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Final Report:

Case Study for the ARRA-funded Ground Source Heat Pump Demonstration at Denver Museum of Nature & Science

Piljae Im, PhD
Xiaobing Liu, PhD

November 30, 2015

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OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

ORNL/TM-2015/473

Energy and Transportation Science Division

FINAL REPORT: CASE STUDY FOR ARRA-FUNDED GROUND-SOURCE HEAT PUMP) DEMONSTRATION AT DENVER MUSEUM OF NATURE & SCIENCE

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ACRONYMS

AHU	air handler unit
ARRA	American Recovery and Reinvestment Act
BAS	building automation system
COP	Coefficient of Performance
DHHW	domestic hot water
DMNS	Denver Museum of Nature & Science
GSHP	ground-source heat pump
HVAC	heating, ventilation, and air-conditioning
HW	hot water
HX	heat exchanger
LWT	leaving water temperature
OA	outdoor air
RW	recycled water
RWHP	recycled water heat pump
TRWS	recycled water supply temperature
TSL	Source loop temperature
VAV	variable air volume
WB	wet bulb
WHP	water heat pump
WWHP	water-to-water heat pump

EXECUTIVE SUMMARY

High initial costs and lack of public awareness of ground-source heat pump (GSHP) technology are the two major barriers preventing rapid deployment of this energy-saving technology in the United States. Under the American Recovery and Reinvestment Act (ARRA), 26 GSHP projects were competitively selected and carried out to demonstrate the benefits of GSHP systems and innovative technologies for cost reduction and/or performance improvement. This report highlights the findings of a case study of one such GSHP demonstration projects that uses a recycled water heat pump (RWHP) system installed at the Denver Museum of Nature & Science in Denver, Colorado. The RWHP system uses recycled water from the city's water system as the heat sink and source for a modular water-to-water heat pump (WWHP).

This case study was conducted based on the available measured performance data from December 2014 through August 2015, utility bills of the building in 2014 and 2015, construction drawings, maintenance records, personal communications, and construction costs. The annual energy consumption of the RWHP system was calculated based on the available measured data and other related information. It was compared with the performance of a baseline scenario— a conventional VAV system using a water-cooled chiller and a natural gas fired boiler, both of which have the minimum energy efficiencies allowed by ASHRAE 90.1-2010. The comparison was made to determine energy savings, operating cost savings, and CO_2 emission reductions achieved by the RWHP system. A cost analysis was performed to evaluate the simple payback of the RWHP system. Summarized below are the results of the performance analysis, the learned lessons, and recommended improvement in the operation of the RWHP system.

- The measured recycled water temperature from the demonstration site during the encompassed period shows that the recycled water temperature is more favorable than the outdoor air temperature for effective operation of the vapor compression refrigeration cycle of the heat pump. The maximum outdoor air temperature was about 94.5°F during the cooling season, whereas the maximum recycled water temperature was about 83.2°F. The lowest recycled water temperature was about 38.8°F during the heating season, whereas the lowest outdoor air temperature was below 10°F.

- Effective COPs of the WWHP unit and the entire RWHP system, which account for the simultaneous cooling and heating, were calculated based on the measured data. The effective COP of the WWHP unit ranges from 4.6 through 6.0, whereas the effective COP of the RWHP system, which includes power consumptions of circulation pumps and the cooling tower, ranges from 2.6 to 4.4 during the 8 months investigation period of this study. The system COP increases with the increase of OA temperature, which is in part due to the increased simultaneous heating and cooling demands.

- The demonstrated RWHP system saved 3,930 MMBtu of source energy (a 46.1% savings) and $16,295 in energy costs (a 33.8% savings) annually, compared with a conventional VAV system using a water-cooled chiller and a natural gas fired boiler, both of which have the minimum energy efficiencies allowed by ASHRAE 90.1-2010. The energy savings also resulted in 41% reduction in CO_2 emissions.

- The normalized cost of the RWHP system (including the VAV system inside the building) is $25,210/ton of installed cooling capacity, or $37.8/ ft^2 of building floor space. With the achieved annual energy cost savings, the simple payback of this system is about 58 years. This long payback period is due to the high cost for constructing the 3,300 ft long two-way pipeline to access the recycled water. The pipeline cost is $1.1 million, which accounts for about 20% of the total system cost. If the length of the pipeline were 1,000 ft, the simple payback would have been reduced to 11 years. The RWHP system would be economically more competitive if the recycled water is closer to the building.

- Contributions of the steam HXs were very small and it is likely that the RWHP system can work well without the boiler and the steam HXs, or just with a smaller water heater as a backup. It will reduce the complexity and the associated cost of the RWHP system.

- The run-around heat recovery through the precooling loop is very effective and it significantly reduced the demand for external heat sources (e.g., the recycled water and the steam HX). The wet cooling tower rejected more heat than the recycled water due to the relatively dry air in the Denver area. Recycled water can serve as both the heat source and sink. However, its contribution was limited in this project. If the source water temperature is allowed to vary in a larger range (i.e., lower in heating season and higher in cooling season), recycled water may contributed more, which can reduce the need for supplemental heating and the water consumption associated with the operation of the cooling tower.

1. INTRODUCTION

In 2009, 26 projects were competitively selected and funded with American Recovery and Reinvestment Act (ARRA) grants to demonstrate innovative ground source heat pump (GSHP) technologies. Denver Museum of Nature & Science (DMNS) in Denver, Colorado (Fig. 1) was one of the 26 demonstration project sites. The new facility is a five-story, 140,000-gross-square-foot addition to the museum. The innovation of the demonstrated GSHP technology in this site is that this system uses water from the city's underground municipal recycled (non-potable) water system as the heat sink and source for the heat pump. This project is believed to be the first GSHP system in the United States that utilizes a municipal recycled water system as a heat sink/source. Because the proposed system is using recycled water instead of the conventional borehole field, a large land requirement for the borehole field and the associated cost for drilling and installation of a ground heat exchanger could be eliminated. In addition, the environmental and regulatory permitting process could be minimized by avoiding drilling vertical bores in the ground. The success of this project could encourage applications of the demonstrated technology, which is named as recycled water heat pump (RWHP) systems, in many urban areas, given existing recycled water distribution systems in many cities. For example, the existing recycled water system in Denver is over 70 miles long and is still expanding, and currently 171 water districts in 11 states in the United States have existing recycled water systems[1]. The recycled water is mainly used for landscape irrigation and pond water-level management. The RWHP application presents a new opportunity for local municipalities to develop and expand the use of underground municipal recycled (non-potable) water system.

This case study evaluates the performance of the demonstrated RWHP system based on measured performance data, utility bills, and other relevant information. The evaluated performance metrics include the energy efficiency of the overall RWHP system, electricity usage of all major equipment of the RWHP system, the achieved benefits (e.g., energy and cost savings and carbon emission reductions) compared with a new conventional HVAC system, and the cost-effectiveness of the RWHP system. This case study also identifies opportunities for improving the operational efficiency and reducing the installed cost of similar systems in the future.

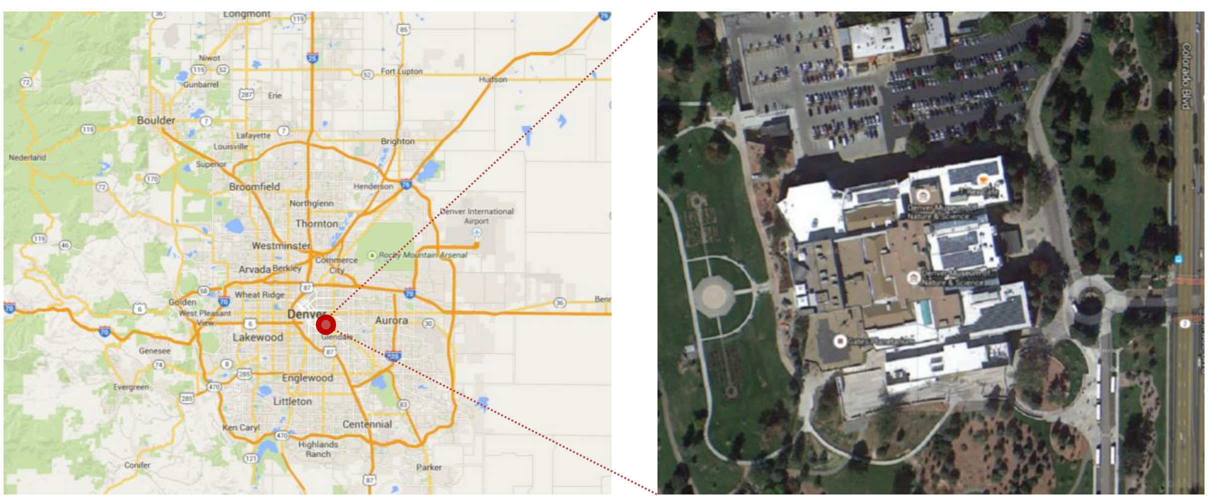


Fig. 1. Geographic location of the recycled water heat pump demonstration site at the Denver Museum of Nature & Science.

[1] http://www.denverwater.org/WaterQuality/RecycledWater/

1.1 BUILDING INFORMATION

The host building is a new addition, the new Education and Collection Facility (ECF) building, to the existing DMNS building. This 140,000 ft^2 building has five stories (including two stories underground). In addition to the RWHP system, this building also integrates a mix of other technologies, such as automated louvers, electrochromatic glass, a rooftop solar thermal system, and an LED lighting system.

The new addition consists of exhibition halls, classrooms, studios, research facilities, and collection storage. The building has earned LEED Platinum certification, which is the highest level of Leadership in Energy & Environmental Design, from the US Green Building Council. This museum building has critical requirements for indoor climate control: the humidity and temperature in the 70,000 ft^2 collection storage area need to be precisely controlled to maintain humidity at 50±3% and temperature at 70±2°F.

1.2 DESCRIPTION OF RWHP SYSTEM

The RWHP system uses the Denver Water (DW) existing underground municipal recycled (non-potable) water system as the heat sink and heat source in lieu of a borehole field used in conventional GSHP systems. Take-offs from the mains of the existing recycled water distribution system and a new pipeline were constructed to supply the recycled water to the building and return it to the mains after exchanging heat with the heat pumps.

The RWHP system uses a ClimaCool UCH series water-to-water heat pump (WWHP), which consists of seven 30-ton modules. The total installed capacity of the WWHP is 210 tons. Each module of the WWHP uses R-410A refrigerant and has two compressors and can independently provide either hot or chilled water to the building. A master controller modulates the number and operation mode of each module to satisfy the varying heating and cooling demands of the building. The WWHP can provide hot water and chilled water simultaneously. In addition, a 65 kBtu/h Heat Harvester WWHP, which extracts heat from the recycled water, and two Next Generation Energy solar thermal collection arrays are used to produce domestic hot water for the building.

The recycled water is not always available because of routine maintenance or other reasons. For example, the recycled water supply was shut off for 3 weeks in 2014. To ensure continuous air conditioning at the museum, the demonstrated RWHP system also has two steam heat exchangers (HXs) to provide supplemental heating. A cooling tower and another steam HX serve as a backup heat sink and source when the recycled water is not available or not sufficient to keep the source water temperature of the heat pumps within desired range. A new boiler was installed to provide steam to the HXs.

As shown in Fig. 2, the RWHP system has five water loops: the recycled water loop, source water loop, chilled water loop, hot water loop, and precooling loop. Each loop has its own circulation pump and associated control. A building automation system controls and monitors the operation of the WWHPs and other equipment. The design specifications of each water loop and major equipment of the RWHP system are described in following subsections.

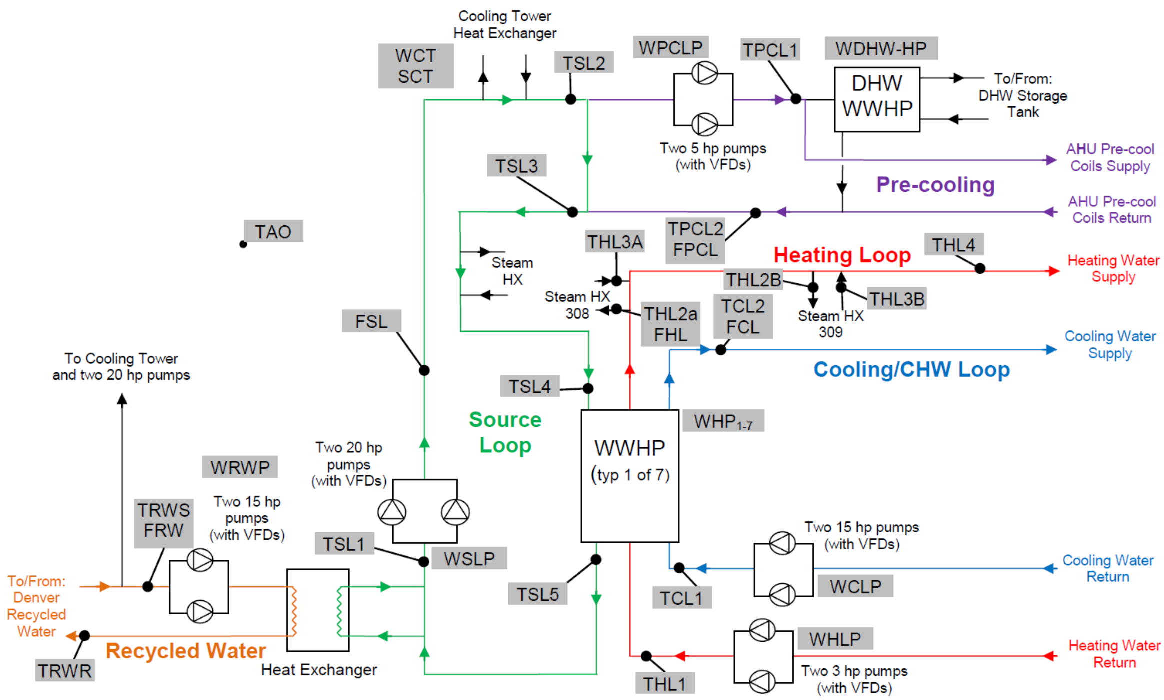


Fig. 2. A schematic of the recycled water heat pump system with monitored data points shown.

1.2.1 Recycled water loop

The new pipeline for the recycled water was constructed between the DW conduit located in City Park Golf Course to the ECF building. Two 8 inch PVC pipes (one for supply and the other for return) were installed side by side in a 48 inch wide trench. The supply line was insulated with 2 inch of foam insulation to reduce heat transfer between the supply and return lines. Fig. 3 (a) shows the new piping (in pink color) for the recycled water. Trench depth varied from 6 feet to 15 feet through the 3,300 foot long pipeline (in each direction). Isolation valves and a meter were installed at the conduit connection. Remote water sampling stations were required on the lines between the conduit and building entry points. Isolation valves were installed prior to entering the building.

Recycled water is pumped through a plate frame heat exchanger (referred as “RW HX” hereinafter and shown in Fig. 3) by two 15 hp redundant variable speed pumps (referred as the “RW pump” hereinafter) to exchange heat with the source water of the heat pump. The control sequence for the RW pump is different in heating and cooling seasons. During cooling season, the RW pump is turned on when the leaving water temperature from the RW HX (TSL1 in Fig. 2) is above 55°F and the leaving water temperature from the modular WWHP (TSL5 in Fig. 2) is at least 2°F higher than the RW supply temperature (TRWS in Fig. 2). During heating season, the RW pump is turned on when TSL1 is below 55°F and the TSL5 is at least 2°F lower than TRWS. When it is turned on, the speed of the RW pump is modulated to maintain the temperature differential of the recycled water at 10°F across the RW HX.

(a) (b)

Fig. 3. Recycled water loop: (a) new piping, and (b) plate heat exchanger for the recycled water.

1.2.2 Source water loop

The source water loop connects all the heat sinks and heat sources of the heat pumps. In addition to the recycled water heat exchanger, this loop also has a steam HX and a cooling tower (connected through a heat exchanger). Water is circulated in the loop by two redundant 20 hp pressure-controlled variable speed pumps. The source loop water temperature is maintained within a narrow range (with a design setpoint of 55°F to provide useful precooling for the building) by operation of the various heat sinks and heat sources.

1.2.3 Hot water loop

The hot water loop provides hot water to the air handling units (AHUs) in the building, terminal reheat coils in the variable air volume (VAV) boxes, and other heating terminals. The hot water is circulated by two redundant 3 hp pressure-controlled variable speed pumps. The supply hot water temperature is designed to be within 105–125°F. The hot water loop also has two steam HXs (see Fig. 4) to further raise the temperature of the hot water produced by the modular WWHP.

