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**This article presents annual energy savings of more than $600,000 per year and an annual reduction in carbon dioxide emissions of 4,438 tons per year via a water to water heat pump installed at the Novartis Flu Vaccine Facility.**

# Increasing Central Plant Efficiency via a Water to Water Heat Pump

by Jim Heemer, Alexander Mitrovic, and Michael Scheer

Pharmaceutical central utility plants often generate chilled water and steam year round to handle both process and HVAC loads. In addition, simultaneous heating and cooling are often required to maintain both humidity and space temperature set points in Good Manufacturing Practices (GMP) spaces driving utility demands higher. Power requirements can be substantial. Typical plant design includes both chillers and boilers running year round to meet demand. A heat pump (heat recovery chiller) may be installed to allow for recovery of the waste heat off the chiller condenser water to generate heating hot water for plant heating in addition to generating useful Chilled Water (CW). This will allow for the reduction of loading on the chillers, steam boilers, cooling tower fans, and cooling tower water makeup. The installation of a heat pump was considered and implemented as part of the original plant design at the Novartis Flu Vaccine Facility in Holly Springs, North Carolina.

Some of the challenges faced by the team and calculations required included:

- conveying a clear understanding of the basic concept and the potential energy savings
- basic system configuration to minimize/eliminate impact on plant reliability
- overcoming the perception that heating hot water needs to be delivered at 180°F (82°C) to the HVAC heating coils
- determining energy savings
- determining economic feasibility
- reviewing environmental benefits
- ensuring all design issues were addressed to maximize plant success

## Basic Concept and Potential Energy Savings

A heat pump is nothing more than a chiller. The difference is that a chiller typically operates with a condenser water supply temperature to the chiller of 55°F (13°C) to 85°F (29°C) and a condenser leaving water temperature of 60°F (16°C) to 95°F (35°). This leaving water temperature is too low to be utilized effectively as a heating source for process or HVAC loads. However, a heat pump can be utilized to generate Chilled Water (CW) and work at higher condenser water temperature up to 170°F (77°C), which makes for ideal use as a heating hot water source in HVAC systems.

The basic simplified economics of the heat pump comes down to comparing energy input and output of the heat pump to a natural gas fired boiler and chiller system. The heat pump can have a Coefficient of Performance (COP) – "useful energy out/energy in" of 6.3 versus a COP that may be below 0.8 for a steam boiler, steam to Heating Hot Water (HHW) converter combination. The simple payback calculation for the heat pump is shown in Figure 1 which shows the energy input required to generate the same heat output as a steam boiler plus the additional benefit of the chilled water generated. With the projects boiler and heat exchanger combination, one unit of energy is input to get 0.82 units of useful energy out of the system. This includes a gas fired steam boiler efficiency of 83.5% with an assumed additional 1.5% loss in the steam to hot water converter. Even though the unit cost of electricity for the site is $21.97 per decatherm (Dth) (1,055 MJ) versus $6.75 per Dth (1,055 MJ) for natural gas, the greater COP of the heat pump overcomes the higher unit power cost of electricity over natural gas.

## Basic System Configuration

For installation in a pharmaceutical plant, chilled water and heating hot water flows and supply temperatures can be critical to plant operation and product viability. To this end, the best approach is to install the heat pump in side

