

Water-to-Water Heat Pumps

By Roy Hubbard, Member ASHRAE

Many owners and designers of large commercial, institutional, and industrial (CII) facilities are considering the economic and environmental benefits of a water-to-water heat pump as a supplement to, or substitute for, a fossil fuel boiler. While a typical hot water boiler has a coefficient of performance (COP) of 0.85, heat pumps can have COPs of 3.50 or higher, which makes a compelling case for including heat pumps in many facilities.

An overview of the benefits and some of the applications for heat pumps appeared in an article titled “Using Waste Heat for Energy Savings,” which was published in the April 2006 issue of *ASHRAE Journal*.

In CII facilities, a variety of water

streams can act as heat sources for a heat pump. This article examines one application in detail: a facility that has a simultaneous requirement for chilled water and hot water, wherein the heat pump can provide or supplement both.

Facilities in which chilled water and

hot water are often used simultaneously include: hospitals, pharmaceutical plants, hotels, and campus central utility plants. In these facilities, a heat pump can substantially cut energy consumption, and reduce a facility’s carbon footprint.

This article discusses several system design guidelines, energy consumption calculations, green technology benefits, and capital constraint solutions for this specific heat pump application.

System Design Guidelines

These guidelines have been developed in conjunction with many facility owners

About the Author

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and consulting engineers. They are general, rather than exhaustive, and focus on basic application questions, such as loads and hot water temperatures.

More detailed design guidelines, such as control systems and operation procedures, are the subject of a future article.

Load Profile. The ideal facility for this application would have a load profile similar to *Figure 1*, which illustrates a typical 24-hour day in each of the four seasons. The heat available from a heat pump (green line) is approximately 35% greater than the cooling load (blue line) because the heat of compression is included.

From *Figure 1*, it can be seen that during most of the operating season, the heat available in the chilled water loop is more than adequate to satisfy all or most of the hot water requirement (red line). Only during the periods represented by the patterned portion of the graph is the heat pump not able to produce 100% of the facility's hot water requirements. During these times, the heat pump can significantly supplement traditional sources of heat.

The heat pump should be the first heat source to be used, because it is most likely the low-cost heat source. That can be verified by the following calculations, which use energy costs of \$0.068 per kWh of electricity and \$11.21 per 1,000 ft³ (\$0.40 per m³) of natural gas:

Energy Cost of Natural Gas Boiler

$$100,000 \text{ Btu} \div 0.85 \text{ COP} \div 1,000 \text{ Btu/ft}^3 \times \$11.21/1000 \text{ ft}^3 \\ = \$1.32 \text{ per } 100,000 \text{ Btu}$$

$$(105,000 \text{ kJ} \div 0.85 \text{ COP} \div 37,500 \text{ kJ/m}^3 \times \$0.40/\text{m}^3 \\ = \$1.32 \text{ per } 105,000 \text{ kJ})$$

Energy Cost of Electric Water-to-Water Heat Pump

$$100,000 \text{ Btu} \div 3.83 \text{ COP} \div 3,415 \text{ Btu/kW} \times \$0.068/\text{kWh} \\ = \$0.52 \text{ per } 100,000 \text{ Btu}$$

$$(105,000 \text{ kJ} \div 3.83 \text{ COP} \div 3600 \text{ kJ/kWh} \times \$0.068/\text{kWh} \\ = \$0.52 \text{ per } 105,000 \text{ kJ})$$

Location of Heat Pump. As illustrated in *Figure 2*, the most popular location for the heat pump is in a side-stream arrangement, between both water streams.

The heat pump is situated in this location for two reasons: 1) so it can be preferentially loaded before any of the chillers are brought on-line, and 2) so that the warmest return water is cooled in the heat pump, which slightly improves its COP.

Hot Water Temperature. One difference between the traditional boiler system and a heat pump system is that the hot water temperature supplied by the heat pump may be significantly lower. This is due to the necessity of balancing the economics of operating the heat pump, versus the capital and operating costs of the connected heating system.