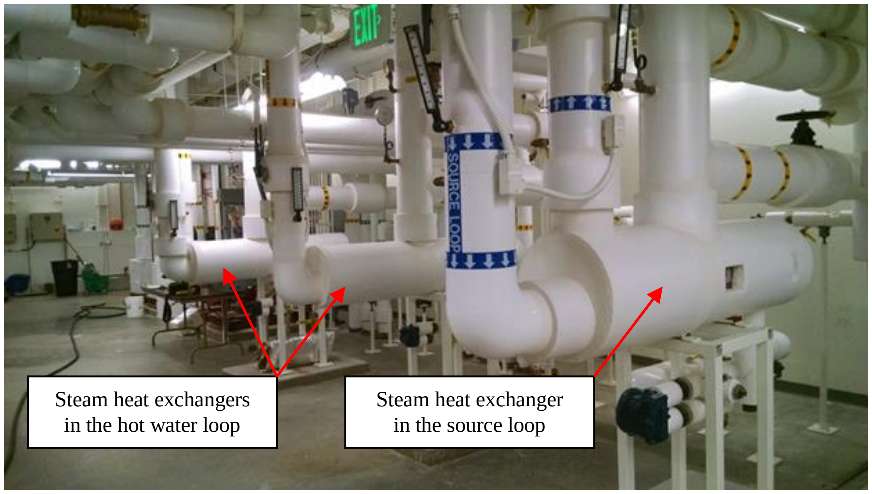


Fig. 4. Three steam heat exchangers in the recycled water heat pump system (two steam heat exchangers are in the hot water loop, and the third one is in the source loop).

1.2.4 Chilled water loop

The chilled water loop provides chilled water to the AHUs' main cooling coils or the precooling coils. The chilled water is circulated by two redundant 15 hp pressure-controlled variable speed pumps. The supply chilled water temperature is designed to be between 45 and 55°F with a maximum 10°F temperature rise in the return water.

1.2.5 Precooling loop

This loop provides cold water to the AHUs' precooling coils and serves as the heat source for the Heat Harvester WWHP unit for DHW heating. Water in this loop is cooled by the source water loop and the Heat Harvester WWHP when it produces domestic hot water. Cold water is circulated by two redundant 5 hp pressure-controlled variable speed pumps. The supply cold water temperature is designed to be between 45 and 75°F with a maximum 10°F temperature rise in the return water. The heat rejected from the precooling loop goes to the source water loop and becomes a heat source for the modular WWHP.

1.2.6 Air handling units

Five AHUs in the building (one for each floor) provide space conditioning through VAV systems, which have hot water (HW) reheat at each VAV terminal box. The design maximum air flow of each AHU is about 30,000 cfm and with 10% outdoor air (OA). Each AHU has multiple sections to preheat, precool, cool, or heat the air. Because the building requires precise humidity control, many VAV boxes have ultrasonic humidifiers, which are fed with a deionized water system. Figure 5 shows a typical AHU in one of the building's mechanical rooms.

Fig. 5. One of the five air handling units.

1.2.7 Cooling tower and steam heat exchangers

A single cell cooling tower (shown in Fig. 6) is installed in the source water loop as a backup or supplemental heat sink. It has about 3,150 kBtu/h cooling capacity. The cooling tower fan modulates to maintain leaving water from the cooling tower at 50°F, or a temperature that the ambient air would allow. The source loop steam HX uses 5 psig steam and has a 2,581 kBtu/h capacity. In heating operation, the source loop steam HX is activated when the source water temperature after exchanging heat with the precooling loop (TSL3 in Fig. 2) is lower than 50°F and it is deactivated when TSL3 is higher than 55°F. Two steam HXs are also connected to the hot water loop. Each of them uses 5 psig steam and has about 1,688 kBtu/h capacity. Controls for the hot water loop steam HXs will be discussed in Sect. 3.3.2. Steam is produced by a newly installed natural gas fired boiler, which has a thermal efficiency of 75%.

Fig. 6. Cooling tower.

1.2.8 Domestic hot water system

The Heat Harvester WWHP, in conjunction with the solar energy recovery system, provides hot water to maintain the water temperature in a DHW storage tank at 140°F (adjustable).

2. MONITORING AND ANALYSIS PLAN

2.1 DATA COLLECTION

Performance monitoring and data collection for the RWHP system are provided by the on-site Andover Continuum building automation system (BAS). The BAS polls the sensors once per second and provides 15 min totals or averages of each sensor depending on the sensor type. Temperatures and flow rates are averaged values. The kilowatt readings are instantaneous values, whereas kilowatt-hours are cumulative readings. Figure 2 shows the location of the monitored data points, and Table 1 gives a brief description of each data point. Performance data are collected at 15 min intervals and stored in column-oriented, time-stamped, comma-delimited files.

Table 1. RWHP system monitoring points

No.	M-306 Point Identifier	Data Point	Description	Units
Recycled Water Loop				
1	3 (T1)	TRWS	Recycled Water Supply Temperature	deg F
2	4 (Btu1)	TRWR	Recycled Water Return Temperature	deg F
3	4 (Btu1)	FRW	Recycled Water Flow	GPM
4	VFD	WRWP	Power Recycle Water Pumps - from VFD	kW
Source Loop				
5	16 (T2)	TSL1	Temperature Source Loop after Recycled HX	deg F
6	42 (T3)	TSL2	Temperature Source Loop after Cooling Tower	deg F
7	40	SCT	Cooling Tower Status	
8	43 (T4)	TSL3	Temperature Source Loop after Pre-cool Loop	deg F
9	61 (T5)	TSL4	Temperature Source Loop after Steam HX	deg F
10	63 (T6)	TSL5	Temperature Source Loop after WWHPs	deg F
11	62 (Btu3)	FSL	Flow Source Loop	GPM
12	VFD	WSLP	Power Source Loop Pumps - from VFD	kW
Heat Pumps and Major Equipment				
13	SB1MCB	WHP_{1-7}	Power Heat Pump (WWHP-1 through WWHP-7) - from SB1MCB	
14	109 (Btu4)	THL1	Temperature Heating Loop to WWHPs 1-7	deg F
15	98	THL2a	Heating Loop Temp before Steam HX 308	
16	104	THL2b	Heating Loop Temp before Steam HX 309	deg F
17	99	THL3a	Heating Loop Temp after Steam HX 308	deg F
18	105	THL3b	Heating Loop Temp after Steam HX 309	
19	109 (Btu4)	FHL	Flow Heating Loop	GPM
20	VFD	WHLP	Power Heating Loop Pumps - from VFD	kW
21	112 (Btu5)	TCL1	Temperature Cooling Loop to WWHPs 1-7	deg F
22	112 (Btu5)	TCL2	Temperature Cooling Loop from WWHPs 1-7	deg F
23	112 (Btu5)	FCL	Flow Cooling Loop	GPM
24	VFD	WCLP	Power Cooling Loop Pumps - from VFD	kW
25		WDHW-HP	Power DHW Heat Pump	
26	53 (Btu2)	TPCL1	Temperature pre-Cooling Loop prior to DHW WWHP	deg F
27	53 (Btu2)	TPCL2	Temperature pre-Cooling Loop after DHW WWHP	deg F
28	53 (Btu2)	FPCL	Flow pre-Cooling Loop	GPM
29	VFD	WPCLP	Power pre-Cooling Loop Pumps - from VFD	kW
30	VFD	WCT	Power Cooling Tower - from fan VFD	kW
31	122	SDHWHP	DHW Heat Pump Status	on/off
32	123	TDHWHPS	DHW Heat Pump Supply Temp	deg F
Ambient Conditions				
33	1	TAO	Ambient Temperature	deg F

2.2 DATA ANALYSIS PLAN

For the data analysis, the following quantities were evaluated with the measured data as explained below.

- **Net heat transfer to the municipal recycled water system**

$$Q_{RWL} = K \times FRW \times (TRWS-TRWR)/1{,}000 \tag{1}$$

Where:

Q_{RWL}	=	Heat transfer rate through recycled water loop (kBtu/h) (negative values for heat rejection, positive values for heat extraction)
K	=	A factor that incorporates conversion factors and the specific gravity of the fluid, which is 500 Btu/h•GPM•°F for pure water
FRW	=	Recycled water flow rate (GPM)
TRWS	=	Recycled water supply temperature (°F)
TRWR	=	Recycled water return temperature (°F)

- **Heating output from the modular WWHP to the hot water loop**

$$Q_{HL} = K \times FHL \times (THL2a-THL1)/1{,}000 \tag{2}$$

Where:

Q_{HL}	=	Heating output of the modular WWHP (kBtu/h)
FHL	=	Hot water flow rate (GPM)
THL1	=	Entering hot water temperature to the load-side of the modular WWHP (°F)
THL2a	=	Leaving hot water temperature from the load-side of the modular WWHP (°F)

- **Cooling output from the modular WWHP to the chilled water loop**

$$Q_{CL} = K \times FCL \times (TCL1-TCL2)/1{,}000 \tag{3}$$

Where:

Q_{CL}	=	Cooling output from the modular WWHP (kBtu/h)
FCL	=	Chilled water flow rate (GPM)
TCL1	=	Entering chilled water temperature to the load-side of the modular WWHP (°F)
TCL2	=	Leaving chilled water temperature from the load-side of the modular WWHP (°F)

- **Heat rejected/extracted by the modular WWHP to/from the source water loop**

$$Q_{SLH} = K \times FSL \times (TSL5-TSL4)/1{,}000 \tag{4}$$

$$Q_{SLC} = K \times FSL \times (TSL4-TSL5)/1{,}000 \tag{5}$$

Where:

Q_{SLH}	=	Heat rejected to the source water loop by the modular WWHP (kBtu/h)
Q_{SLC}	=	Heat rejected to the source water loop by the modular WWHP (kBtu/h)
FSL	=	Source water flow rate (GPM)
TSL4	=	Source water temperature entering the modular WWHP (°F)
TSL5	=	Source water temperature leaving the modular WWHP (°F)

- **Additional heat added by the steam HX to the source water loop**

$$Q_{SP1} = K \times FSL \times (TSL4\text{-}TSL3)\ /1{,}000 \quad (6)$$

Where:

Q_{SP1} = Heat added to the source water loop by the steam HX (kBtu/h)
FSL = Source water flow rate (GPM)
TSL3 = Entering water temperature to the steam HX in the source loop (°F)
TSL4 = Leaving water temperature from the steam HX in the source loop (°F)

- **Additional heat added by stream HXs to the hot water loop**

$$Q_{SP2} = K \times FHL \times (THL3b\text{-}THL2a)\ /1{,}000 \quad (7)$$

Where:

Q_{SP2} = Heat added by the two steam HXs in the hot water loop (kBtu/h)
FHL = Hot water flow rate (GPM)
THL2a = Entering water temperature to the two steam HXs in the heating loop (°F)
THL3b = Leaving water temperature from the two steam HXs in the heating loop (°F)

- **Heat exchanged with the DHW WWHP and the precooling loop:**

$$Q_{precool} = K \times FPCL \times (TPCL1\text{-}TPCL2)\ /1{,}000 \quad (8)$$

Where:

$Q_{precool}$ = Heat exchanged with the DHW WWHP and the precooling loop (kBtu/h)
FPCL = Precooling loop water flow rate (GPM)
TPCL1 = Supply water temperature of precooling loop (°F)
TPCL2 = Return water temperature of precooling loop (°F)

- **Heat extracted from the source water loop by the cooling tower:**

$$Q_{CT} = K \times FSL \times (TSL1\text{-}TSL2)\ /1{,}000 \quad (9)$$

Where:

Q_{CT} = Heat extracted from the source water loop by the cooling tower (kBtu/h)
FSL = Source water flow rate (GPM)
TSL1 = Source water temperature entering the cooling tower (°F)
TSL2 = Source water temperature leaving the cooling tower (°F)

Because the modular WWHP and the entire RWHP system provide simultaneous heating and cooling, the effective Coefficient of Performance (COP), which is a performance metric for evaluating the energy efficiency of combined heating and cooling operation, was calculated with Eq. (10) and (11) for the WWHP and the entire RWHP system, respectively, based on the cumulative heating and cooling outputs and the associated power consumptions during the 8 months period encompassed in this study. To account for the supplemental heat added to the source water loop by the steam HX, the same amount of heat was subtracted from the effective heating provided by the RWHP system, as expressed in Eq. (11).

$$WWHP_{COP} = (Q_{CL} + Q_{HL})/(WHP_{1\text{-}7} \times 3.413) \quad (10)$$

Where:

$WWHP_{COP}$ = Effective COP of the modular WWHP
QHL = Heating output from the modular WWHP (kBtu)

QCL	=	Cooling output from the modular WWHP (kBtu)
$WHP_{1\text{-}7}$	=	Power consumption of the modular WWHP (kWh)

The effective COP for the entire RWHP system is calculated as shown below.

$$RWHP_{COP} = (Q_{CL} + Q_{HL} - Q_{SP1})/[(WHP_{1\text{-}7} + WRWP + WCT + WSLP) \times 3.413] \tag{11}$$

Where:

$GSHP_{COP}$	=	Effective COP of the RWHP system
WHP1-7	=	Power consumption of the modular WWHP (kWh)
WRWP	=	Power consumption of recycled water loop pumps (kWh)
WCT	=	Power consumption of cooling tower (kWh)
WSLP	=	Power consumption of source loop pumps (kWh)

3. DATA ANALYSIS RESULTS

3.1 RECYCLED WATER TEMPERATURE

Hourly recycled water (RW) temperatures during the period from January through August 2015 were plotted in Fig. 7 along with the hourly outdoor air (OA) temperatures. As shown in Fig. 7, the RW temperature was relatively stable throughout the monitored period, whereas the OA temperature fluctuated to a much larger degree during the same period.

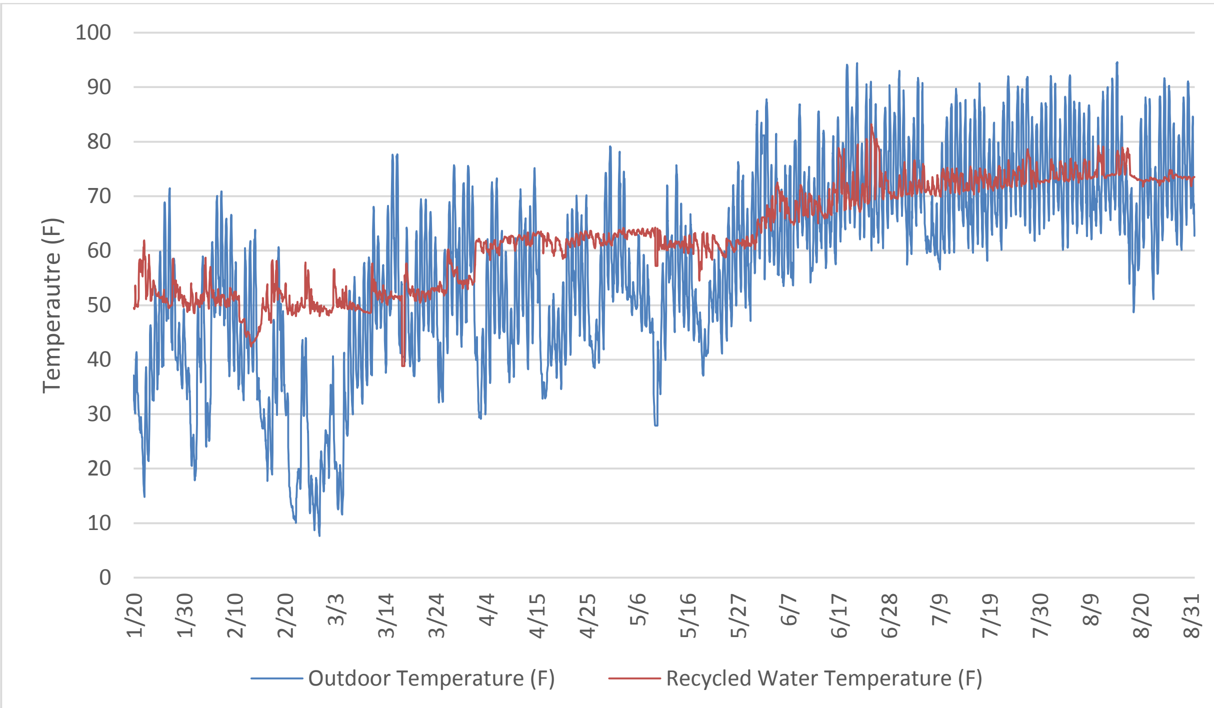
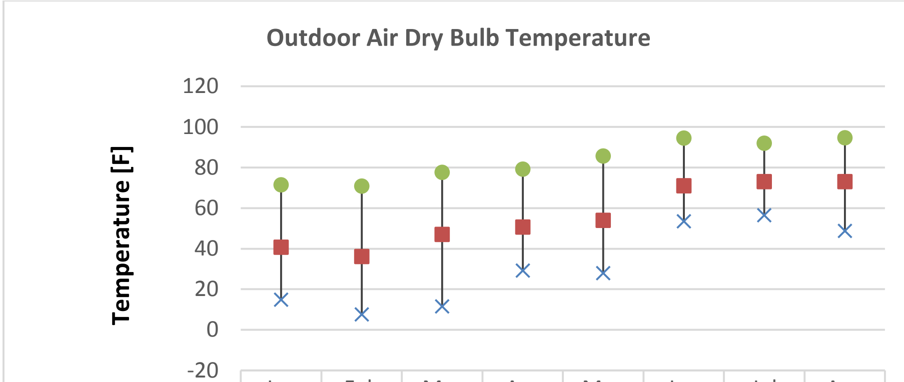


