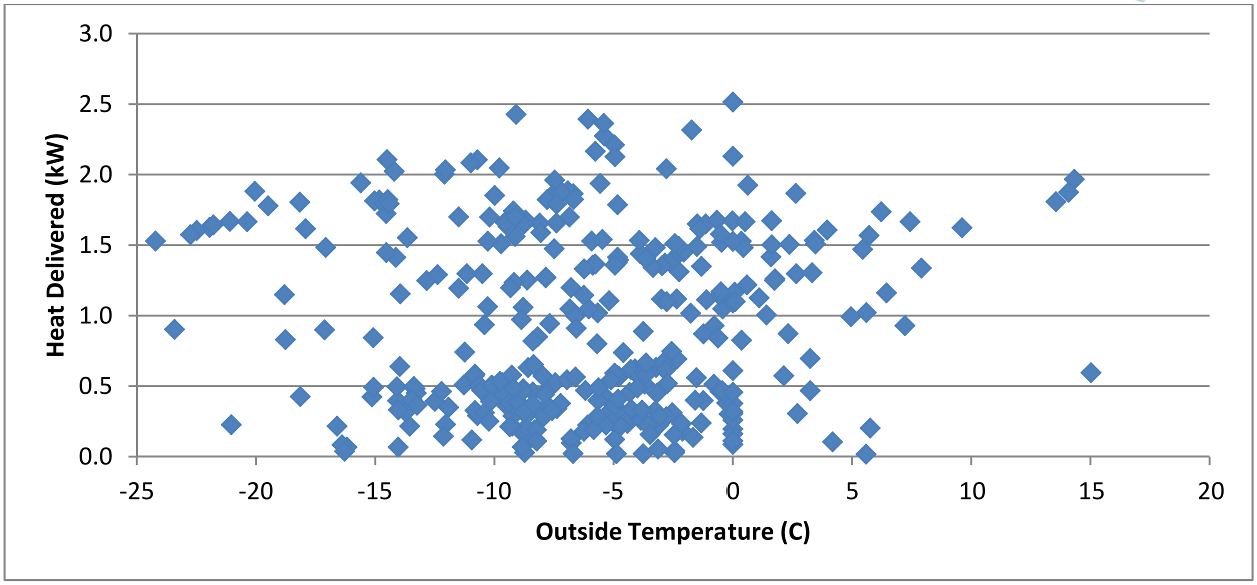

Figure 10. Heat delivered by the heat pump. The heat pump did not reach its delivery capacity probably due to the high return temperatures that depressed the overall performance of the heat pump.

ASHP Performance

The heat pump efficiency improved minimally with the second configuration. There is the potential to see a slight trend in the higher temperatures (Figure 11), but it did not run above 15°C in this study. The temperature difference across the ASHP was still less than 30°C (Figure 12).