Since the COP of a noncondensing boiler varies little over a large range of supply temperatures, traditional hot water heating designs standardized on a supply temperature of 180°F (82°C)

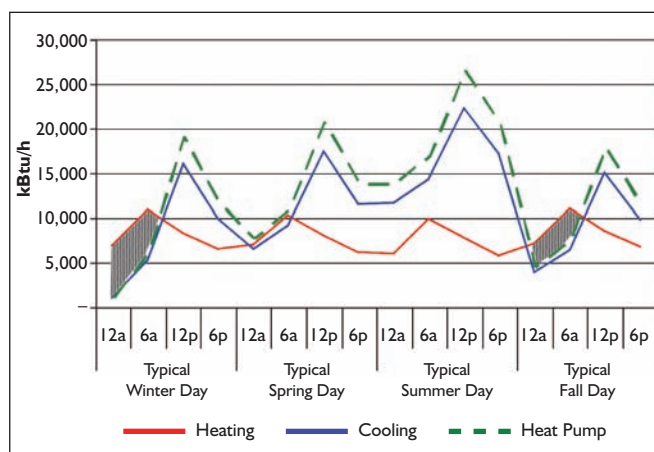


Figure 1: Sample load profile for facility with simultaneous heating and cooling loads.

with a rise of 30°F–40°F (17°C–22°C). This offered the benefit of low water flow rates, smaller piping, lower pumping costs, and less expensive heating coils.

On the other hand, the COP of a heat pump decreases significantly as the hot water supply temperature increases, as shown in *Figure 3*. Using the COP values in this graph can assist the system designer in selecting the optimum heating design temperature.

The COP values in *Figure 3* are based on a chiller manufacturer's rating data for a heat pump system with a constant leaving chilled water temperature of 42°F (6°C), which is representative of many chilled water systems. For systems in which the leaving chilled water temperature is significantly different, heat pump manufacturers can supply revised data.

Specific utility rates, labor rates, system design, and material costs all contribute to the determination of the hot water supply temperature in a heat pump system. However, most system designers are finding that the optimum temperature is between 120°F and 150°F (49°C and 66°C).

Service Hot Water. Sometimes, the hot water temperature may be the minimum temperature required to ensure a bacteria-free service water supply. If the service hot water represents a relatively small percentage of the total hot water heating load, then consideration should be given to elevating the temperature of the service water with a separate fossil fuel or electric boiler.

Booster Heating. It is also possible that a specific heating system requirement, or an existing heating system design, may dictate a hot water supply temperature greater than the heat pump can supply. In that case, the heat pump condenser can be piped in series with a hot water boiler or steam converter, which can supply the final hot water temperature (Note: If this is done with a boiler, it is important to consult with the boiler manufacturer to ensure that the boiler can operate with a reduced hot water temperature difference and/or increased hot water flow rates).

In fact, effective operation of the heat pump dictates its capacity be less than the design chilled water and hot water

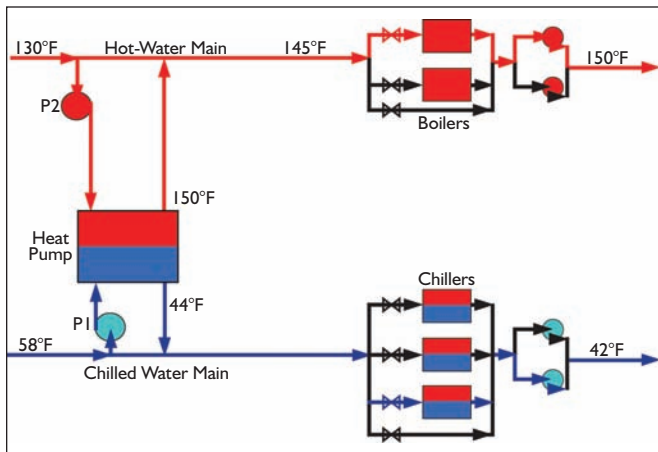


Figure 2: Heat pump location.

loads. This is because any reduction of the cooling load handled by the heat pump will also reduce its heat output. So, it is desirable to keep the heat pump as close to fully loaded as possible. Therefore, one or more chillers, and one or more boilers, will be required to supplement the capacity of the heat pump.

Potable Water Isolation. Most building codes require two layers of separation between the oil and refrigerant in a heat pump condenser and any potable water supply. In that case, an isolation heat exchanger will be required. The additional heat transfer loss will slightly reduce the heat pump COP.