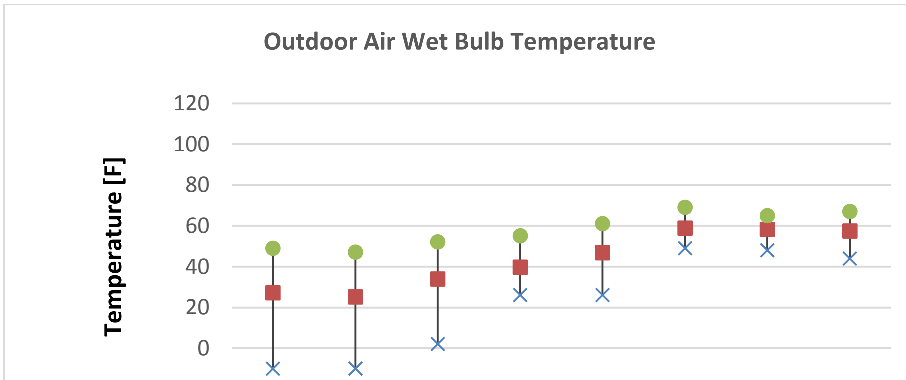
Fig. 2. Hourly OA temperature vs. RW temperature.

Figure 8 shows the monthly minimum, average, and maximum dry bulb and wet bulb temperatures of OA and RW temperatures. Note that although the monthly average RW and OA dry bulb temperatures during the cooling season (June through August) were close to each other, the OA temperature fluctuated in a much larger range during each month. The maximum OA dry bulb temperature was 94.5°F during the 8 month period, whereas the maximum RW temperature was 83.2°F during the same period. On the other hand, the monthly average OA wet bulb temperature at Denver is always below 60°F during the same period, which indicates that a wet cooling tower would be very effective to cool the source water in this climate. The minimum RW temperature (38.8°F) was much higher than the minimum OA dry bulb temperature (7.6°F), which indicates that RW is a better heat source than OA.

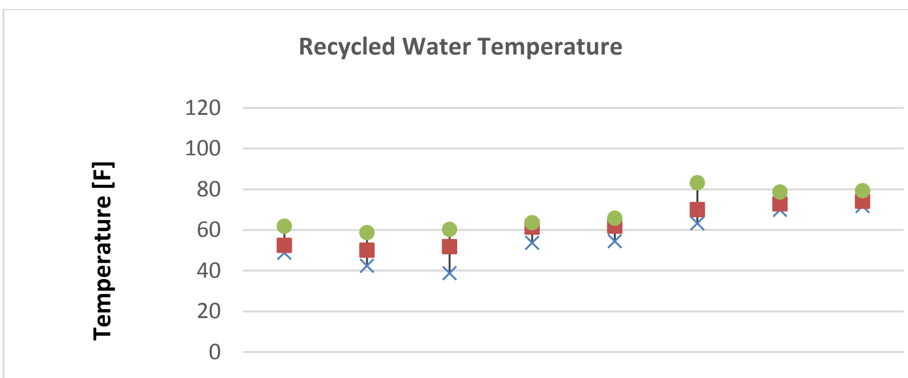
Further close-up look at the OA and RW temperatures from July 15 through 17 reveals that whereas the RW supply temperature (indicated as "TRWS") was lower than the OA dry bulb temperature (indicated as "OAT") during daytime, it was higher than the OAT during nighttime (see the upper chart in Fig. 9). Since lower heat sink temperature will lead to higher the cooling efficiency of a heat pump, using RW as heat sink during daytime can result in less cooling energy consumption than using OA (i.e., through a dry cooler). On the other hand, as shown in the lower chart of Fig. 9, TRWS was higher than OAT all the time during typical days in winter (from Jan 20 through 22).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Min	14.82	7.61	11.56	29.14	27.90	53.50	56.58	48.70
Average of TOA	40.74	36.09	47.02	50.72	54.01	71.01	73.00	73.14
Max	71.47	70.89	77.68	79.17	85.65	94.45	92.00	94.60

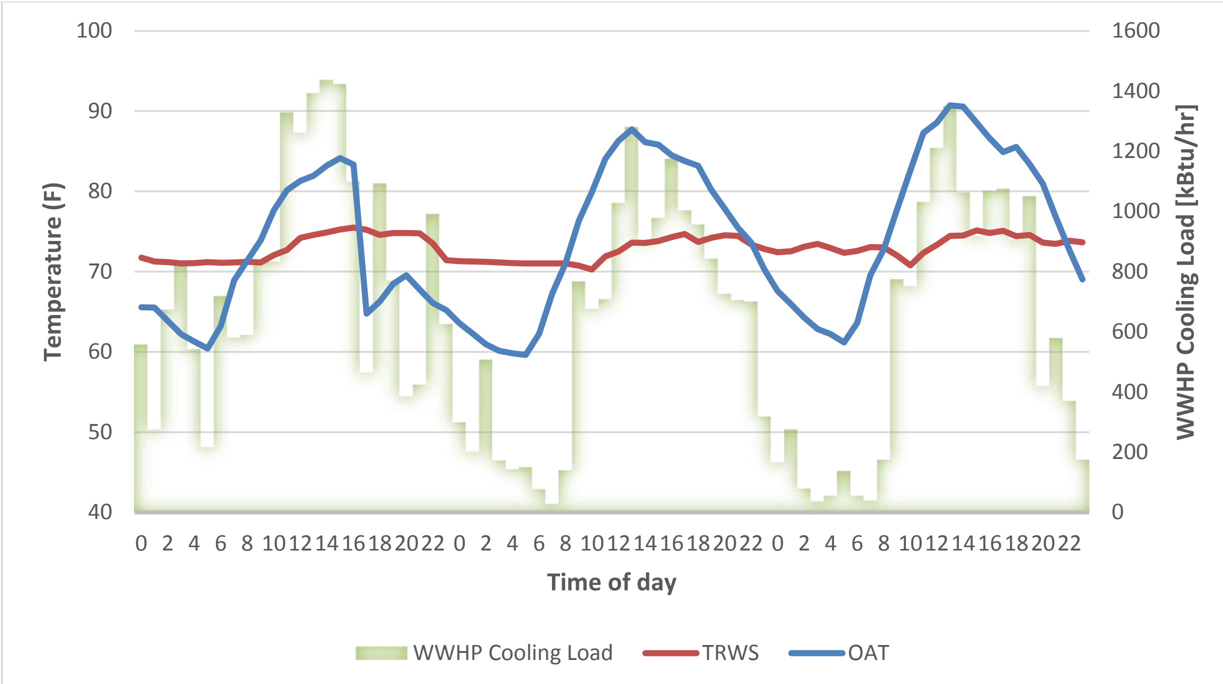


	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Min	-10.00	-10.00	2.00	26.00	26.00	49.00	48.00	44.00
Average of WB	27.12	25.11	33.94	39.75	46.74	58.76	58.20	57.35
Max	49.00	47.00	52.00	55.00	61.00	69.00	65.00	67.00



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Min	48.77	42.41	38.81	53.73	54.50	63.25	69.90	71.78
Average of TRWS	52.48	50.06	51.79	61.46	61.80	70.02	72.84	74.09
Max	61.92	58.71	60.22	63.63	65.78	83.20	78.65	79.30

Fig. 3. Monthly outdoor air dry bulb and wet bulb temperatures and recycled water temperature.



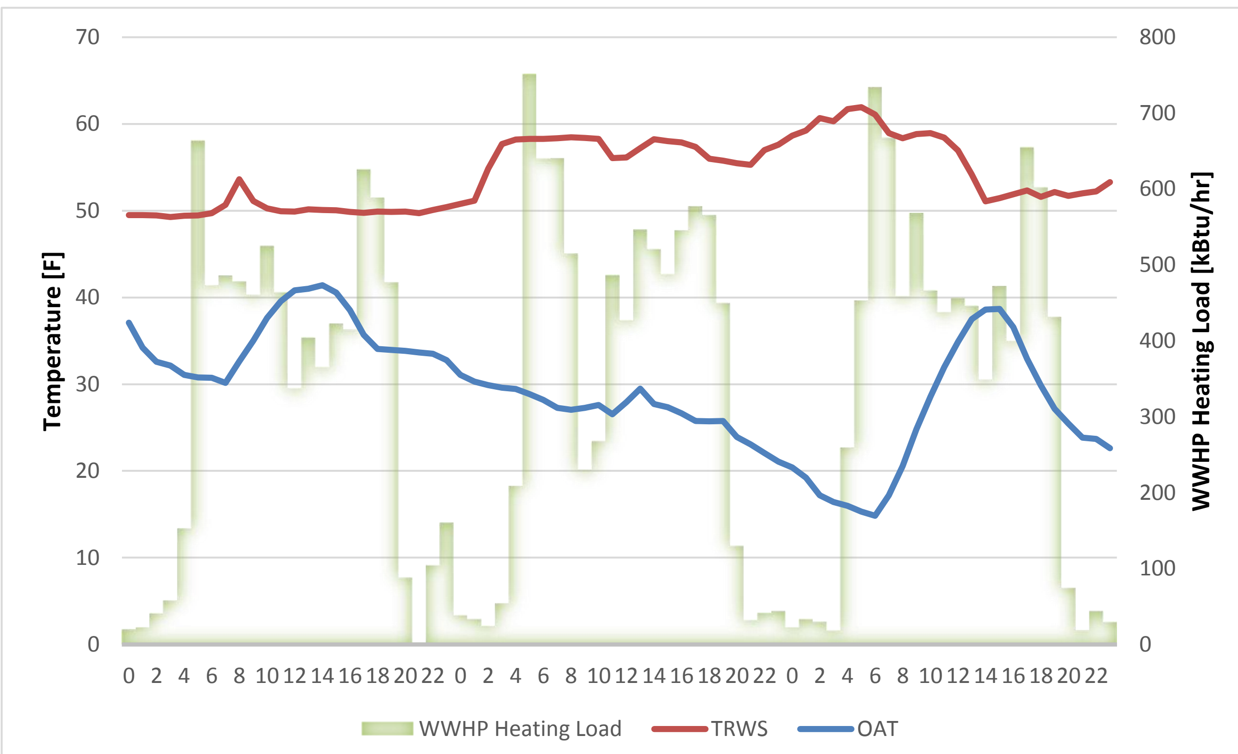


Fig. 4. Outdoor air (OA) dry bulb temperature, recycled water (RW) temperature, and water-to-water heat pump (WWHP) loads during typical days in the cooling season (top) and heating season (bottom).

3.2 SOURCE WATER LOOP ANALYSIS

As shown in Fig. 2, the source water is tempered with several different heat sinks and sources, including the recycled water, the cooling tower, the precooling loop, and the steam HX. The source water temperature was kept low, with a setpoint of 55°F, in order to provide useful precooling. The design intent was that the recycled water would serve as the main heat source and sink, and the cooling tower and the steam HX would be used only as a backup when the recycled water was not available or not sufficient to maintain the source water temperature at the setpoint. An analysis of the measured source water temperature and the heat balance in the source water loop is presented in following sections.

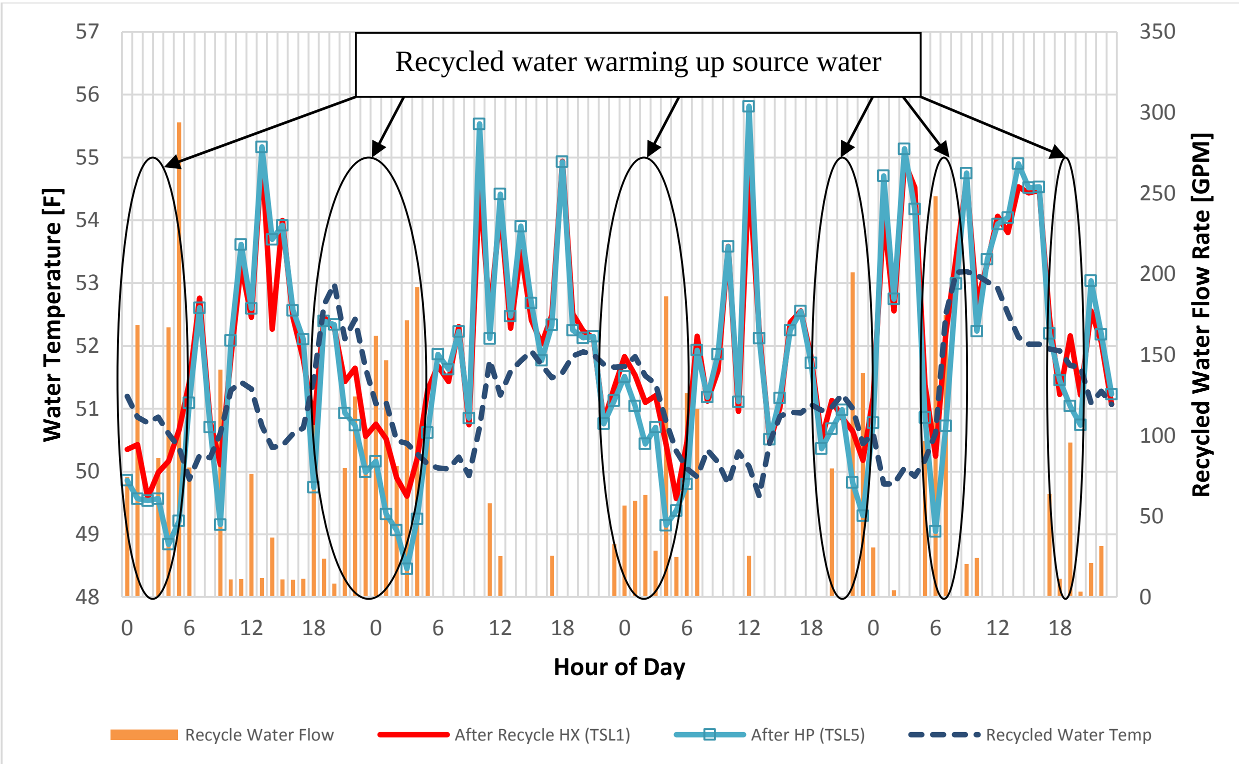
3.2.1 Source Water Temperature

Figures 10 and 11 show the temperature and flow rate of the recycled water, as well as water temperatures at several different locations in the source water loop during a few typical days in heating and cooling seasons, respectively. As described in Section 1.2.1, during heating season, the RW pump is turned on only when TSL1 (the source water temperature leaving the RW HX) is below 55°F and TSL5 (the source water temperature leaving the WWHP) is at least 2°F lower than TRWS (the recycled water supply temperature). Given this control strategy, as shown in Fig. 10 (a), the recycled water provided heat to the source water mostly during nighttime when the space heating load was high. Leaving from the RW HX, the source water temperature was raised by 2–4°F after exchanging heat with the precooling loop as shown in Fig. 10 (b). There were only a few occasions when the steam HX was activated to raise the source water temperature beyond 52°F, as indicated by the periods when the leaving water temperature from the steam HX (TSL4) was higher than the entering water temperature (TSL3). This supplemental heating usually occurred for a couple of hours around 6 am each day. This figure also shows that TSL4 was lower than TSL3 when the steam HX was not activated, which indicates that the source water lost some heat at the steam HX.