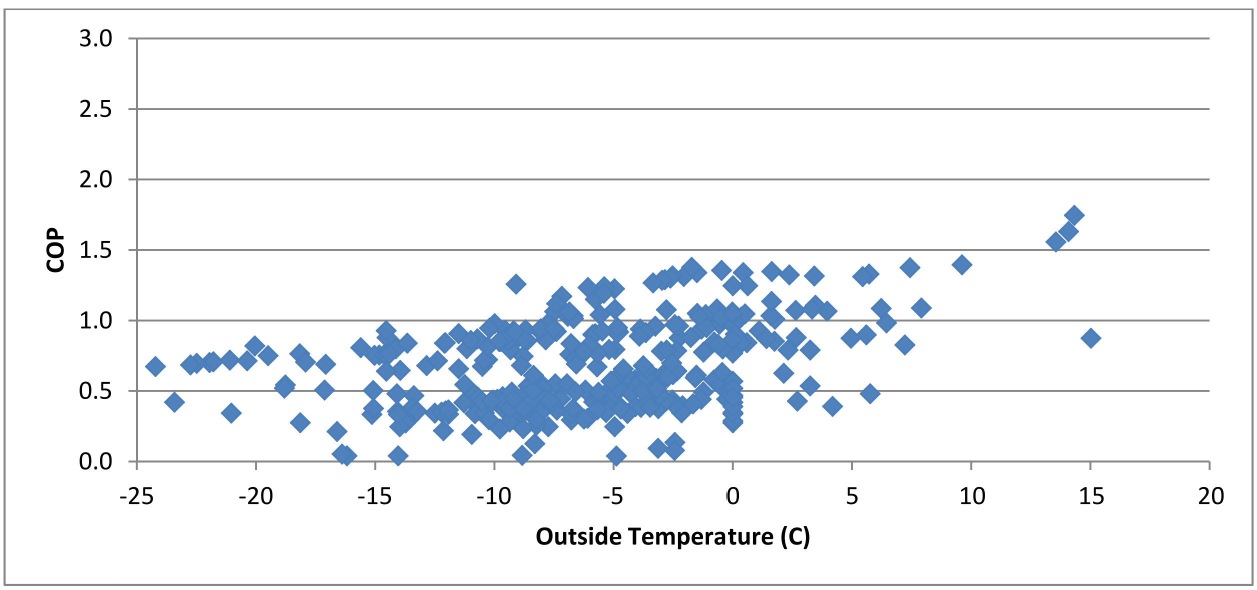

Figure 11.COP and outside temperature in second winter.

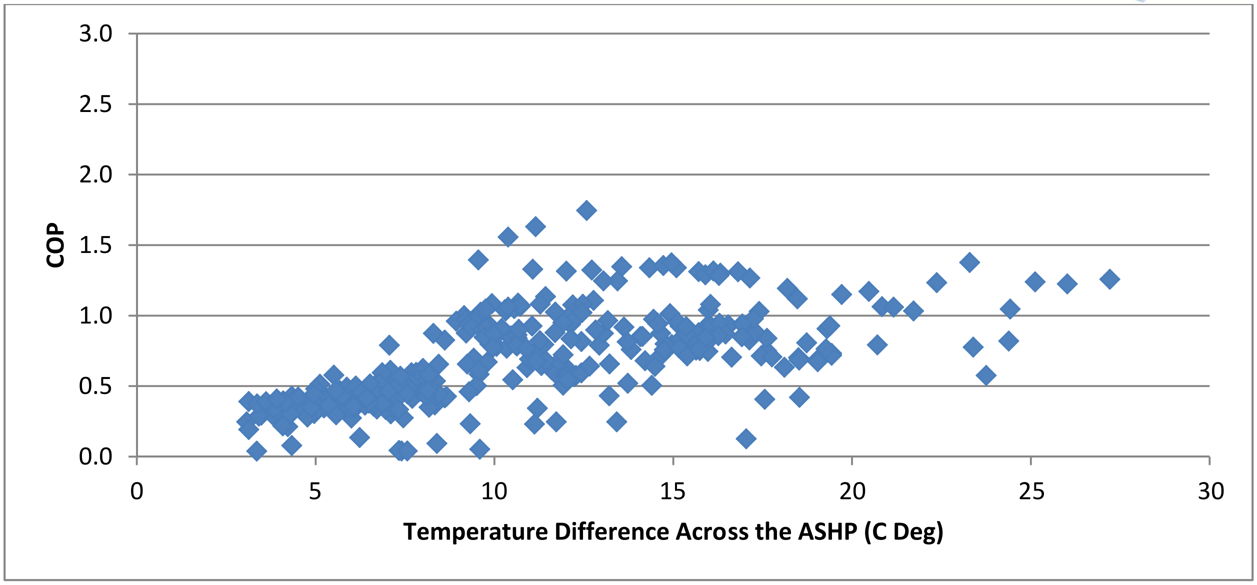

Figure 12.COP and the delta T across the heat pump.The heat pump is designed to have a high temperature difference, these low differences most likely caused the poor performance of the heat pump.

ASHP Defrost

The heat pump has three mechanisms for dealing with below-freezing temperatures. The manufacturer encourages the use of electrical heat tape on the piping in areas where below-freezing temperatures might be present. There is also a freeze protection cycle that runs if the outside temperature is below -1°C. The heat pump will run every 1–4 hours depending on the outside temperature; it will run until the water returning to the heat exchanger reaches 122°F. Figure 13 shows a sample of data where the heat pump ran its freeze protection cycles at 15:30 and 17:59 on 2/12 (to name a few) when there was no call for heat in the tank. Each cycle ran about 15 minutes.

The ASHP also has a defrost cycle that runs to remove any ice buildup from the outdoor coils. The Sanden documentation says that the unit calculates when it needs to defrost based on outdoor conditions. If the ASHP is running for at least 12 minutes and the outdoor condition sensor determines it needs to defrost, the compressor speed increases and the expansion valve opens fully, allowing hot gas into the evaporator coil to melt any frost. The defrost ends when the defrost sensor reaches a certain temperature or once it has been engaged for 20 minutes. You can see this defrost cycle in the data in Figure 13 at 11:30 and 12:30 on 2/12 (among several times) when power to the compressor jumps up for a few minutes and then drops back to its heating mode. Figure 14 shows a zoomed in version of the two most visible defrost cycles.