Energy Consumption Calculations

How much energy can a heat pump save in this type of application, and is it a good investment? An energy analysis of an actual facility demonstrates the economic potential of a heat pump. It also shows how these applications can be analyzed.

This analysis was recently performed for an Arizona hospital. It compares a conventional plant, which includes variable speed, centrifugal chillers and natural gas boilers, to an alternate plant that adds a heat pump to the conventional plant.

Several analysis methods are available. The two most popular are bin analysis and hour-by-hour analysis, and a close correlation has been found when both methods are used. For simplicity of presentation in this article, the bin method will be demonstrated.

Conventional System. The summertime design ambient temperatures are 120°F (49°C) dry bulb/72°F (22°C) wet bulb, and 27°F (-3°C) dry bulb/24°F (-4°C) wet bulb in the winter. The cooling towers produce 81°F (27°C) water in the summer, and are limited to 55°F (13°C) water in the winter. The design hot water load is 27,000 kBtu/h (7913 kW) and the efficiency of the boilers is 85%. A base hot water load of approximately 7,000 kBtu/h (2051 kW) exists at all times. The design cooling load is 4,200 tons (14 770 kW), and the variable speed chillers' efficiency values are drawn from the chiller ratings. The facility uses airside economizers below

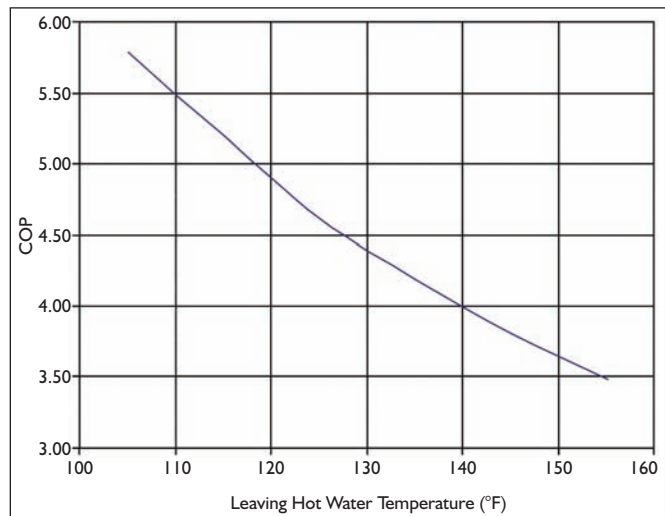


Figure 3: Heat pump COP versus hot-water supply temperature, with 42°F (6°C) chilled water supply temperature.

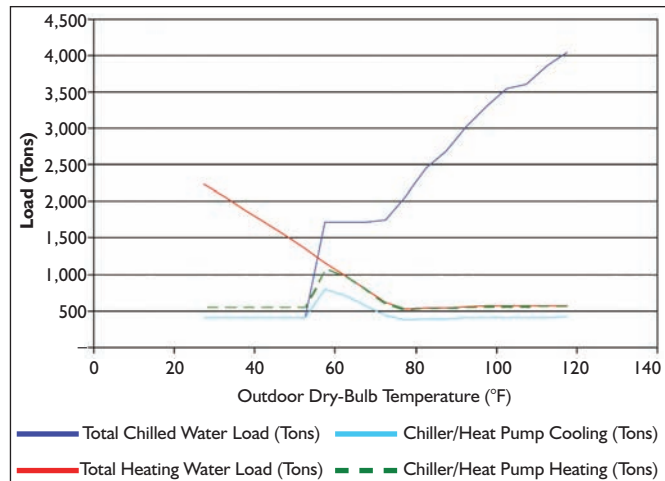


Figure 4: Loads versus outdoor temperature.

55°F (13°C) dry-bulb ambient, but a base chilled water load of 400 tons (1,407 kW) exists at all times. Figure 4 shows the loads versus outdoor temperature.

The electrical rates from this particular utility vary by season and time-of-day, and these variations are approximated in the bin analysis varying the rates in each bin. For comparison purposes, the weighted average used in this analysis is \$0.068/kWh. The average natural gas rate used in the analysis is \$11.21/Mcf (\$0.40/m³). Both rates are representative of rates found in North America.

The chillers and boilers will be analyzed separately and combined to establish a total cost. The analyses are shown in Tables 1 and 2 respectively.