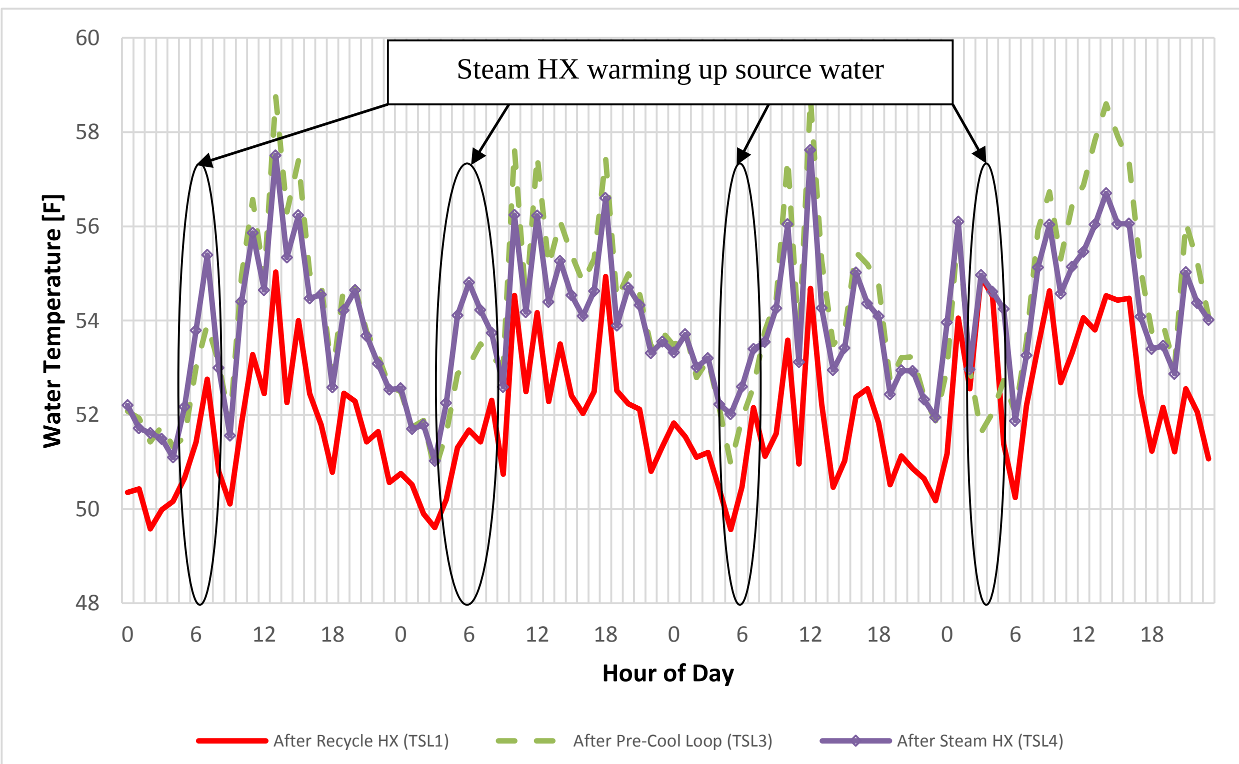
As shown in Fig. 11, in the cooling season, the source water was cooled down to near the recycled water temperature only during daytime (see TSL1 in the figure). Leaving from the RW HX, the source water was cooled down below 68°F by the cooling tower during day and night (see TSL2 in the figure). The source water was then warmed up by 2–3°F by the precooling loop before entering the WWHP (see TSL3 in the figure). The wet cooling tower in this location was very effective and it kept TSL4 (the entering source water temperature at the WWHP) below 68°F during all the summer months. As a result, the maximum TSL5 (leaving source water temperature from the WWHP) was less than 80°F and very close to TRWS (i.e., around 75°F). The small difference between TSL5 and TRWS limited the heat rejection to the recycled water.

Figure 12 shows the RW pump power draw verses TSL1. It shows that the RW pump ran mostly when TSL1 was either around 50°F (heating season) or between 70-80°F (cooling season). Also can be seen, the power draw of the RW pump varied to a large degree even for the same TSL1. This was caused by the varying RW flow rate (as shown in Figs. 10 and 11), which was modulated through the variable speed RW pump based on the temperature difference between TRWS and TSL1. Consistent with the higher RW flow rate in cooling season, the power draw of the RW pump was also higher in cooling season compared with that in the heating season.

Fig. 13 shows the air conditioning process of the VAV system on the psychometric chart. As illustrated in Fig. 13, there is a run-around cycle in the process—the heat removed from the precooling process was rejected to the source water loop and used by the modular WWHP to produce hot water, which then heats up the precooled air through the reheat coils at the VAV boxes to provide space heating to the building. As discussed later, this heat recovery significantly reduces the energy consumption of the RWHP system.



(a)



(b)

Fig. 5. Source water temperature from February 6 to 9, 2015 (heating season).

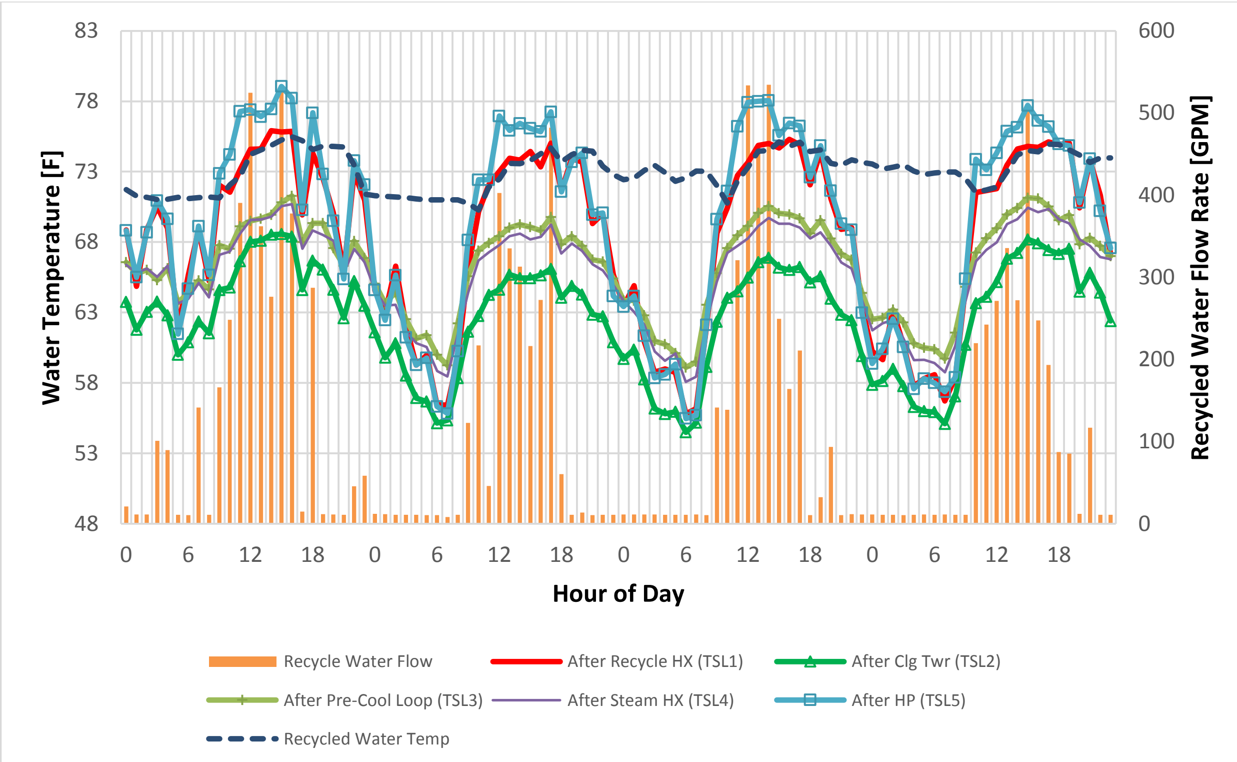


Fig. 6. Source loop temperature from July 15 to 18, 2015 (cooling season).

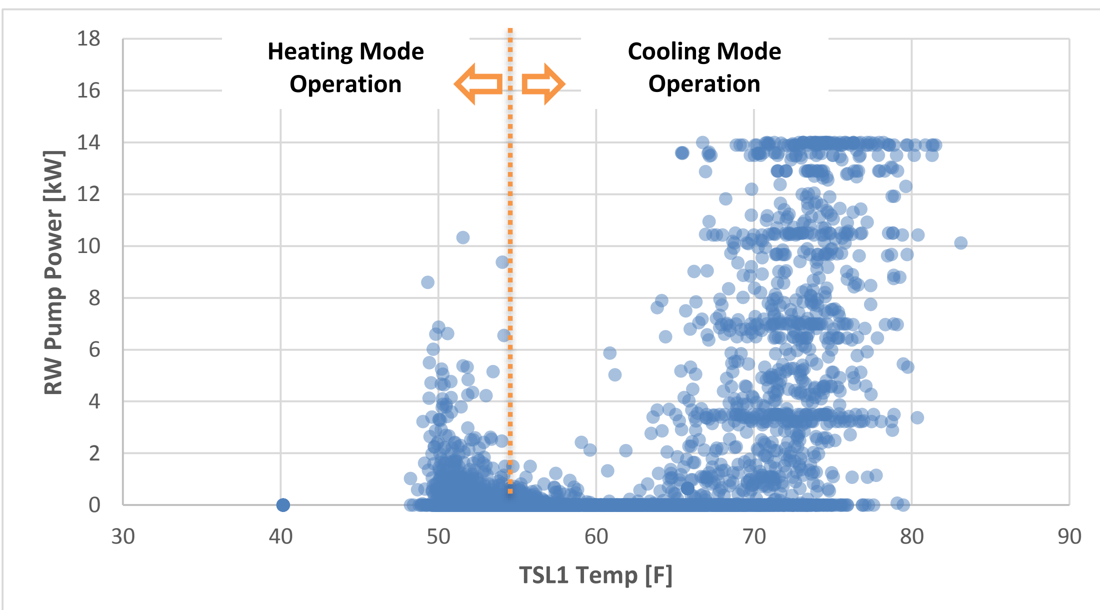


Fig. 7. Hourly recycled water (RW) pump power vs. TSL1 (leaving water temperature from the RW heat exchanger).

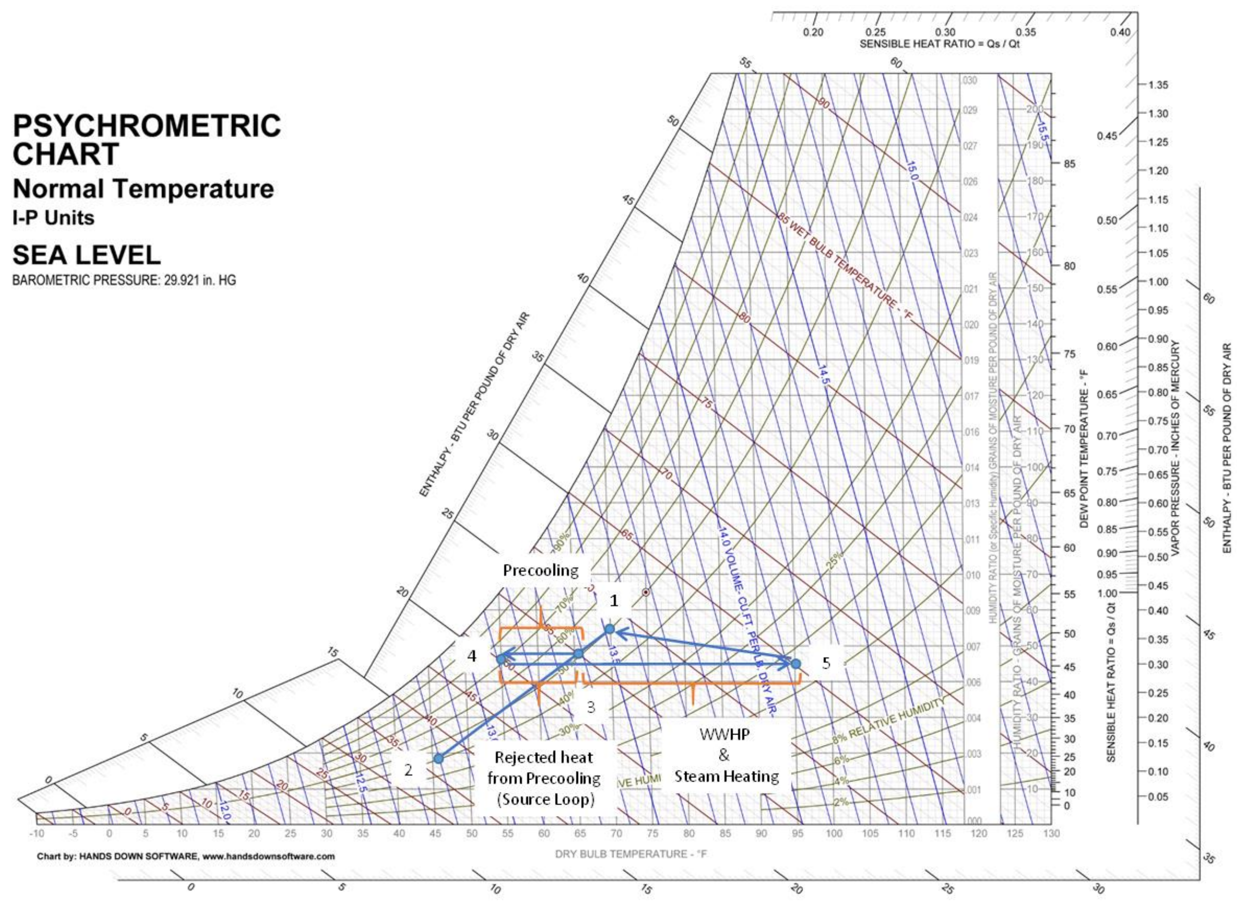


Fig. 8. Air conditioning process of the HVAC system. (Notes—1: return air; 2: outdoor air; 3: mixed air; 3–4: precooling process; 4–5: reheating process; 5–1: space heating process)

3.2.2 Heat Flow Analysis

Heat flow from the various heat sinks and sources in the source water loop were analyzed to quantify their contributions. Fig. 14 shows the monthly heat flows and they are grouped into two categories: heat extracted from the various heat sources (with positive values) and heat rejected to various heat sinks (with negative values). As can be seen in Fig. 14, the heat flows demonstrated two different patterns. During heating season (i.e., December 2014 through May 2015), most heat (~70%) was extracted from the precooling loop and the rest was extracted from the recycled water and the steam HX. While most of these heat additions was rejected to the WWHP and used to generate hot water, a fair amount of heat was rejected to the cooling tower and the recycled water. As discussed before, such heat rejection was to make the source water cool enough to be able to precool the air in the VAV system. In contrast, during cooling seasons (June through August, 2015), roughly equal amount of heat was extracted from the WWHP (i.e., the condensing heat from the cooling operation of the WWHP) and the preccooling loop. Only a small amount of heat was extracted from the recycled water. Most of the heat (~60-70%) added to the source water was rejected to the ambient air by the wet cooling tower and about 20-30% of the heat was rejected to the recycled water. The rest was rejected to the WWHP when it ran in heating mode.