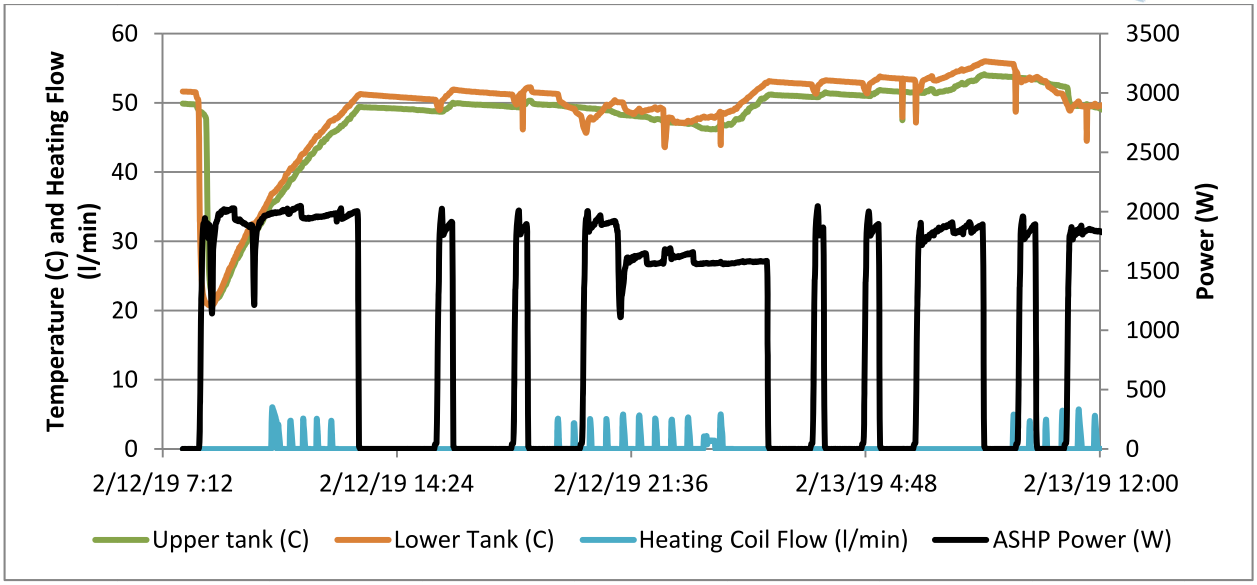

Figure 13.Three heating cycles of the ASHP. The spikes in the black line show when there was a defrost or warming cycle.

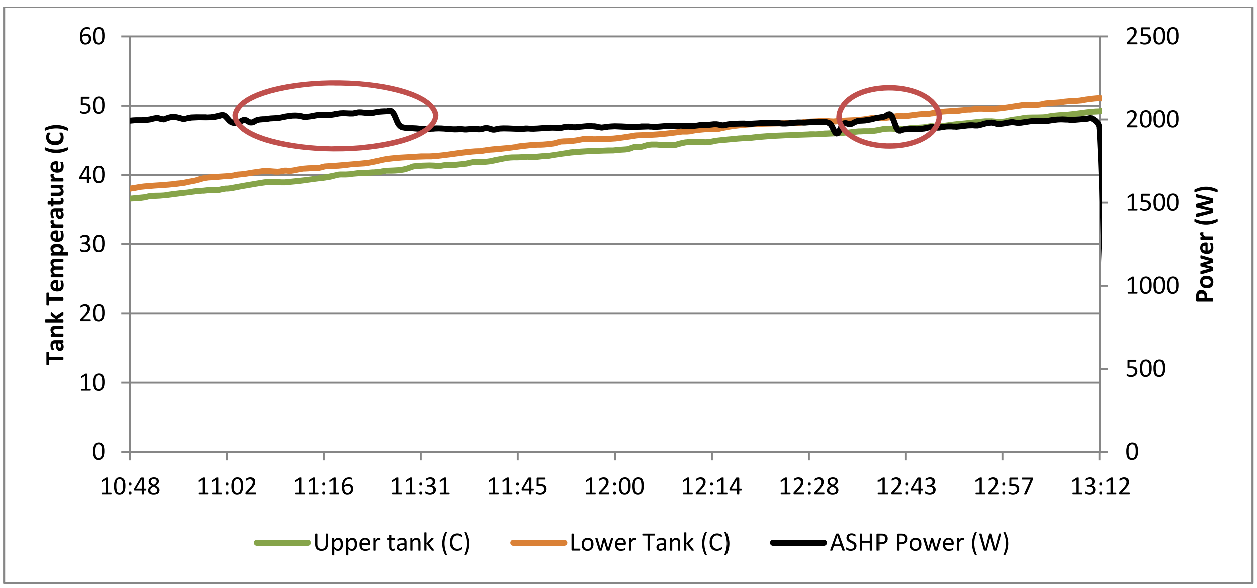

Figure 14. Defrost cycles from Figure 13 called out. The first defrost cycle ran 20 minutes the second was shorter only running about 6 minutes.