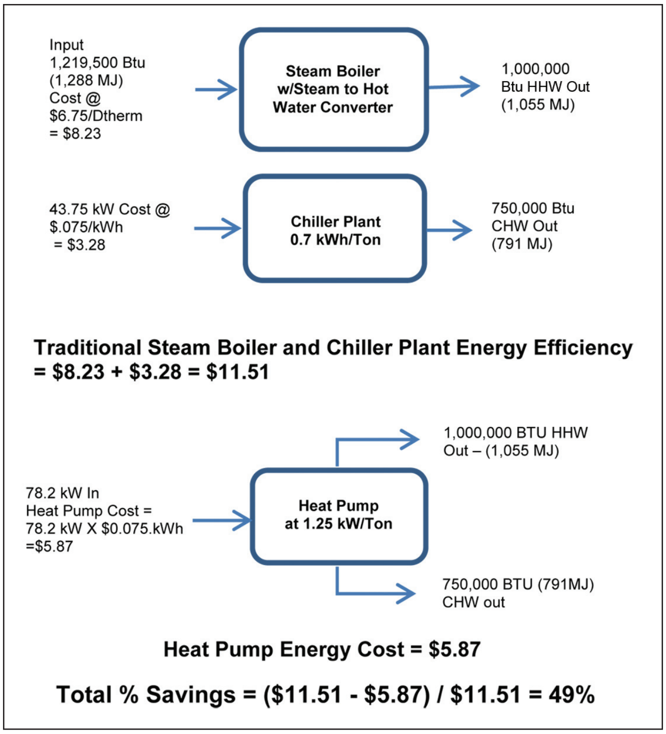


Figure 1. Basic concept.

car arrangement as shown in Figure 2. This approach serves several purposes: 1. it allows for independent control of the main chillers and heating plant, 2. it allows for less complex control, and 3. it protects the plant from out of range chilled water and/or heating hot water temperatures if the heat pump should fail.

Installing the heat pump in side car arrangement allows both the main chillers and heating hot water plant to run independently of the heat pump for the most part. The chillers run as needed to maintain critical discharge temperature to both process and HVAC loads regardless of heat pump operation.

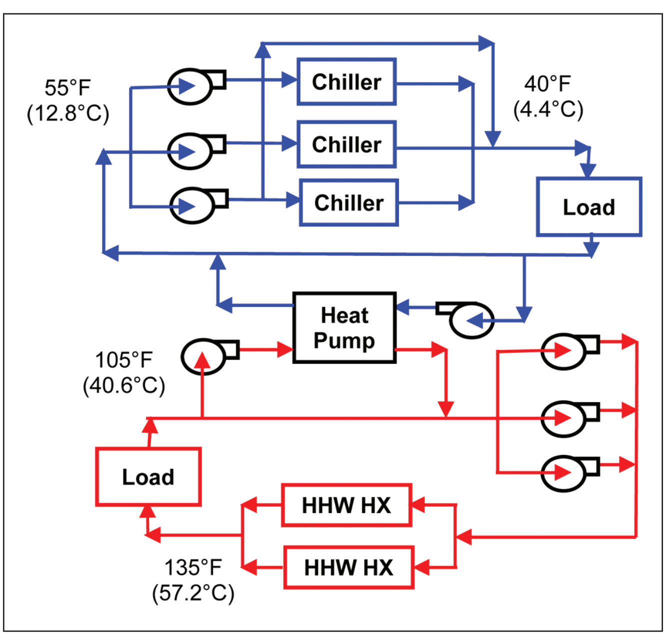


Figure 2. Flow diagram.

The load on the main chillers will vary as a function of plant loading and heat pump operation, but handles both via its own independent control system. The same goes for the heating hot water side of the plant.

Since the control of the heat pump does not need to be tied in with the other equipment, control logic becomes simpler and troubleshooting control issues easier. One caveat is control during low load. The plant personnel may not want to have the main chillers shutdown if the heat pump should be able to cover the entire load, so sequences can be set up to ensure the heat pump capacity is reduced to maintain at least one main chiller running at low load. If the load is too low to allow for the heat pump and the main chiller to both run, the heat pump can automatically shut off.

The chilled water system services both HVAC and process loads. Some of the process loads are critical, thus making the chilled water a qualified system requiring tight temperature control. With the main chillers delivering set point chilled water to the plant downstream of the heat pump, the delivered chilled water temperature to the load is not impacted by heat pump operation. If the heat pump should fail, the chillers and the steam to heating hot water heat exchanger will continue to control to leaving water temperature, so failure of the heat pump should have no impact on supply temperatures to the plant. For redundancy, the main chillers and heating hot water heat exchanger should be sized as a minimum to handle the entire load if the heat pump should fail.