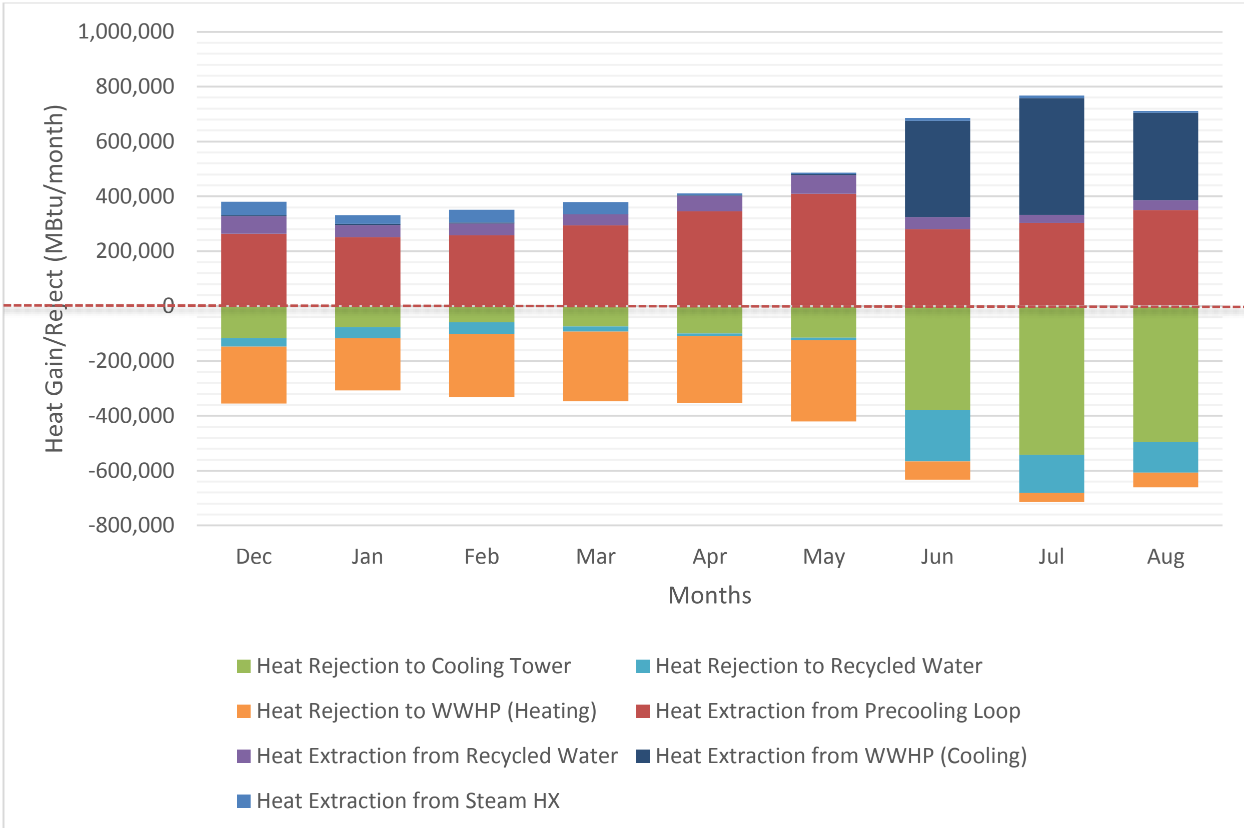


Fig. 9. Monthly heat lows in the source water loop.

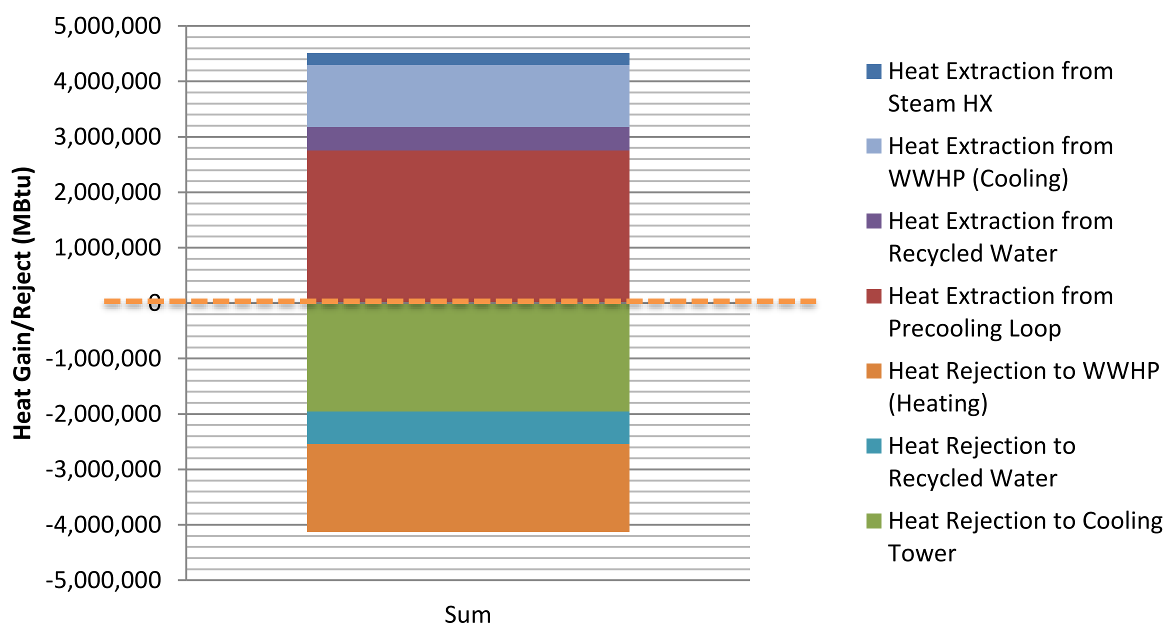


Fig. 10. Cumulative heat lows in the source water loop.

Fig. 15 shows the cumulative heat flows during the 8-month period. It indicates that the largest heat source is the precooling loop, which contributed 61% to the overall heat addition to the source water. The second heat source is the WWHP running in cooling mode (25%). Recycled water is the third heat source (9%) and the steam HX's contribution is 5%. On the other hand, the wet cooling tower is the largest heat sink and it contributed about 47% to the total heat rejection from the source water. WWHP running in heating mode and the recycled water contributed 38% and 15%, respectively, to the total heat rejection.

The above data indicate that the run-around heat recovery through the precooling loop is very effective and it significantly reduced the demand of external heat sources (e.g., the recycled water and the steam HX). The wet cooling tower rejected more heat than the recycled water due to the relatively dry air in the Denver area. Recycled water can serve as both the heat source and sink. However, its contribution was limited in this project. If the source water temperature is allowed to vary in a larger range (i.e., lower in heating season and higher in cooling season), recycled water may contributed more, which may reduce the need for supplemental heating and the water consumption associated with the operation of the cooling tower. The demand for the supplemental steam HX is minimal and it could have been eliminated if the lower limit of the source water temperature set point were lowered.

3.3 ANALYSIS FOR THE CHILLED WATER AND HOT WATER LOOPS

In this section, heat transfer rates of the precooling loop, chilled water loop, and hot water loop are analyzed. In addition, two different controls for the hot water supply temperature are also analyzed to evaluate their impacts on the system energy use.

3.3.1 Cooling and Heating Outputs

Figures 16 and 17 show the average hourly cooling and heating outputs of the RWHP system within each 5°F bin of the OA temperature. As shown in Fig. 16, the cooling output was provided by both the precooling loop and the modules of the WWHP running in cooling mode. The cooling output of the precooling loop was relatively stable and did not vary much with the change of the OA temperature, whereas the WWHP worked in cooling mode only when the OA temperature was above 50°F, and its cooling output did increase as the OA became warmer. Fig. 17 shows that the modular WWHP provided heating all year round, even during the cooling season, which was to satisfy the reheat needs at the VAV terminal boxes. The steam HXs #308 or #309 (see Fig. 2) in the hot water loop provided a small amount of supplemental heating when the OA temperature was below 40°F. Fig. 18 presents the total hourly cooling output (the aggregated outputs from the precooling loop and the WWHP) and the total hourly heating output (the aggregated outputs from the steam HXs and the WWHP) versus the OA temperature. As shown in Fig. 18, although the total heating and cooling outputs varied with the OA temperature in opposite relationship, there was simultaneous heating and cooling outputs over the entire OA temperature range experienced during the 8-month period.

These hourly total heating and cooling outputs are later used as the loads to be satisfied with the baseline HVAC system and the associated energy consumptions are computed to be compared with the measured energy consumptions of the RWHP system.

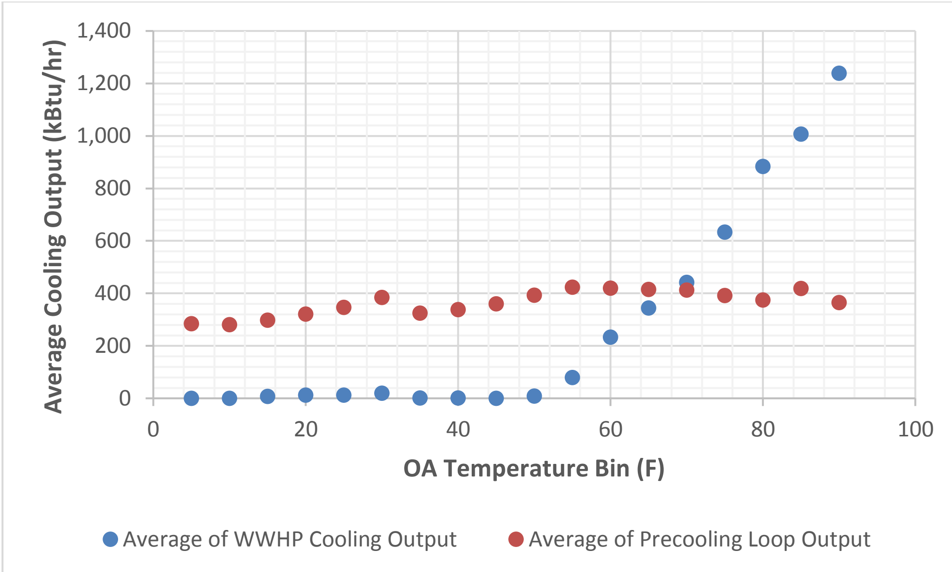


Fig. 11. Hourly cooling outputs by sources (averaged in 5°F bins).

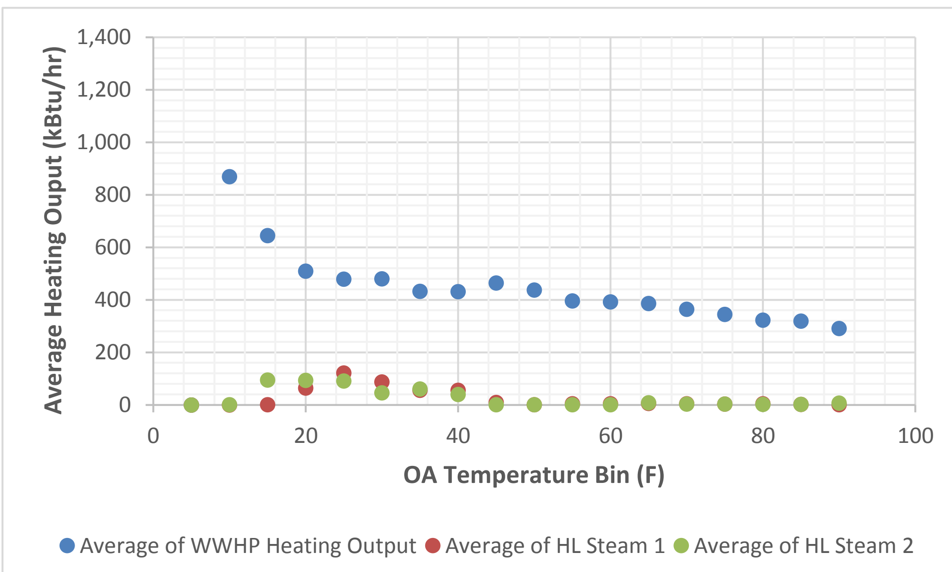


Fig. 12. Hourly heating outputs by sources (averaged in 5°F bins).

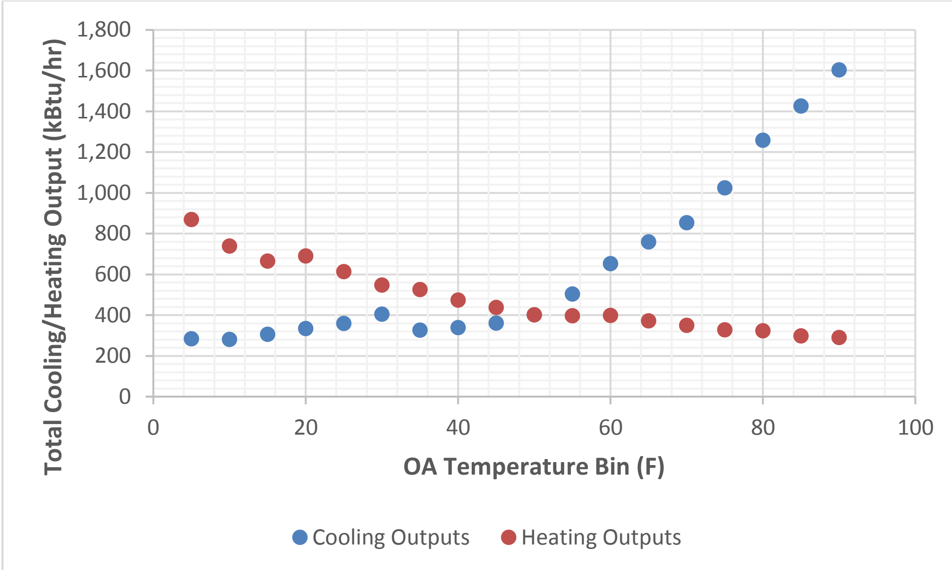


Fig. 13. Hourly aggregated cooling and heating outputs (averaged in 5°F bins).

3.3.2 Temperature Control in the Hot Water Loop

The control strategy for the steam HX in the hot water loop and the load-side leaving water temperature (LWT) of the WWHP was changed on January 15, 2015. Figure 19 shows the load-side LWT of the WWHP and the hot water loop supply temperature in typical days before and after changing the control strategy. As shown in Fig. 19, before the control was changed, the WWHP constantly provided hot water at about 115°F, and the steam HXs at the downstream of the WWHP further raised the HW supply temperature to about 120°F. Since January 2015, the setpoint of the load-side LWT was lifted up to 125°F and the HW supply temperature was reset based on the AHU heating valve position[2]. The HW supply temperature could be reset to as higher as ~135–140°F. Such a high supply temperature resulted in a return temperature that is higher than the allowed entering water temperature to the WWHP, which triggered the high pressure protection and shut off the WWHP.

Fig. 20 shows nearly constant heat output from the steam HXs when the OA temperature was below 50°F before the control was changed. In contrast, after the control change, the heat output from the steam HXs increased when OA became cooler (i.e., heating demand became higher).

The impacts of the two different control strategies were analyzed in terms of source energy consumptions and operating costs. Based on the measured data before the control change, the daily heating outputs of the WWHP and the steam HXs were plotted in Fig. 21. A set of correlations between the heating outputs and the OA temperature were derived with a curve-fit regression. These correlations were then used to estimate the heating outputs of the WWHP and the steam HXs from January 20 through February 28 should the original control were still in place. Fig. 22 compares the outputs of the WWHP and the steam HXs resulting from the two different controls. As shown in Fig. 22, the total heating outputs resulting from the two controls are close to each other, but the contributions between the WWHP and steam HXs are different. With the new control strategy, the contribution of WWHP increases from 66% to 76% of the total heating output, and the contribution of the steam HXs decreases accordingly.

The estimated outputs from WWHP and steam HXs are used to calculate the associated source energy consumptions and energy costs. Table 2 presents the total electricity and natural gas use resulting from

[2] The HW supply temperature set point was increased to maintain temperature of some vestibule zones.

the two different controls during January 20 through February 28. It shows that the new control saves about 5% in energy cost and 10% in source energy consumption. The relatively lower cost savings are due to inexpensive natural gas ($4.84/MMBtu based on 2014–15 utility bills provided by the grantee).

If the HW supply temperature setpoint used in the new control were lower, the contribution of the WWHP would have been larger and so does the energy cost saving. Further investigation of potential adjustment to the HW temperature reset control is recommended. One possibility could be that resetting HW temperature up to 125°F could continue to be based on AHU valve position, with resetting over 125°F based on OA temperature (i.e., further increasing HW supply temperature only when OA temperature is low enough to cause vestibules to be below acceptable temperature). Besides, installation of auxiliary heaters, or replacement of the existing fan coil units with units that can work with lower water temperatures, could also be considered.