DHW Analysis

A simulated domestic hot water draw was run over the course of 4 different weeks in the second winter. Generally, the metered DHW use did not have much effect on the temperature in the buffer tank if there was no call for heat. In an effort to analyze the recovery time of the buffer tank using the ASHP, the hot water was removed from the tank and replaced with new water (the domestic incoming water was around 21°C). Figure 15 shows the DHW temperature and incoming water temperature as the hot water was used.

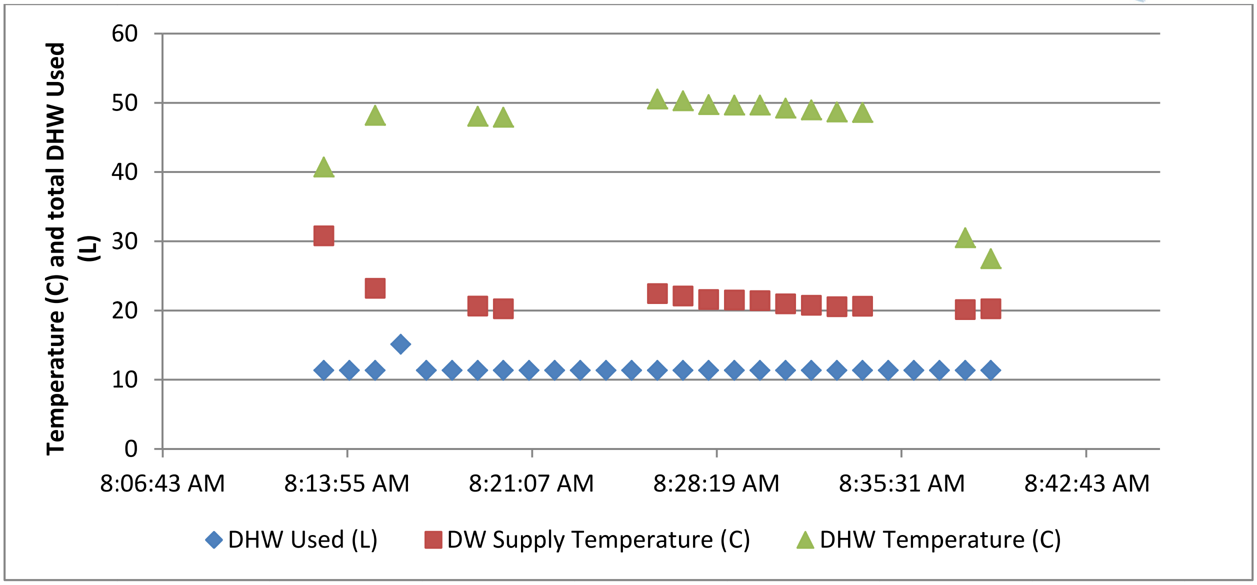

Figure 15.Removing all the hot water in the DHW tank. Holes in the data have to do with faulty data collection equipment.

Figure 16 shows the recovery in the tank temperature from the heat pump. The tank took more than 5 hours to recover its original temperature with only the heat pump operating. There were several calls for heat from the buffer tank at that time, which is probably the reason the tank took so long to recover.