## Lowering Heating Water Temperature

Typical HVAC heating hot water temperatures for pharmaceutical plants is 180°F (82°C) supply and 160°F (71°C) return. At these temperatures, it is difficult to find a heat pump that will be effective from both a capital cost and operating cost standpoint. The lower the heating hot water temperature, the more applicable a heat pump is, due to increasing efficiencies as heating hot water temperature drops. However, as temperature of the hot water and air temperature approach one another, the more heating hot water coil surface is required to meet design conditions. Larger surface areas equates to higher first cost. In addition, the larger coil translates to higher pressure drop on both the airside and waterside of the coil. The additional power required must be compared to the power savings obtained from the heat pump, due to lower heating hot water temperature. Consideration also needs to be given to ASHRAE 90.1-2007 (American Society of Heating, Refrigeration, and Air-Conditioning Engineers – Energy Standard for Buildings Except Low-Rise Residential Buildings) allowable fan horsepower with the increasing airside pressure drop through the coil.[1]

The design team looked at the increased pump and fan power, due to the increased heating hot water coil pressure drop on both airside and water side at lower supply heating hot water temperatures along with reduced power consumption of a heat pump. For the plant, temperature from GMP chilled water coils was set at 48°F (9°C) for dehumidification. With high air change rates for GMP spaces, it was found that air delivery temperatures were needed in the 60° F to 66°F (16°C to 19°C) range to maintain room space temperatures

| Heating Hot Water | | Airside Side Delta-P (1) WC"(cm) | Water Side Delta-P (1) ft (m) | Additional (HP) | | Added Pump and Fan Power (kW) | Annual Power Increase (kWh) | 100 Ton Heat Pump | | Power Savings (kW) |
|---|---|---|---|---|---|---|---|---|---|---|
| Supply °F (°C) | Return °F (°C) | | | Fan (HP) | Pump (HP) | | | Reduced Power (kW/Ton) | Annual Reduction (kWh) | |
| 155 (68) | 125 (52) | 0.35 (.89) | 7.45 (2.27) | - | - | - | - | - | - | - |
| 145 (63) | 115 (46) | 0.37 (0.94) | 7.5 (2..29) | 0.20 | 0.002 | 0.15 | 1,320 | 0.081 | 70,956 | 69,636 |
| 135 (57) | 105 (41) | 0.42 (1.07) | 7.58 (2.31) | 0.72 | 0.005 | 0.54 | 4,736 | 0.162 | 141,912 | 137,176 |
| 125 (52) | 95 (35) | 0.58 (1.47) | 11.05 (3.37) | 2.35 | 0.130 | 1.85 | 16,200 | 0.243 | 212,868 | 196,668 |
| 115 (46) | 85 (29) | 0.69 (1.75) | 11.17 (3.4) | 3.48 | 0.134 | 2.69 | 23,608 | 0.324 | 283,824 | 260,216 |
| 105 (41) | 75 (24) | 1.06 (2.69) | 18.29 (5.57) | 7.26 | 0.391 | 5.71 | 49,979 | 0.455 | 398,580 | 348,601 |
| Assumes 100 ton heat pump delivering 1,600,000 Btuh heat.<br>Lifting air temperature through coils from 55°F to 85°F for 42,318 CFM.<br>Fan Hp = CFM X TP /(6356 X Fan Eff.); Fan Efficiency 65%. | | | | | | At 30°F delta-T water flow = 107 gpm<br>.7545 kW = 1 HP<br>Pump HP = gpm X Hd (ft) /(3,960 X Pump Eff.); Pump Eff. = 75% | | | | |

Table A. Heating water temperature verses system power consumption with heat pump.