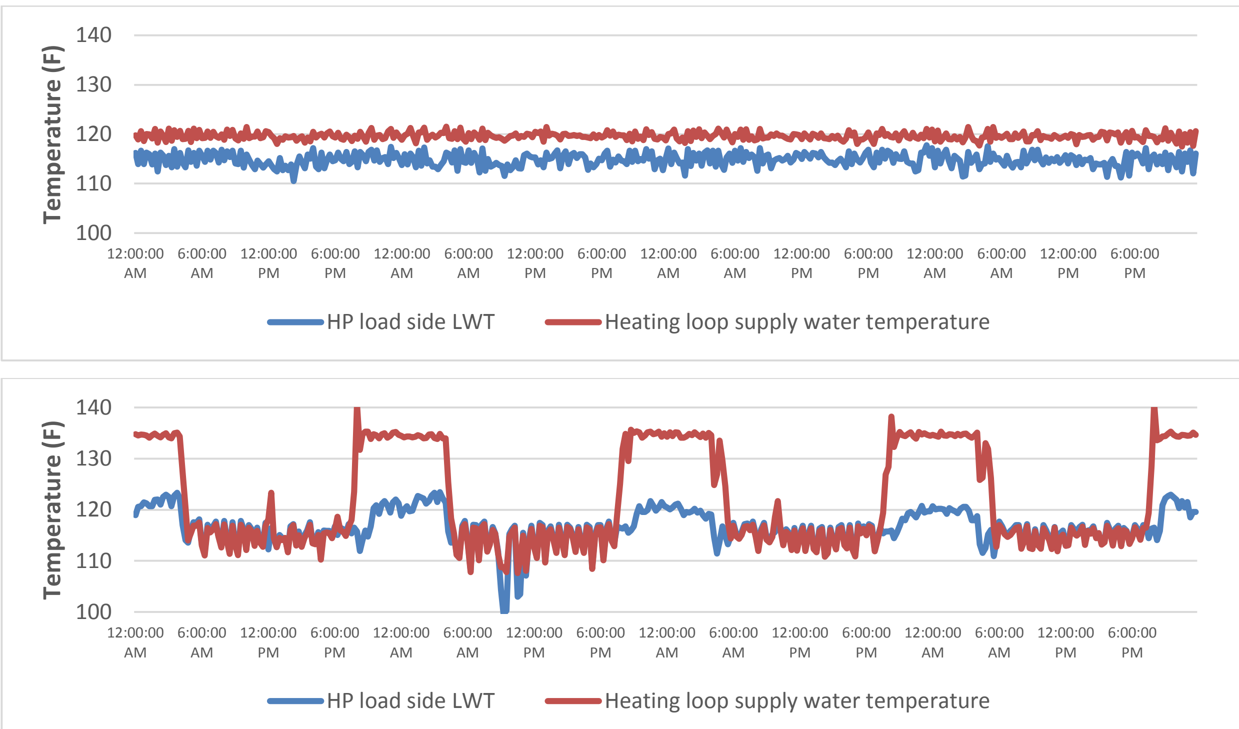


Fig. 14. Hot water loop supply temperature before (top) and after (bottom) the control change.

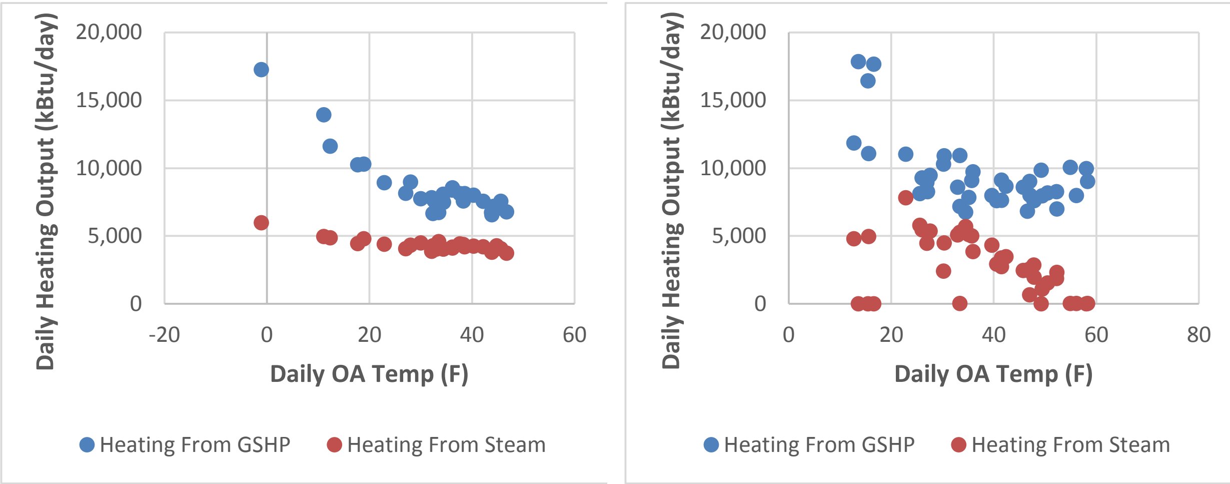


Fig. 15. Daily heating outputs before (left) and after (right) the control change.

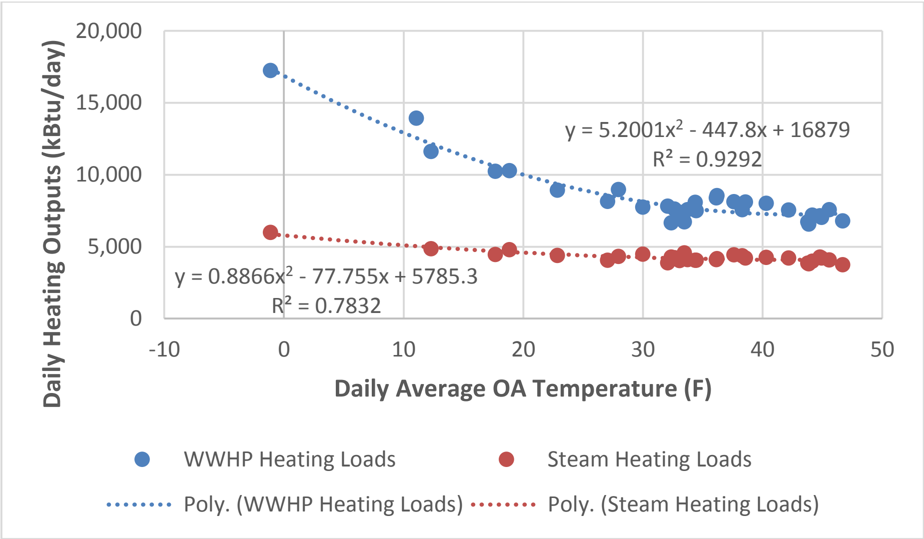


Fig. 16. Daily heating outputs before the control change and regression curve-fit correlations for the daily data.

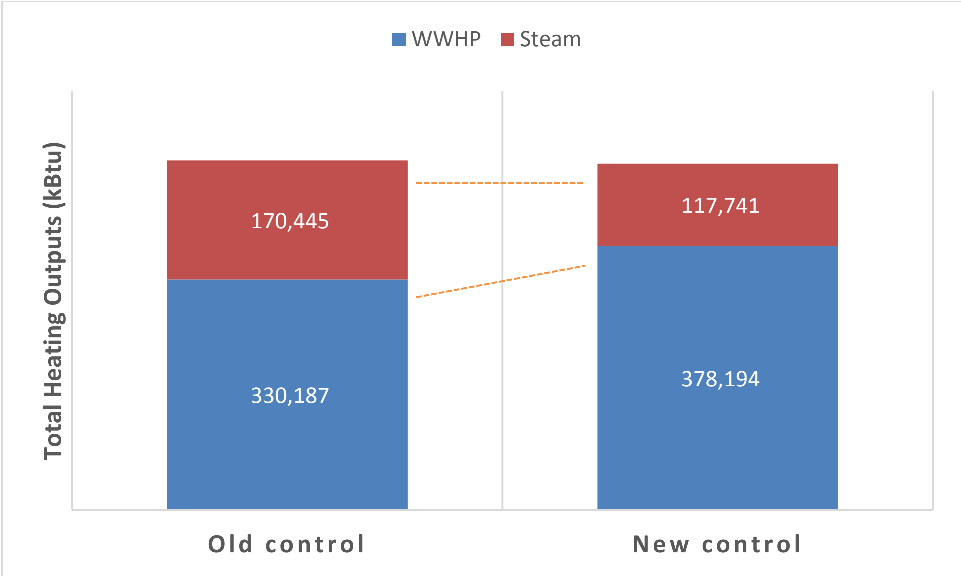


Fig. 17. Energy use during January 20 through February 28 resulting from the two different controls.

Table 2. Source energy and energy cost savings resulting from the new control

	Electricity (kWh)	Natural gas (MMBtu)	Source energy (MMBtu)	Electricity cost ($)	Natural gas cost ($)	Total cost ($)
New	21,734	157	397	1,652	758	2,410
Old	18,975	227	441	1,442	1,097	2,539
Savings			44			130
Savings (%)			10%			5%

3.4 ENERGY USE OF THE RWHP SYSTEM

The energy use of the demonstrated RWHP system includes power consumptions of the modular WWHP units, the cooling tower, and the various circulation pumps, as well as the heat output of the steam HXs. Figure 23 shows the power draw of the modular WWHP (left side) and the output of the steam HXs (right side). The peak power draws of the WWHP units in heating and cooling seasons were about 70 kW and 120 kW, respectively. The heating output from the two steam HXs in the heating loop had a peak of 800 kBtu/h during heating season, and the source loop steam HX had a peak output of 700 KBtu/h during the heating season. The steam HX at the source water loop provided most output from late February to early March when the building heating load was high (as indicated by the elevated power draw of the WWHP) and the RW temperature was low (as shown in Fig. 8). The cumulative heating outputs from the steam HXs at the source water loop and hot water loop were about 143,900 MMBtu and 143,700 MMBtu, respectively, during the 8 months.

Figure 24 presents power draws of various pumps and the cooling tower. The following characteristics can be observed in this figure:

- The recycled water pump operated intermittently—at relatively lower speeds during the heating season than in the summer months (from June through August). The peak power draw was 14 kW. Its operation was almost negligible in April and May. It is likely that during this time period a heat balance was reached between the heat rejection (from the precooling loop and the condenser of the WWHP module running in cooling mode) and the heat extraction (by the evaporator of the WWHP module running in heating mode and the cooling tower) so neither the RW nor the steam HX provided significant heat to the source water loop.

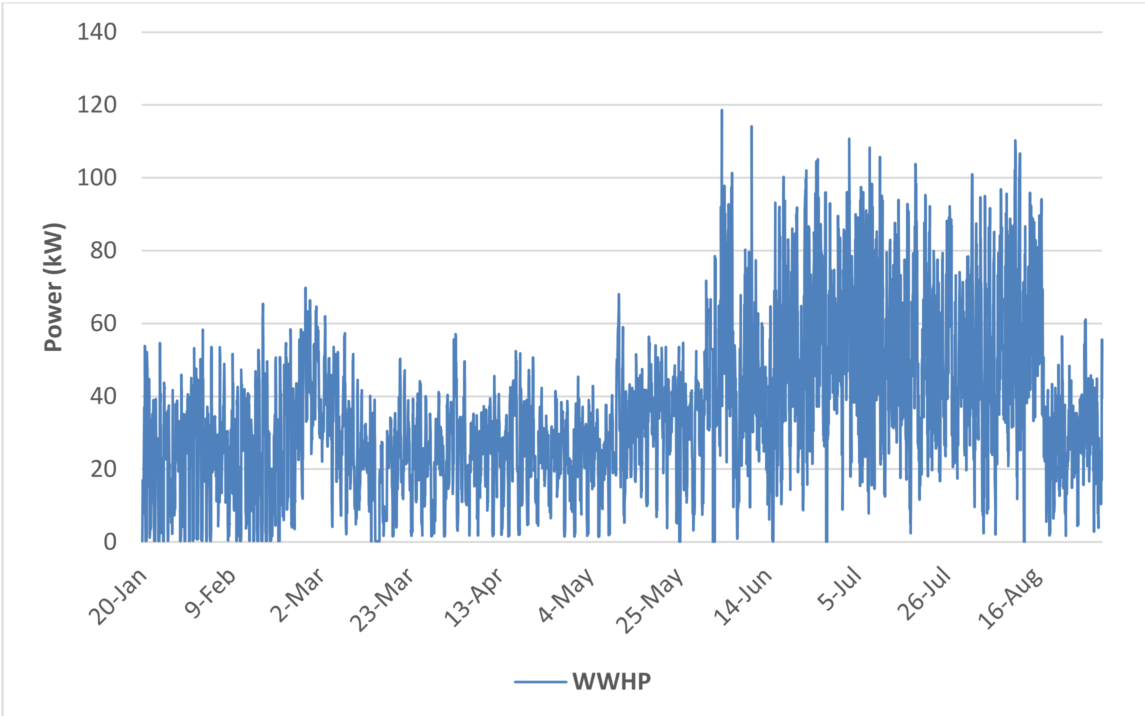
- The source water loop pump ran continuously year-round. Its power draw varied from 1 to 5 kW.

- The hot water loop pump ran continuously year-round (with less than 2 kW power draw) even during summer months. It indicates that there were simultaneous heating and cooling during summer months, which is due to the needs of reheating at the VAV boxes.

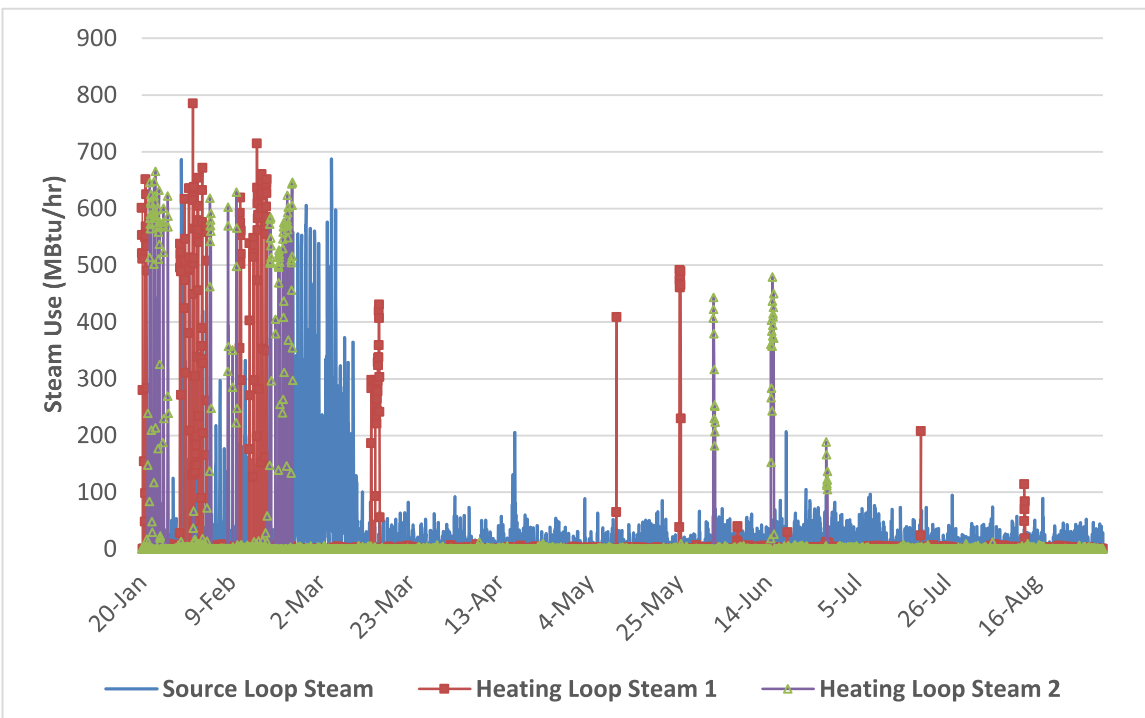
- The chilled water loop pump had a peak power draw of about 10 kW during the summer months. It was off or ran at low speeds during heating season when cooling demand was low.

- The precooling loop pump ran continuously throughout the year but at higher speeds during summer months and with a peak power draw of about 4 kW. It indicates that the precooling loop rejects heat to the source water loop all year long and with higher rate at summer months.

- The cooling tower ran occasionally with low power draw (less than 1 kW) during heating season, and it ran more often since March and had a peak power draw at about 12 kW during summer months.



(a)



(b)

Fig. 18. RWHP system end energy use: (a) power draw of the modular WWHP and (b) heat output of the steam HXs.