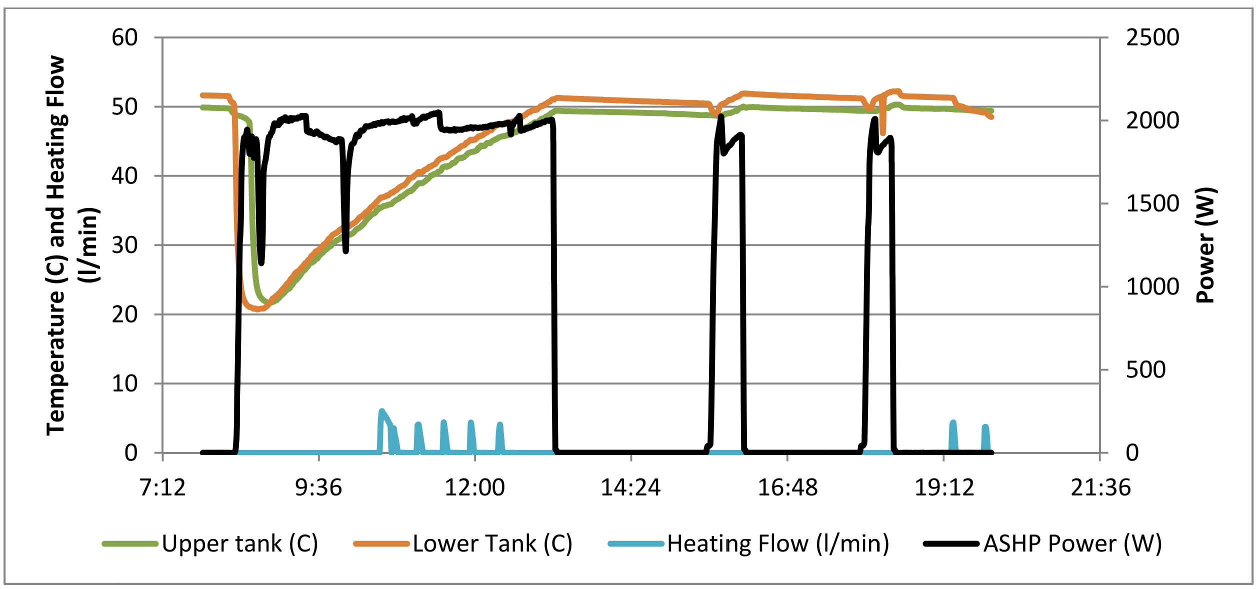

Figure 16. Recovery time for the full tank of DHW (February 12, 2019). The calls for heat shown by the blue line slowed the recovery of the tank down.

Lessons Learned

1. The ASHP choice
    a. The use of the Sanden, which is designed for an open system where domestic water flows through, for a closed loop heating scenario was problematic

   b. Plastic components proved to be an issue due to their susceptibility to breaking. This is especially an issue if any maintenance needs to occur outside during below-freezing temperatures
   c. The ASHP seems to be very susceptible to Fairbanks' imperfect electrical service. The main circuit board had to be replaced once and just as the study was ending the ASHP was starting to see error codes that were unrelated.
2. The controls
   a. The Tekmar controls were not flexible enough for this application
   b. More robust programmable controls will need to be found for future installs
3. The buffer tank
   a. The heat coils in the buffer tank were too restrictive for the tank to reach the high temperature necessary for the BrHEAThe heating coil

Conclusions

The installation of the integrated heating and ventilation system with a boiler and an air source heat pump at CCHRC's laboratory was functional. Operation of the system was intermittently successful.

The Sanden GS3-45HPA appears to be an inappropriate component for the combined heating and ventilation system. The application of the ASHP for both space heating and domestic hot water does not seem to be feasible for the project's design conditions. Reconfiguration of the system from the closed loop design to an open loop design would allow for a lower return temperatures to the Sanden ASHP, which is required if this installation were to be optimized.

A different air source heat pump that is designed to deliver heated glycol to the space might be a better option for this application. The Ecologix or Nordic brand systems seem to be promising for this application; however, they are quite a bit more expensive than the Sanden.

References

Edwards, S., Beausoleil-Morrision, I., &Laperrière, A. (2015).Representative hot water draw profiles at high temporal resolutionfor simulating the performance of solar thermal systems. *Solar Energy*. 111: 43-52.

Appendix A-Installation Photos

Figure A 1 BrHEAThe filter and coil box assembly with off-the-shelf ducting components

Figure A 2 Assembled BrHEAThe coil box tied into CCHRC's HRV

Figure A 3 CCHRC HRV connection to the filter and coil box

Figure A 4 Inline fan added to filter and coil box

Figure A 5 CCHRC boiler tied into the system

Figure A 6 Heat exchanger between the boiler and the system

Figure A 7 Staging of plumbing components for installation

Figure A 8 Plumbing BrHEAThe coil to the tank with variable speed circulator

Figure A 9 Plumbing from the boiler, tank, and BrHEAThe coil including temperature and flow sensors