from 66°F to 70°F (19°C to 21°C). For some of the office and utility spaces, supply air temperatures were required to be in the low 80's (27°C) for adequate space heating. With this, the analysis of temperature delivery was based on an entering air temperature to the heating hot water preheat coil of 50°F (10°C), assumed 2°F (1°C) rise across the supply fan with a discharge temperature of 85°F (29°C). This assumption would yield conservatively high power consumption through the coil since it is based on the lowest heating hot water coil air to water side temperature differential. A reference temperature of 155°F (68°C) supply with a 30°F (-1°C) delta-T was used as the base case for the heating hot water for the high end supply temperature. Refer to Table A for increased power savings as the temperature is lowered from 155°F (68°C) supply to 105°F (41°C). Table B shows increase in capital cost of the coils verses discharge temperature and net present value. Based on the data, the supply heating hot water temperature of 105°F (41°C) provides the best economics. However, various team members were uncomfortable with using 105°F (41°C) heating hot water supply temperature. They were concerned with freezing outdoor air coils at winter design outdoor air temperature of 13°F (-10°C). Pumped recirculation loops were considered to allow for lower temperature water, but it was agreed that a 135°F (57°C) supply temperature would be used so pump loops would not be needed.

The decision to use a 30°F (17°C) delta-T was based on cutting water flow and associated pump power by 33% while keeping the return water temperature high enough to maintain heat transfer in the coils. Pressure increase on the air side of the coils is minimal having little impact on fan power in relation to ASHRAE 90.1-2007 maximum fan horsepower requirements. Also to be considered is the type of heating system to be used in unison with the heat pump and temperature limitations on the equipment. For example, using a noncondensing boiler is problematic at these low temperatures.

## Determining Energy Savings

Typically, the chiller(s) and boiler(s) are sized to match the plant load. In the case of a heat pump, the machine sees a hot water heating load and a chilled water load. The unit matches the smaller of the two loads the machine sees. Roughly one quarter of the energy input into the hot water is electric power input to the heat pump converted to heat. The remaining three quarters of the heat pump energy supplied to the heating hot water is heat transferred from the returning chilled water. Note that this varies depending on machine efficiency and operating temperatures.

Selecting the correct size heat pump is based on determining coincident heating hot water and chilled water loads throughout a typical year. Since both the heating hot water load and chilled water loads are highly dependent on outdoor air temperature, a good approach is to develop a profile relative to outdoor air

| HHW Temperatures | | Coil Capital Cost | | Annual Power Savings | | Net Present Value at 15% ROR |
|---|---|---|---|---|---|---|
| Supply °F (°C) | Return °F (°C) | 42,318 CFM Coil Cost ($) | Additional Coil Cost ($) | Power Reduction (kWh) | Annual Savings ($) | |
| 155 (68) | 125 (52) | $6,705 | - | - | - | - |
| 145 (63) | 115 (46) | $6,804 | $99 | 69,636 | $5,223 | $32,592 |
| 135 (57) | 105 (41) | $7,126 | $421 | 137,176 | $10,288 | $63,976 |
| 125 (52) | 95 (35) | $8,954 | $2,249 | 196,602 | $17,203 | $105,429 |
| 115 (46) | 85 (29) | $9,515 | $2,810 | 260,216 | $19,516 | $119,348 |
| 105 (41) | 75 (24) | $13,828 | $7,123 | 348,536 | $26,140 | $156,497 |
| Electric cost $0.075 per kWh; Blended rate at the site.<br>NPV at 15% rate of return for 20 years | | | | Cfm basis; (100 tons X 1.33 X 12,000 Btu/Ton)/1.08 X 30°F = 42,318<br>Coil cost based on 20,000 Cfm coils.[2] | | |

Table B. NPV at various HHW temperatures for a 100 ton heat pump.