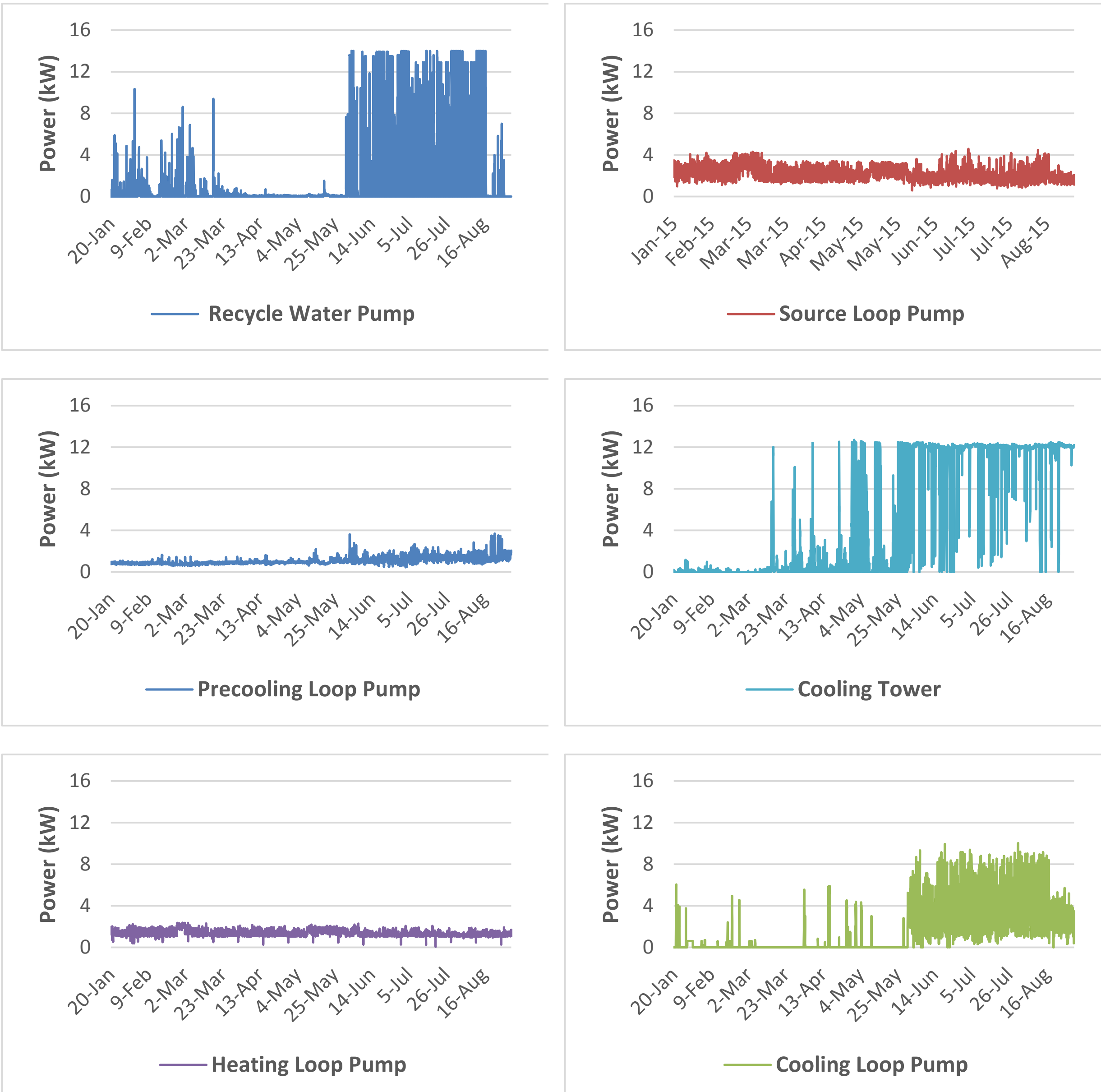


Fig. 19. Hourly power draws of circulation pumps and the cooling tower.

3.5 ENERGY AND COST SAVINGS POTENTIAL

To estimate the energy saving potential of the RWHP system, the energy consumption of a conventional VAV system using a water-cooled chiller and a natural gas boiler was calculated as a baseline for providing the same heating and cooling outputs as the RWHP system. The energy efficiency of the chiller and the boiler used in the baseline were the minimum values allowed by ASHRAE 90.1-2010. Major assumptions for calculating the baseline energy consumption and energy savings are listed below:

- It is assumed that there is no difference in power consumptions of the source loop pump, cooling loop pump, and heating loop pump for satisfying the same heating and cooling loads with both the baseline and RWHP systems.

- The water-cooled chiller has a nominal COP of 5.54. A generic performance curve for water-cooled chillers was adopted from the US Department of Energy's DOE-2 program (DOE 1980) and used to calculate the chiller power consumption for providing the same hourly cooling output as the RWHP systems (including outputs from both the precooling and cooling loops).

- The natural gas fired boiler has a thermal efficiency of 80%, and it provides the same hourly heating outputs as that of both the WWHP and steam HXs in the heating loop.

- The cooling tower power consumption of the baseline system is calculated based on the average heat rejection efficiency of a typical cooling tower, which depends on the average wet-bulb temperature in each month.

- Average utility rates from the 2014 and 2015 utility bills were used for energy cost calculations. The average electricity rate is \$0.076/kWh, and the natural gas rate is \$4.84/MMBtu.

Although recycled water was used in the RWHP system only as heat sink and source to exchange heat with the heat pump (without changing the amount of recycled water in the municipal water system), it was not free. The cost is \$0.078 per 1,000 gallons of recycled water passing though the heat exchanger, which is about 25% of the cost of using recycled water for irrigation. The cost of the recycled water was included in the total operating cost of the RWHP system.

Table 3 and Table 4 list the monthly energy uses and associated costs for the baseline system and the RWHP system, respectively. The source energy consumptions of the two systems were calculated based on the site-source energy conversion factors suggested by Deru and Tocellini (2007)—3.443 for delivered electricity, which is an average value for the US Eastern Interconnection, and 1.092 for the on-site consumed natural gas. Because power consumptions of the circulation pumps in the source loop, heating loop, and cooling loop of the two systems are assumed the same, they cancel each other out and are not listed in Tables 3 and 4.

For the 8 months encompassed in this study, the RWHP system saved 2,507 MMBtu of source energy (a 47% savings) and \$11,386 in energy costs (a 37% reduction) compared with the baseline system. Considering the costs associated with using recycled water and additional cooling tower make-up water for the baseline system, which are about \$807 and \$500, respectively, the operating cost savings is \$10,157 (33% savings).

The source energy end uses of both systems are shown in Fig. 25. For the RWHP system, the WWHP uses the most energy (65%) followed by the steam boiler (13%), which produced steam for the steam HXs in the source loop and the heating loop. The circulation pumps (i.e., the recycled water pump and pumps in the source loop, heating loop, precooling loop, and cooling loop) accounted for about 12% of the total system energy use.

For the baseline system, the boiler uses the most energy (53%) followed by the chiller (36%). The circulation pumps account for about 5% of the total system energy use.

Table 3. Monthly energy uses and costs of the baseline system

Month	OA temperature (°F)	Cooling load (kBtu)	Heating load (kBtu)	Chiller power consumption (kWh)	Boiler energy (MMBtu)	Cooling tower power consumption (kWh)	Cost ($)	Source energy (MMBtu)
1[a]	40.74	95,823	137,890	8,492	172	29	1,482	272
2	36.09	235,026	358,045	20,336	448	38	3,715	688
3	47.02	268,412	313,354	22,304	392	323	3,615	654
4	50.72	300,256	291,569	21,880	364	634	3,475	624
5	54.00	361,990	359,641	23,586	452	2,308	4,155	752
6	70.40	667,389	271,116	29,228	346	10,410	4,687	788
7	73.00	799,068	286,069	31,683	358	10,272	4,919	825
8	73.14	706,285	244,071	28,535	305	9,978	4,404	733
Total		**3,434,249**	**2,261,755**	**186,045**	**2,837**	**33,991**	**30,452**	**5,334**

[a] January data is from January 20 through January 31.

Table 4. Monthly energy uses and costs of the RWHP system

Month	OA temperature (°F)	WWHP power consumption (kWh)	Boiler energy (MMBtu)	Recycled water pump power consumption (kWh)	Cooling tower power consumption (kWh)	Cost ($)	Source energy (MMBtu)
1[a]	40.74	5,951	74	343	21	839	146
2	36.09	17,256	164	1,015	26	2,184	368
3	47.02	18,645	70	1,029	299	1,856	287
4	50.72	17,893	10	764	629	1,512	217
5	54.00	22,267	13	850	2,273	1,992	285
6	70.40	34,437	29	1,854	7,543	3,471	500
7	73.00	39,786	13	2,268	8,655	3,917	557
8	73.14	32,050	10	2,059	8,590	3,295	468
Total		**188,284**	**383**	**10,182**	**28,037**	**19,067**	**2,827**

[a] January data is from January 20 through January 31.

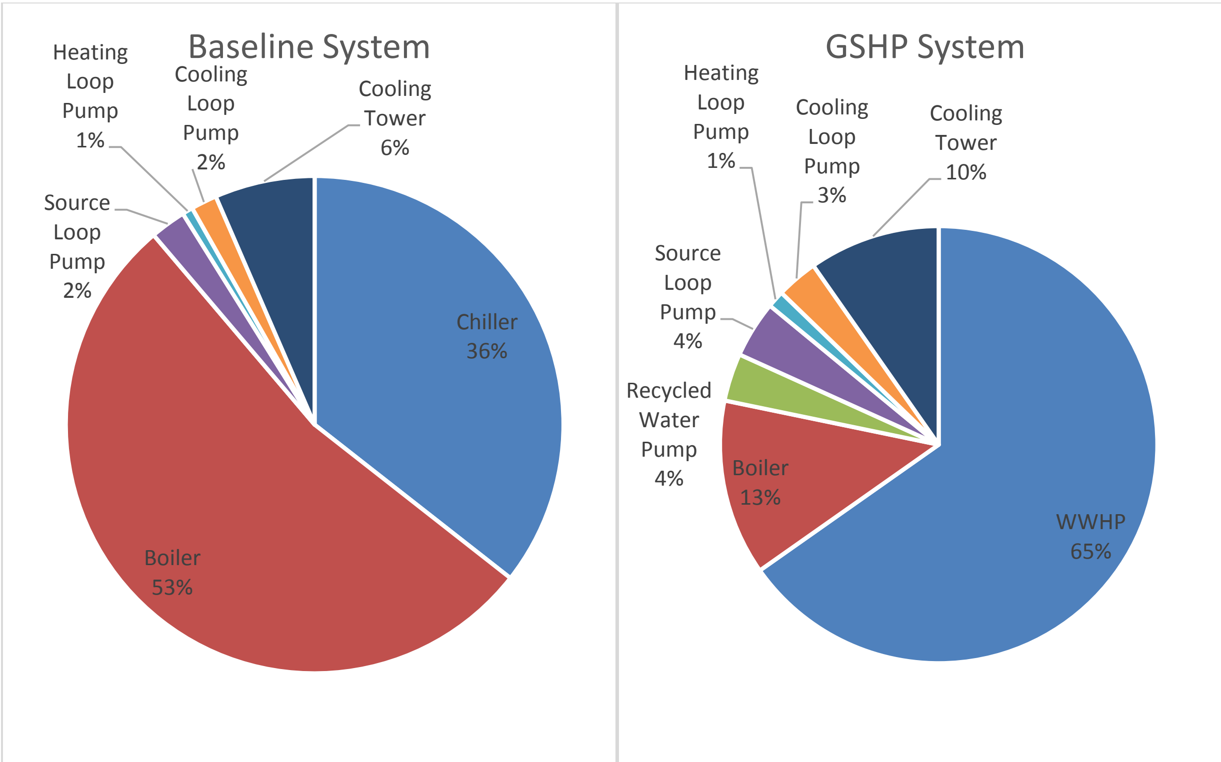


Fig. 20. Source energy end uses of the baseline and RWHP systems.

3.5.1 Prediction of Annual Energy Savings

Because the available measured data only cover 8 months, energy uses of the two systems during the rest of a 1-year period (September through December in 2014) were estimated to assess the annual energy savings potential of the RWHP system. The estimation procedure includes two steps:

1. Derive correlations between the monthly energy use of each major component of the two systems and the monthly average OA temperatures based on available data from January through August in 2015
2. Estimate the energy uses of the two systems with the derived correlations and the historical OA temperatures from September through December 2014.

As listed in Appendix A, for the baseline system, the correlations between the monthly average OA temperature and chiller electricity use, boiler natural gas use, or cooling tower electricity use were derived respectively. For the RWHP system, the correlations between the monthly average OA temperature and WWHP electricity use, boiler natural gas use, cooling tower electricity use, or recycled water pump electricity use also were derived respectively. The pump energy uses for the source loop and heating and cooling loops were not accounted for, given the pump energy uses between the two systems would be the same and thus canceled off each other. The annual (September 2014 through August 2015) energy uses, operating costs, and CO_2 emissions of the two systems are listed in The analysis shows that the total annual energy cost savings would be \$16,295 (34% savings), and there will be about 41% CO_2 emission reductions associated with the energy savings.

Table 5. The CO_2 emissions were calculated with conversion factors suggested by Deru and Tocellini (2007): 1.64 lb CO_2 equivalents per 1 kWh of electricity and 133.6 lb CO_2 equivalents per 1 MMBtu of

on-site natural gas consumption (which accounts for the emissions from both the on-site combustion and precombustion processes).

The analysis shows that the total annual energy cost savings would be $16,295 (34% savings), and there will be about 41% CO_2 emission reductions associated with the energy savings.

Table 5. Comparison of annual performance between the baseline and RWHP systems

	Baseline system		RWHP system	
	Electricity	**Natural gas**	**Electricity**	**Natural gas**
Annual HVAC related site energy	331,509 kWh	4,742 MMBtu	334,419 kWh	969 MMBtu
Annual HVAC related source energy (MMBtu)	8,528.5		4,598.2	
Source energy savings (MMBtu)	–		3,930.3	
% of source energy savings	–		**46.1%**	
Energy cost by fuel type ($)	$25,195	$22,953	$25,416	$4,692
Total energy cost ($)	$48,148		$30,108	
Recycled water use ($)	–		$2,398	
Additional make-up water ($)	$654			
Annual cost savings ($)	–		$16,295	
% of cost savings	–		**33.8%**	
CO_2 emissions (lb) by fuel type	543,675	578,565	548,447	118,278
Total CO_2 emissions (lb)	1,122,239		666,725	
CO_2 emission reductions (lb)	–		455,515	
% of CO_2 emission reductions	–		**40.6%**	

3.5.2 Effective COP of the RWHP System

Because the modular WWHP system provided simultaneous cooling and heating, but the available measured data did not distinguish the heating or cooling operation of each module of the WWHP, the "effective COP," which accounts for both the heating and cooling operations as described in Chap. 2, was calculated to evaluate the performance of the WWHP and the entire GSHP system instead of the COPs for heating and cooling modes, respectively.

Figure 26 presents effective COP for the WWHP unit and the RWHP system for each 10°F bin of the OA temperature. It shows, in general, the effective COP increases with the increase of OA temperature. The effective COP of the WWHP is about 5.6–6.0 when the OA temperature is higher than 70°F (i.e., when most modules of the modular WWHP ran in cooling mode). It is consistent with the manufacture's catalog data, which indicates the cooling COP of the WWHP ranges within 5.9– 6.2 at similar operating condition (i.e., 75°F water entering condenser and 45°F water leaving evaporator)[3].

The effective COP of the entire RWHP system, which accounts for the supplemental heat input from the steam HX in the source loop as well as the power consumptions of the cooling tower, the recycled water

[3] http://www.climacoolcorp.com/sites/climacool/uploads/documents/Archives/ClimaCool_TM_Flex_2_10_Manual.pdf

pump, and the source loop pump, rose from 2.6 to 4.4 with the increase of OA temperature, which is coincidental with the increased simultaneous heating and cooling operations.