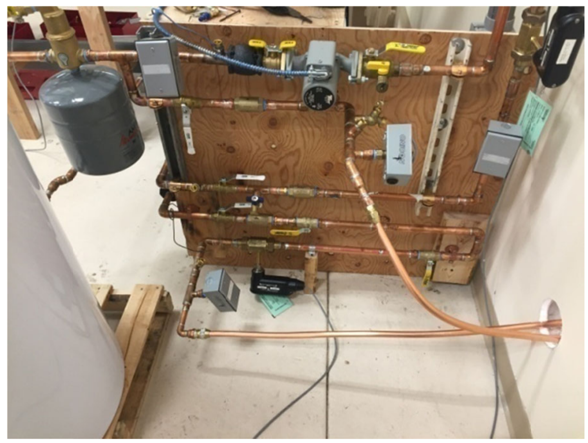

Figure A 10 Plumbing from the boiler, tank, BrHEAThe coil, and ASHP with single speed circulator

Figure A 11 ASHP with site-built stand to allow for any condensate or snow melt to be cleared from the unit

Figure A 12 ASHP installed outside CCHRC South Laboratory

Figure A 13 ASHP plumbed through exterior wall of South Laboratory

Figure A 14 Fully plumbed and controls being installed.

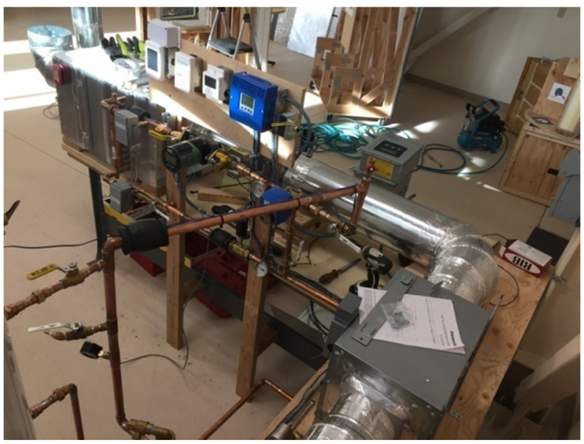

Figure A 15 Completing controls installation and connecting power to the system

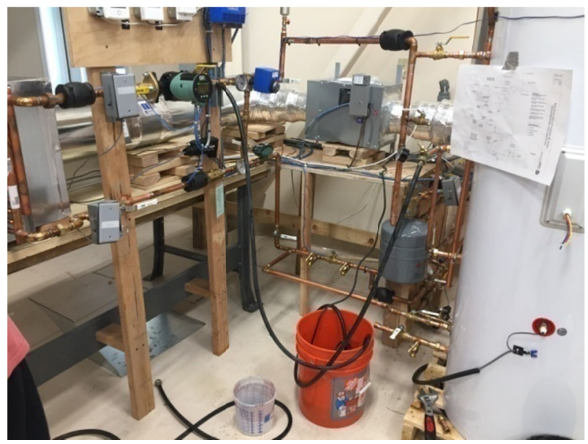

Figure A 16 Filling the system with glycol mix

Figure A 17 ASHP disassembly after cracked ASHP pump casing leaked glycol

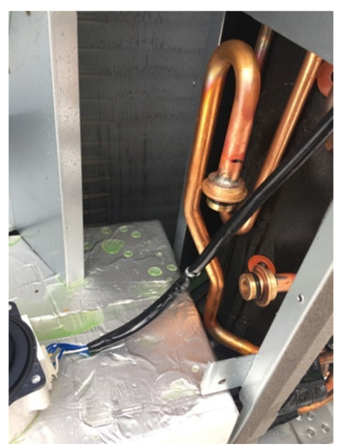

Figure A 18 ASHP copper to plastic connections with rubber o-rings.

Figure A 19 Cracked ASHP pump casing (side A)

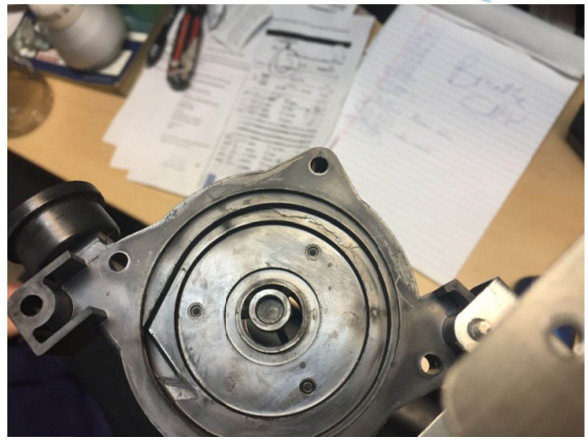

Figure A 20 Cracked ASHP pump casing (side B)