The calculations used in Tables 1 and 2 (as well as Tables 3 through 5) are not complicated, but an explanation of the computations in one bin should ensure there is no confusion.

All weather data comes from *Engineering Weather Data*, which was compiled by the Air Force Combat Climatology Center and was published in July 1978. Looking at the

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Bin Weather Data				Standard VSD Chiller Operating Cost					
OADB (°F)	MCWB (°F)	ECWT (°F)	Bin Hours	Total Chilled Water Load (Tons)	Chiller Efficiency (kW/Ton)	Chiller Power (kW)	Chiller Energy (kWh)	Blended Electrical Use Rate (\$/kWh)	Chiller Operating Cost
117.5	72	80.1	2	4,045	0.589	2,382	4,765	0.073	\$350
112.5	71	78.9	30	3,864	0.583	2253	67,580	0.073	\$4,960
107.5	71	78.6	184	3,612	0.580	2095	385,428	0.073	\$28,290
102.5	70	77.5	353	3,538	0.579	2048	723,073	0.073	\$53,074
97.5	69	76.3	473	3,297	0.572	1886	892,110	0.073	\$65,481
92.5	67	74.3	628	3,009	0.499	1502	943,021	0.073	\$69,218
87.5	65	72.3	680	2,686	0.439	1179	801,680	0.073	\$58,843
82.5	62	69.5	963	2,457	0.380	934	899,105	0.067	\$59,790
77.5	59	66.6	827	2,062	0.351	724	598,495	0.067	\$39,800
72.5	55	62.9	711	1,745	0.277	483	343,713	0.067	\$22,857
67.5	52	59.5	638	1,721	0.231	398	253,697	0.067	\$16,871
62.5	49	57.0	872	1,721	0.227	391	340,741	0.067	\$22,659
57.5	47	55.0	791	1,721	0.229	394	311,813	0.067	\$20,736
52.5	44	55.0	677	400	0.229	92	62,013	0.067	\$4,124
47.5	41	55.0	486	400	0.229	92	44,518	0.067	\$2,960
42.5	37	55.0	249	400	0.229	92	22,808	0.059	\$1,337
37.5	33	55.0	165	400	0.229	92	15,114	0.059	\$866
32.5	28	55.0	25	400	0.229	92	2,290	0.059	\$134
27.5	24	55.0	6	400	0.229	92	550	0.059	\$32
Total Seasonal Chiller Operating Cost =									\$472,402

Table 1: Chiller analysis.

Bin Weather Data				Boiler Operating Cost			
OADB (°F)	MCWB (°F)	ECWT (°F)	Bin Hours	Hot Water Heating Load (MBH)	Heating Input to 85% Efficient Boiler (MBH)	Natural Gas Consumption (MBtu)	Natural Gas Consumption Cost (\$)
117.5	72	80.1	2	6,928	8,150	16,300	\$179
112.5	71	78.9	30	6,894	8,110	243,313	\$2,676
107.5	71	78.6	184	6,826	8,031	1,477,668	\$16,254
102.5	70	77.5	353	6,836	8,042	2,838,890	\$31,228
97.5	69	76.3	473	6,773	7,968	3,768,978	\$41,459
92.5	67	74.3	628	6,681	7,860	4,936,189	\$54,298
87.5	65	72.3	680	6,565	7,724	5,252,094	\$57,773
82.5	62	69.5	963	6,497	7,644	7,361,210	\$80,973
77.5	59	66.6	827	6,333	7,451	6,161,693	\$67,779
72.5	55	62.9	711	7,341	8,636	6,140,161	\$67,542
67.5	52	59.5	638	9,544	11,228	7,163,693	\$78,801
62.5	49	57.0	872	11,757	13,832	12,061,629	\$132,678
57.5	47	55.0	791	13,975	16,442	13,005,318	\$143,058
52.5	44	55.0	677	16,193	19,051	12,897,586	\$141,873
47.5	41	55.0	486	18,382	21,626	10,510,446	\$115,615
42.5	37	55.0	249	20,538	24,162	6,016,329	\$66,180
37.5	33	55.0	165	22,678	26,680	4,402,271	\$48,425
32.5	28	55.0	25	24,780	29,153	728,835	\$8,017
27.5	24	55.0	6	26,853	31,592	189,553	\$2,085
Total Season Boiler Operating Cost =							\$1,156,894

Table 2: Boiler analysis.