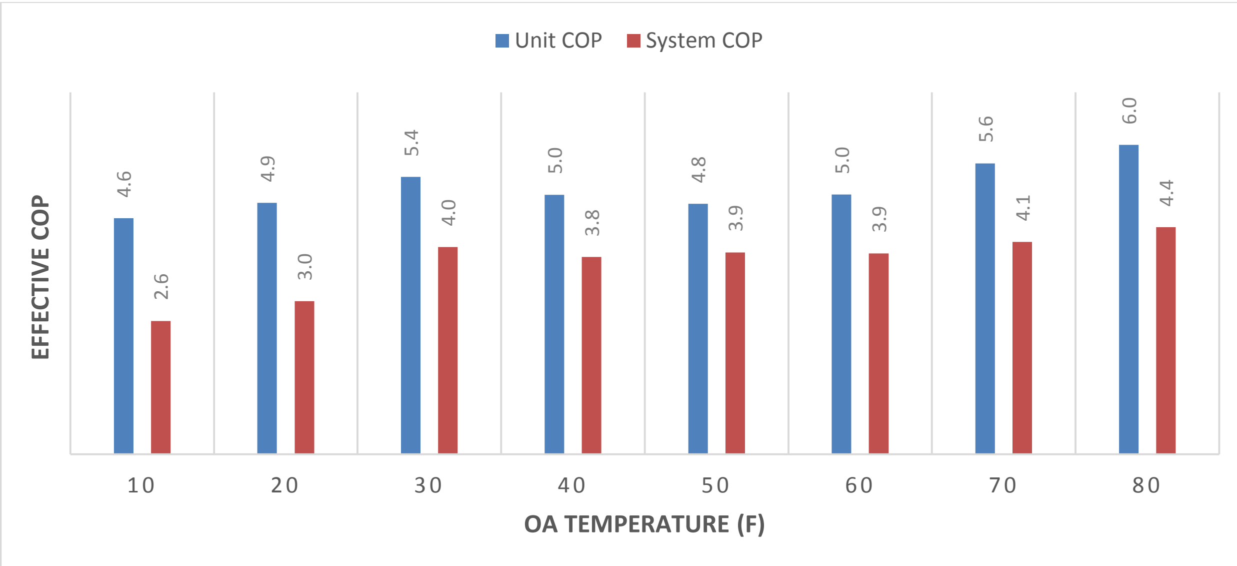


Fig. 21. Effective COPs of the WWHP unit and the RWHP system verses OA temperatures.

3.5.3 Analysis of Cost Effectiveness

The RWHP system's cost premium is the difference between the installed cost of the RWHP system and the cost of the baseline system defined in Sect. 3.5. The RWHP system's cost information was provided by the grantee (i.e., DMNS), and the baseline system cost was estimated based on RSMeans Construction Cost Data (RSMeans 2014), and the actual historical construction cost provided by DMNS. The RWHP cost data does not include the cost for the backup steam boiler systems because the steam is provided by the existing steam plant. Furthermore, as discussed earlier, contributions of the steam HXs were small and the RWHP system can work well without the boiler and the steam HXs. In case the recycled water is temporarily not available, the precooling loop and the cooling tower would be able to keep the system running. Without the steam HXs, the WWHP need provide more heating. However, it only results in a very minor increase (less than 1%) in the annual operating cost of the RWHP system.

As discussed in Chap. 1, one of the reasons for the high installed cost of the demonstrated RWHP system is the installation cost of the 3,300 ft long two-way branch pipeline (i.e., $1.1 million, or about 20% of the total system cost) to access the city's recycled water main pipeline. If the main pipeline were closer to the building, the total installed cost would have been much lower. Assuming the main pipeline is about 1,000 ft away from the building, the total installed cost can be reduced to $4.5 million, and the cost premium is reduced to $179,649. With this assumption, the total installed cost can be normalized as $21,560/ton or $32.3/ ft^2 of building floor space. The simple payback can thus be reduced to 11 years. If the main pipeline were even closer to the building (i.e., 400 ft away from the building), the cost premium will be negative, which means the capital cost for the conventional baseline system would be more expensive than the RWHP system. An instant simple payback can thus be achieved in this condition.

summarizes the itemized costs of the installed RWHP system and the baseline system. The total installed costs of the RWHP system and the baseline system are $5,294,283 and $4,347,967, respectively. The cost premium is $946,316.

Given the 210 ton installed cooling capacity of the RWHP system and the 140,000 ft^2 building floor space, the installed cost can be normalized as $25,210/ton or $37.8/ ft^2 of building floor space. Based on the annual energy cost savings discussed in Sect. 3.5.1, the simple payback of this system is about 58 years.

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Table 6. Cost effectiveness of the recycled water heat pump (RWHP) system compared with the baseline system

Cost item	RWHP system	Baseline system
HVAC equipment (AHUs)	$1,075,000	$1,075,000
Hydronic piping (to AHUs)	$146,000	$146,000
Air distribution system (duct work, etc.) and controls	$439,060	$439,060
Temperature control system	$330,000	$330,000
RWHP equipment (heat pumps, heat exchangers, circulation pumps, control system)	$288,747	
Pipeline installation (recycled water main to the museum)	$1,100,000	
RWHP equipment Installation	$624,045	
Baseline water cooled chiller system (two 300 ton chillers)[1]		$360,000
Steam boiler plant (including construction of boiler room)[2]		$1,370,000
Design, other professional cost, and indirect cost	$1,291,431	$627,907
Total	$5,294,283	$4,347,967
Cost premium		**$946,316**
Simple payback (years)		**58**
Total (if the length of the recycled water pipeline branch is 1,000 ft)	$4,527,616	$4,347,967
Cost premium		**$179,649**
Simple payback (years)		**11**

Note:

1. Assuming two 300 Ton centrifugal chiller as one backup system would be required. The cost was from RSMeans 2014. It was presumed the footprint of chillers would fit in existing GSHP footprint.

2. The boiler installation cost was the actual costs provided by DMNS for installing the boiler: $170k for equipment, $240k for installation. $960k is attributed to the construction cost to house a boiler and condensate system comparable to existing space.

4. CONCLUSIONS AND LESSONS LEARNED

The operating performance, energy and cost savings potential, and other achieved benefits of a RWHP system, which uses the recycled water from Denver's municipal water system as the heat sink and source, was investigated in this case study. The RWHP system was installed in a new addition building of the Denver Museum of Nature & Science in Denver, Colorado. This case study was conducted based on the available measured performance data from December 2014 through August 2015, utility bills of the building in 2014 and 2015, construction drawings, maintenance records, personal communications, and construction costs. The annual energy consumption of the RWHP system was calculated based on the available measured data and other related information. It was compared with the performance of a baseline scenario— a conventional VAV system using a water-cooled chiller and a natural gas fired boiler, both of which have the minimum energy efficiencies allowed by ASHRAE 90.1-2010. The comparison was made to determine energy savings, operating cost savings, and CO_2 emission reductions achieved by the RWHP system. A cost analysis was performed to evaluate the simple payback of the RWHP system. The following sections summarize the results of the analysis, the lessons learned, and recommendations for improvement in the operation of the RWHP system.

4.1 ENERGY PERFORMANCE AND COST-EFFECTIVENESS

- The measured recycled water temperature from the demonstration site during the encompassed period shows that the recycled water temperature is more favorable than the outdoor air temperature for effective operation of the vapor compression refrigeration cycle of the heat pump. The maximum outdoor air temperature was about 94.5°F during the cooling season, whereas the maximum recycled water temperature was about 83.2°F. The lowest recycled water temperature was about 38.8°F during the heating season, whereas the lowest outdoor air temperature was below 10°F.

- Effective COPs of the WWHP unit and the entire RWHP system, which account for the simultaneous cooling and heating, were calculated based on the measured data. The effective COP of the WWHP unit ranges from 4.6 through 6.0, whereas the effective COP of the RWHP system, which includes power consumptions of circulation pumps and the cooling tower, ranges from 2.6 to 4.4 during the 8 months investigation period of this study. The system COP increases with the increase of OA temperature, which is in part due to the increased simultaneous heating and cooling demands.

- The demonstrated RWHP system saved 3,930 MMBtu of source energy (a 46.1% savings) and $16,295 in energy costs (a 33.8% savings) annually, compared with a conventional VAV system using a water-cooled chiller and a natural gas fired boiler, both of which have the minimum energy efficiencies allowed by ASHRAE 90.1-2010. The energy savings also resulted in 41% reduction in CO_2 emissions.

- The normalized cost of the RWHP system (including the VAV system inside the building) is $25,210/ton of installed cooling capacity, or $37.8/ ft^2 of building floor space. With the achieved annual energy cost savings, the simple payback of this system is about 58 years. This long payback period is due to the high cost for constructing the 3,300 ft long two-way pipeline to access the recycled water. The pipeline cost is $1.1 million, which accounts for about 20% of the total system cost. If the length of the pipeline were 1,000 ft, the simple payback would have been reduced to 11 years.

4.2 LESSONS LEARNED

- The run-around heat recovery through the precooling loop is very effective and it significantly reduced the demand for external heat sources (e.g., the recycled water and the steam HX). The wet cooling tower rejected more heat than the recycled water due to the relatively dry air in the Denver area.

- Contributions of the steam HXs were very small and it is likely that the RWHP system can work well without the boiler and the steam HXs, or just with a smaller water heater as a backup. It will reduce the complexity and the associated cost of the RWHP system.

- The RWHP system would be economically more competitive if the recycled water is closer to the building.

4.3 RECOMMENDATIONS FOR FURTHER IMPROVEMENTS

Recycled water can serve as both the heat source and sink. However, its contribution was limited in this project. If the source water temperature is allowed to vary in a larger range (i.e., lower in heating season and higher in cooling season), recycled water may have contributed more, which can reduce the need for supplemental heating and the water consumption associated with the operation of the cooling tower. The allowed source water temperature shall be determined by carefully considering its impacts on the effectiveness of the precooling loop and the increase of cooling load on the WWHP. Although the recycled water may be used more and thus reduce cooling tower energy consumption, this will effectively reduce utilization of the dry Denver climate for indirect evaporative cooling, thus increasing WWHP compressor energy to meet cooling loads. A secondary issue, but still one that should be considered is the additional tradeoff with reduce COP of the WWHP modules for heating and cooling when source temperatures are lower in heating season and higher in cooling season. An identical RWHP system at a climate with less wet bulb depression (e.g., Houston, TX) might have higher utilization of the recycled water as a heat sink.

- One potential configuration than can increase the utilization of the recycled water without sacrificing the utilization of the dry climate for precooling would be to isolate the precooling from the source water loop when operating temperatures dictate. In this case, the precooling loop rejects heat directly through the cooling tower. However, when the recycled water loop is cool enough to supply cooling to the precooling loop, or the source water loop is in need of heating, the cooling tower is bypassed and the precooling loop rejects heat to the source water loop. With this configuration the source water loop could have wider bands of temperature control, allowing for more frequent heat rejection to the recycled water loop, but perhaps at the expense of additional complexity and costs.

5. REFERENCES

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APPENDIX A. MODELS FOR PREDICTING ENERGY CONSUMPTION OF BOTH THE BASELINE AND THE RWHP SYSTEMS

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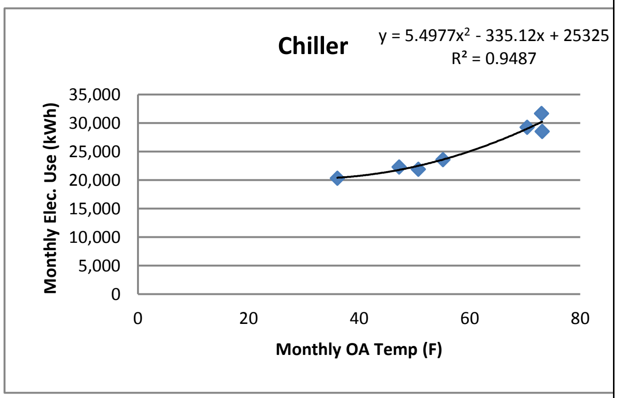
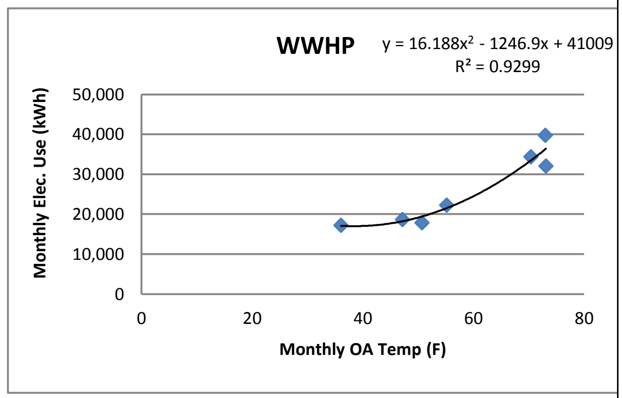
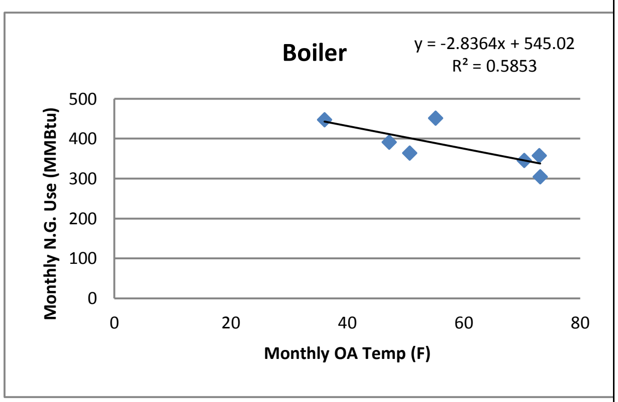
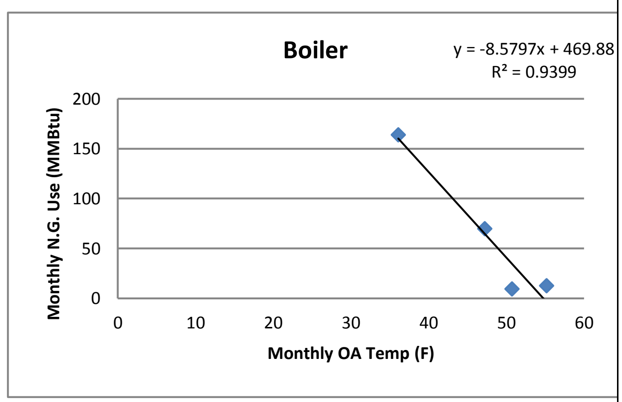
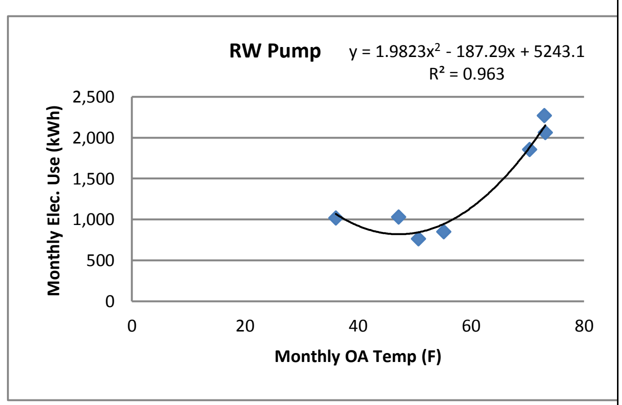
Baseline system	RWHP system
	
	
	

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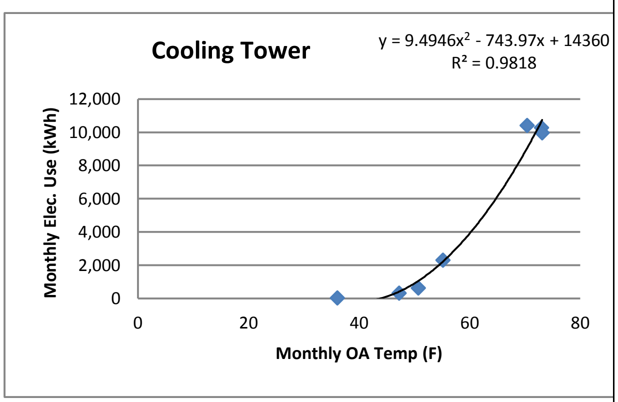
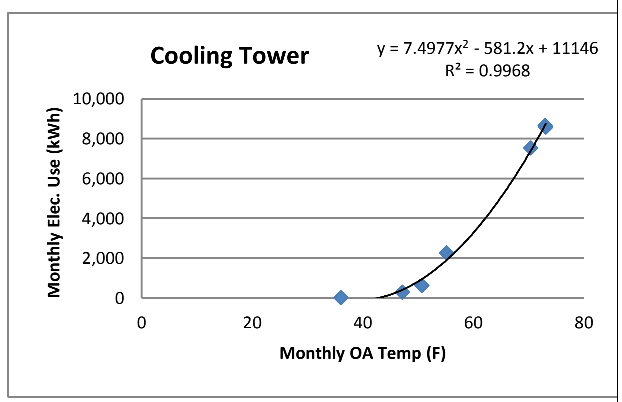
<tr><td>
</td><td>
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