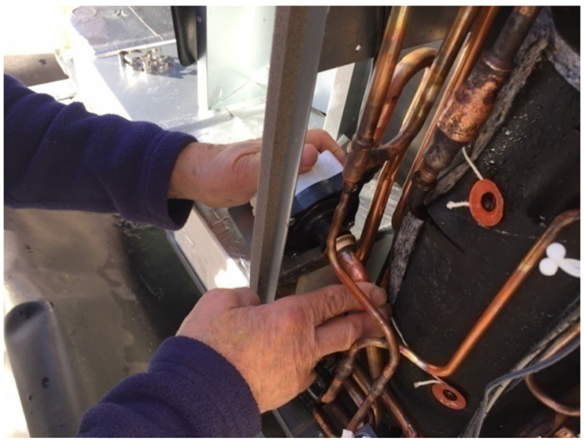

Figure A 21 Replacement pump installation

Figure A 22 Replacement pump installed

Figure A 23 ASHP plastic plumbing connections

Figure A 24 Completed installation of combined heating and ventilation system with integrated boiler and air-source heat pump

Appendix B -Installed Components

Table B 1 Plumbing Components

Materials	COMMON COIL ZONE	BOILER ZONE	ASHP ZONE	COMMON TANK ZONE	TANK DHW	COMMON AIR PRESSURE	CCHRC BOILER ZONE	TOTAL USED
3/4" - ELLS - 90	9	7	7	1	2			26
3/4" - ELLS - 90 STREET								
3/4" - ELLS - 45	1		1	2	1			5
3/4" TEES - SIDE	4							4
3/4" TEES - STRAIGHT	5	2	3					10
3/4" 3/4" 1/2" TEES - STRAIGHT	3	2	2					7
3/4" BALL VALVE - Ferguson	6	3	4					11
3/4" PUMP ISO VALVE								2
3/4" UNION - BRASS	4		1					5
3/4" CHECK VALVE		2	2					4
3/4" Repair Couplings								8
VAR SPD CIRC PUMP	1							1
SIN SPD CIRC PUMP		1						1
1/2" - ELLS - 90		6	1	2				9
1/2" - ELLS - 45						1		1
1/2" TEES - STRAIGHT		1						1
1/2" 1/2" 3/4" TEES - STRAIGHT								
3/4" - 1/2" REDUCER	1	2	2	1	1			7
3/4" - 1/2" FEMALE ADAPTER							4	4
3/4'' FEMALE ADAPTER		1						1

3/4'' MALE ADAPTER - Ferguson	4	2	8		1			15
THERMOMETER	2	2	2					6
1/4" REDUCER	1	1						2
1/4" BALLVALVE	1	1						2
1/8 MPT AUTO AIR VENT							1	1
1/4" 150# AIR VENT							2	2
PRESSURE GAUGE	1							1
1/2" BALL VALVE				2		1		3
1/2'' FEMALE ADAPTER	2	2	4	4	1	2		15
1/2" WROT FTG X FIP ADAPTER								4
1/2" UNION		2		4				6
TACO VAC ZONE SENTRY VALVE	1							1
1/2" NO-KINK HOSE BIBB	2	1	1					4
3/4" SPIROVENT AIR ELIMINATOR	1							1
MIXING VALVE	1							1
EXPANSION TANK - HEAT	1							1
EXPANSION TANK - DHW					1			1
PRESSURE GAUGE	1							1
1/8"FEMALE ADAPTER						1		1
1/8" SHRADER VALVE						1		1
1/2" FLARE NUT			4					4
1/2" FLARE ADAPTER			2					2
T/P VALVE					1			1
3/4" TYPE M COPPER PIPE- FT	8.3	7.4	5.6	2.5	3.25		5	32
1/2" TYPE M COPPER PIPE- FT		19.6	10.8	2.3				16.7
1/2" FLEX COPPER -								16.0

SAMSONS								
MAPP GAS TANK								1
5G 60/40 DOWFROST								1
1/2 PIPE CLIP								1
3/4 PIPE CLIP								1
3/4 BELL HANGER								6
3/4 COPPER STRUT CLAMP								6
Lf 1# BRIDGIT SOLDER - FERGUSON								1
SOLDER - SAMSONS								1
OPEN MESH CLO WP 1.5X10YDS								1
3/4 PLAS HDL FTG BRUSH								1
1 PLAS HDL FTG BRUSH								1

Table B 2 Ventilation Components

Materials	Total Used
16.5”x20” Plenum	2
6" Takeoff Collar	1
8" Takeoff Collar	2
16”x20”Filter Box	1
8"x5' 30 GA Rnd Pipe	3
6"x5' 30 GA Rnd Pipe	2
8" 30 GA 90 ELL	3
6" 30 GA 90 ELL	2
7"x6" 26 GA Reducer	3
16”x20”x2” MERV 8 FLTR	2
CCY 340 CFM Inline Vent Fan	1
1/2" Sheet Metal Screws – 100 ct	1
8"-7" 26 GA Reducer	2
8" Backdraft Damper w/ Gasket	1
15x20 Hot Water Coil	1
2" Foil Tape – 100’	1

Appendix C – Data collection

Table C1. All data collection points.