Bin Weather Data				Standard VSD Chiller Operating Cost							
OADB (°F)	MCWB (°F)	ECWT (°F)	Bin Hours	Total Chilled Water Load (Tons)	Chiller/Heat Pump Cooling Capacity (Tons)	Net Conventional Chilled Water Load (Tons)	Chiller Efficiency (kW/ton)	Chiller Power (kW)	Chiller Energy (kWh)	Blended Electrical Use Rate (\$/kWh)	Chiller Operating Cost
117.5	72	80.1	2	4,045	412	3,633	0.589	2,140	4,280	0.073	\$314
112.5	71	78.9	30	3,864	410	3,454	0.583	2,014	60,409	0.073	\$4,434
107.5	71	78.6	184	3,612	406	3,206	0.580	1,859	342,100	0.073	\$25,110
102.5	70	77.5	353	3,538	406	3,132	0.579	1,813	640,092	0.073	\$46,983
97.5	69	76.3	473	3,297	403	2,894	0.572	1,656	783,076	0.073	\$57,478
92.5	67	74.3	628	3,009	397	2,612	0.499	1,304	818,612	0.073	\$60,086
87.5	65	72.3	680	2,686	390	2,296	0.439	1,008	685,257	0.073	\$50,298
82.5	62	69.5	963	2,457	386	2,071	0.380	787	757,852	0.067	\$50,397
77.5	59	66.6	827	2,062	376	1,686	0.351	592	489,351	0.067	\$32,542
72.5	55	62.9	711	1,745	436	1,309	0.277	363	257,844	0.067	\$17,147
67.5	52	59.5	638	1,721	567	1,154	0.231	267	170,133	0.067	\$11,314
62.5	49	57.0	872	1,721	699	1,022	0.227	232	202,378	0.067	\$13,458
57.5	47	55.0	791	1,721	800	921	0.229	211	166,902	0.067	\$11,099
52.5	44	55.0	677	400	400	-	0.229	0	0	0.067	\$0
47.5	41	55.0	486	400	400	-	0.229	0	0	0.067	\$0
42.5	37	55.0	249	400	400	-	0.229	0	0	0.059	\$0
37.5	33	55.0	165	400	400	-	0.229	0	0	0.059	\$0
32.5	28	55.0	25	400	400	-	0.229	0	0	0.059	\$0
27.5	24	55.0	6	400	400	-	0.229	0	0	0.059	\$0
Total Seasonal Chiller Operating Cost =											\$380,659

Table 3: Chiller analysis.

120°F–115°F (49°C–46°C) bin in the chiller analysis, the Blue Book says that Phoenix spends an average of two hours per year in that temperature range, and that the mean coincident wet-bulb (MCWB) temperature is 72°F (22°C). Cooling tower ratings show that, under those conditions, the towers will supply 80.1°F (27°C) to the condensers of the chillers.

From Figure 4, the average chilled water load in this bin is 4,045 tons (14 226 kW) of refrigeration, and the chiller ratings peg their efficiency as 0.589 kW per ton at those conditions. The chiller power is a product of 4,045 tons × 0.589 kW_{elec}/kW_{cool} = 2382 kW. During the two hours spent in this bin, the chiller energy consumption is two hours × 2,382 kW = 4,765 kWh.

The blended electrical use rate for this bin is \$0.0734 per kWh, so the chiller operating cost is 4,765 kWh × \$0.0734 per kWh = \$350 annually. All the numbers in Tables 1 through 5 are calculated in a similar fashion.

Tables 1 and 2 contain the conventional system results, and show the annual operating cost as:

\$472,402 (Chillers) + \$1,156,894 (Boilers) = \$1,629,296 (Total Annual Cooling and Heating Cost)

Alternate System. Next, a heat pump capable of 800 tons (2814 kW) of cooling and 13,500 MBH (3956 kW) of heating is added to the system. The heat pump is capable of handling

almost the entire hot water load above 60°F (16°C) dry-bulb ambient. It is also capable of handling the entire cooling load below 55°F (13°C) dry-bulb ambient, but its cooling capability above 55°F (13°C) dry-bulb ambient is limited by how much hot water can be used productively. The analysis is shown in Tables 3, 4, and 5.

The summary of the annual operating cost for the heat pump plant is:

\$380,659 (Chillers) + \$252,043 (Boilers) + \$417,049 (Heat Pump) = \$1,049,751 (Total Annual Cooling and Heating Cost)

Therefore, adding the heat pump reduced the operating cost by: \$1,629,296 – \$1,049,751 = \$579,545

The heat pump system, which had an additional capital cost of approximately \$750,000, included the heat pump, piping, pumps, controls, and engineering design services. This investment resulted in a simple payback of 1.3 years, which is typical of the one- to two-year payback found in most hospital projects studied.

Energy Analysis Comments. This analysis does not include evaluation of the many ancillary devices (pumps, towers, etc.), which could be included in a detailed analysis. The energy consumption of these devices is relatively small compared to the major components presented here. In addition, many of

Bin Weather Data				Boiler Operating Cost					
OADB (°F)	MCWB (°F)	ECWT (°F)	Bin Hours	Hot Water Heating Load (MBH)	Chiller/Heat Pump Heating Capacity (MBH)	Net Hot Water Heating Load (MBH)	Heating Input to 85% Efficient Boiler (MBH)	Natural Gas Consumption (MBtu)	Natural Gas Consumption Cost (\$)
117.5	72	80.1	2	6,928	6,928	0	0	0	\$0
112.5	71	78.9	30	6,894	6,894	0	0	0	\$0
107.5	71	78.6	184	6,826	6,826	0	0	0	\$0
102.5	70	77.5	353	6,836	6,836	0	0	0	\$0
97.5	69	76.3	473	6,773	6,773	0	0	0	\$0
92.5	67	74.3	628	6,681	6,681	0	0	0	\$0
87.5	65	72.3	680	6,565	6,565	0	0	0	\$0
82.5	62	69.5	963	6,497	6,497	0	0	0	\$0
77.5	59	66.6	827	6,333	6,333	0	0	0	\$0
72.5	55	62.9	711	7,341	7,341	0	0	0	\$0
67.5	52	59.5	638	9,544	9,544	0	0	0	\$0
62.5	49	57.0	872	11,757	11,757	0	0	0	\$0
57.5	47	55.0	791	13,975	13,090	885	1,042	823,918	\$9,063
52.5	44	55.0	677	16,193	6,690	9,503	11,180	7,569,198	\$83,261
47.5	41	55.0	486	18,382	6,690	11,692	13,756	6,685,341	\$73,539
42.5	37	55.0	249	20,538	6,690	13,848	16,291	4,056,553	\$44,622
37.5	33	55.0	165	22,678	6,690	15,988	18,810	3,103,624	\$34,140
32.5	28	55.0	25	24,780	6,690	18,090	21,283	532,070	\$5,853
27.5	24	55.0	6	26,853	6,690	20,163	23,722	142,330	\$1,566
Total Seasonal Boiler Operating Cost =									\$252,043

Table 4: Boiler analysis.

Bin Weather Data				Chiller/Heat Pump Operating Cost				
OADB (°F)	MCWB (°F)	ECWT (°F)	Bin Hours	Chiller/Heat Pump Heating Capacity (MBH)	Chiller/Heat Pump Power (kW)	Chiller/Heat Pump Electrical Use (kWh)	Blended Electrical Use Rate (\$/kWh)	Chiller/Heat Pump Operating Cost (\$)
117.5	72	80.1	2	6,928	636	1,272	0.073	\$93
112.5	71	78.9	30	6,894	634	19,015	0.073	\$1,396
107.5	71	78.6	184	6,826	630	115,905	0.073	\$8,507
102.5	70	77.5	353	6,836	630	222,559	0.073	\$16,336
97.5	69	76.3	473	6,773	627	296,493	0.073	\$21,763
92.5	67	74.3	628	6,681	622	390,306	0.073	\$28,648
87.5	65	72.3	680	6,565	615	418,048	0.073	\$30,685
82.5	62	69.5	963	6,497	611	588,250	0.067	\$39,119
77.5	59	66.6	827	6,333	582	481,314	0.067	\$32,007
72.5	55	62.9	711	7,341	677	481,347	0.067	\$32,010
67.5	52	59.5	638	9,544	796	507,848	0.067	\$33,772
62.5	49	57.0	872	11,757	968	844,096	0.067	\$56,132
57.5	47	55.0	791	13,090	1,076	851,116	0.067	\$56,599
52.5	44	55.0	677	6,690	580	392,660	0.067	\$26,112
47.5	41	55.0	486	6,690	580	281,880	0.067	\$18,745
42.5	37	55.0	249	6,690	580	144,420	0.059	\$8,463
37.5	33	55.0	165	6,690	580	95,700	0.059	\$5,608
32.5	28	55.0	25	6,690	580	14,500	0.059	\$850
27.5	24	55.0	6	6,690	580	3,480	0.059	\$204
Total Seasonal Chiller/Heat Pump Operating Cost =								\$417,049