Variable	Purpose	Sensor	Unit	Location
ASHP_Power_watts	Heat pump electric use/and defrost cycle	CR1000 power meter	W	In the ASHP switch box
ASHP_pump	Pump power usage			On the AUX AHSP pump[1]
ASHP_flow_lmin[2]	Fluid flow in pipe	Onicon System 10 with F-1300 flow meter	l/min	In the return line to the ASHP
ASHP_cold_C	Return temp		°C	In the return line to the ASHP
ASHP_hot_C	Delivery temp		°C	In the supply line from the ASHP
ASHP_defost_C[3]	To determine when the defrost cycle runs	Thermistor	°C	On the AHSP outside coil
ASHPflow_gpm	Fluid flow in pipe back up	SM6001, electro300	gpm	In return pipe to ASHP
COIL_pumppower_watts_Avg	Pump electrical use	CR1000 power meter	W	On the pump hot wire
Coil_flow_lmin	Fluid flow in pipe	Onicon System 10 with F-1300 flow meter	l/min	In the return line from the coil
Coil_return_C	Return temp		°C	In the return line from the coil
Coil_supply_C	Delivery temp		°C	In the supply line to the coil
BOILER_power_watts_Avg	Pump power usage	CR1000 power meter	W	On the pump hot wire
Boiler_flow_gpm	Fluid flow in pipe	SM6001, electro300	gpm	In the return line to the boiler
Boilerreturn_C	Return temp	Thermistor	°C	In the return line to the boiler
Boilersupply_C	Delivery temp	Thermistor	°C	In the supply line from the boiler
HRV_power_watts_Avg	Electrical use of the HRV	CR1000 power meter	W	In the HRV plug box
HRV_exhaust_C[4]	Exhaust temp	Thermistor	°C	In the HRV exhaust to outside duct
HRV_intake_C	Fresh intake air temp	Thermistor	°C	In the HRV fresh air intake duct
HRV_return_C	Return from space temp	Thermistor	°C	In the HRV duct returning from the building
HRVsupply_C	Supply air temp	Thermistor	°C	In the HRV supply to building duct
HRVsupply_flow_cfm	Air flow from the HRV to the coil box	Nailor 36FMS	cfm	In the HRV supply to building duct
Box_makeup_C	To verify if makeup damper	Thermistor	°C	Behind the makeup damper in

[1] This was never installed
[2] This sensor was not as precise as the gpm sensor
[3] The first thermistor in this set failed
[4] Sensors 1 and 3 have failed

Variable	Purpose	Sensor	Unit	Location
	is open			the coil box
Box_mix_C[5]	Pre-filter coil box temperature	Thermistor	°C	Upstream of the filter in the box
Box_postfilter_C	Post-filter coil box temperature	Thermistor	°C	
Boxsupply_C	Temperature supplied from the filter box	Thermistor	°C	In the supply duct from the filter box to the fan
Boxsupply_flow_cfm	Flow leaving the filter box	Nailor 36FMS	cfm	In the supply duct from the filter box to the fan
Fan_C	Air Temperature supplied to the house	Thermistor	°C	In the duct after the booster fan
Fan_flow_cfm	The flow of air to the house	Nailor 36FMS	cfm	The flow of air to the house
Uppertank_C	Water tank upper temp	Thermistor	°C	In the upper temp well
Lowertank_C	Water tank lower temp	Thermistor	°C	In the lower temp well
Uppertankair_C	The air temp near the tank	Thermistor	°C	Outside the upper temp well
Lowertankair_C	The air temp near the tank	Thermistor	°C	Outside the lower temp well
DHW_draw_L	Total water that has flowed	SM6001, electro300	liters	In the supply line to DHW
DHW_L	Water pulse counter	SM6001, electro300	liters	In the supply line to DHW
Coldtemp_C	Temperature of the incoming water	Thermistor	C	In the supply line to DHW
Hottemp_C	Temperature of the heated water	Thermistor	C	In the heated water line

[5] Sensor 1 has failed