Table 5: Heat pump analysis.

these often offset each other and are not likely to significantly change by adding a heat pump to a system.

Electrical demand charges are a significant portion of most commercial electric utility bills, but they were not presented for simplicity. Adding a heat pump, which is expected to operate during even the hottest portions of the operating season, will increase the demand charges. However, because the heat pump's cooling capacity is displacing cooling that a chiller would normally contribute, only the net difference between the power of the heat pump and the equivalent power of a chiller must be added to calculate the additional demand charge for the heat pump. In most cases, the increase in demand charges is normally less than 5% of the total use costs and has a relatively minor effect on the total economic evaluation.

Green Technology Benefits

Reducing the consumption of fossil fuels to power HVAC equipment reduces the amount of CO₂ emitted to the atmosphere.

It is true that replacing a fossil fuel boiler with an electric drive heat pump causes the building electrical consumption to increase and this will increase CO₂ emissions at the utility power plant. However, this is more than offset by the significant reduction in CO₂ emissions by not burning as much fossil fuel to heat the building.

Also, if the facility owners and designers are interested in obtaining LEED® certification for the building, the addition of a heat pump can help. The U.S. Green Building Council's LEED rating system offers credits for exceeding the efficiency requirements of ASHRAE Standard 90.1. Substituting a heat pump for a hot water boiler helps to achieve this goal.

Capital Constraint Solutions

In spite of the tremendous economic and environmental benefits that heat pumps offer, designers may still find it difficult to incorporate a heat pump into an existing system, due to capital budget constraints. If the building owner is open to creative financing, then the additional equipment, facility, and design costs can be financed with future economic benefits.

In new facilities, another approach to reducing the capital outlay is to eliminate or reduce the size of the redundant chillers by taking advantage of the chilling capacity of the heat pump. The Arizona hospital example can be used to demonstrate this approach.

For this particular facility, the design loads are approximately 4,200 tons (14 770 kW) cooling and 27,000 kBtu/h (7913 kW) heating. Standard design practice for this critical-care facility dictates that a plant with multiple chillers be installed to meet the design load and provide redundant capacity in the unlikely event that one of the chillers is offline for maintenance or repairs during a peak-capacity period. The standard practice is to use an "N + 1" redundancy approach. The boiler system requires N + 1 redundancy for the same reasons.

For this facility, one option is to provide four 1,050 ton (3693 kW) chillers with a redundant 1,050 ton (3693 kW) chiller and two 13,500 kBtu/h (3957 kW) boilers with a redundant 13,500 kBtu/h (3957 kW) boiler. If the proposed 800 ton (2814 kW)/13,500 kBtu/h (3957 kW) heat pump is installed in lieu of the redundant chiller and boiler, and the four chillers are marginally increased in size to 1,133 ton (3985 kW) each, the full heating and cooling redundancy is maintained. The capital saved by not supplying either the redundant chiller or the redundant boiler can be used to offset the cost of the heat pump.

Conclusion

Water-to-water heat pumps have a COP of 3.50 or higher, while a typical hot water boiler has a COP of 0.85. That makes heat pumps worth investigating for many types of facilities. This article has examined some of the system design guidelines, energy consumption calculations, green technology benefits, and capital constraint solutions of a water-to-water heat pump applied in a facility that has simultaneous needs for chilled and hot water.

Given the many benefits that heat pumps offer, it is possible this technology will soon become a design standard in hospitals, pharmaceutical plants, hotels, and campus utility plants.●

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