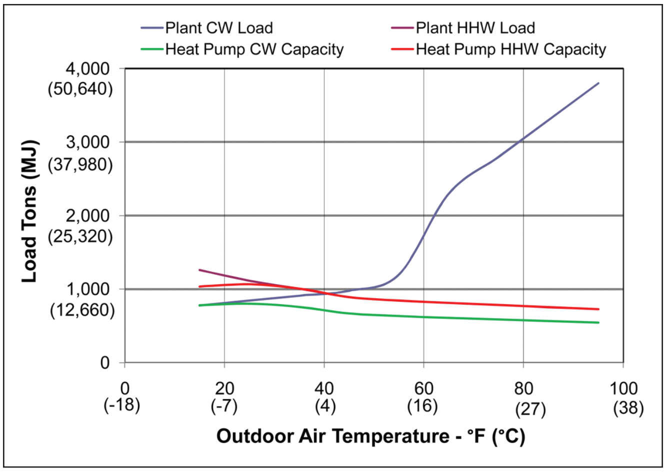


Figure 3. Plant and heat pump loads.

temperature. The more difficult task is determining coinciding process chilled water loads. One solution is to set the process load at its minimum value throughout the entire year to ensure the heat pump is not oversized. Ideally, the heat pump will be sized to handle the peak and minimum coincident loads if load profile allows. Refer to Figure 3 for the overlay of the heating hot water load, chilled water load, and associated heat pump loading for the Project.

For this particular application, the heat pump handles the entire hot water heating load as long as the outdoor temperature is above 28° F (-2°C), which for Raleigh, North Carolina area is 96% of the year. At this outdoor air temperature, the chillers handles both the entire heating hot water and chilled water load. Below this temperature, the heat pump handles the entire chilled water load. With the need for tight pressure control within the GMP spaces, economizers are not used creating the need for year round HVAC cooling, unless air temperature reset is used which may create a compliance risk.

With the exception of peak loading, the heat pump is limited in capacity by whichever load is smaller; the chilled water load or the heating hot water load plus the electric energy input into the heat pump converted to heat in the heating hot water stream. The temperature set point will be satisfied for the smaller of the two loads. For the larger load, the heat transferred will not be enough to hit set point temperature. Therefore, on the load side that is not satisfied, the temperature floats as the transfer of heat allows based on the limiting side load.

The installation increases electrical consumption to drive the heat pump and associated pumps. The additional fan and pump horsepower, due to larger heating hot water coils, needs to be accounted for as discussed previously. Power consumption is reduced to drive the main chillers and the Variable Frequency Drive (VFD) cooling tower fans. The biggest savings come from reduced natural gas consumption when boiler generated heat is replaced with heat from the heat pump. Also to be considered is the cost savings associated for the reduced tower water makeup. Water consumption is reduced by roughly 2 gallons (7.57 L) for every ton-h (12.7 MJ – h). This reduces utility water cost. Chemical treatment is also reduced somewhat, but is not included in this analysis.

Tables C through E provide the operating cost data on the standard chiller plant and the plant with an 800 ton heat pump. The cost of running those items that vary in power consumption, due to the installation of the heat pump, is totaled in the kW/Ton column. These variations include the main chillers operating at reduced load, the condenser water temperature being lowered, possible reduction of the number of condenser water pumps running, and the VFD cooling tower fans running at lower speed depending on the load. The net cost of meeting the annual load with the chilled water plant without the heat pump is $802,042 - *Table C.* For the main chillers with the heat pump, the cost drops to $492,195 annually (Table E), but the cost of running the heat pump and the associated pumps is $526,803 - *Table D.* Total electrical cost for running both the chiller and heat pump to meet the chilled water demand is $1,018,998, so the net increase in electrical operating cost with the heat pump is $216,905 annually.

One other item needs to be factored. When running with the heat pump, every ton-h (12.66 MJ-h) of cooling generated by the heat pump reduces cooling tower water make-up by 2 gallons (7.57 liters). The heat pump replaces 5,558,989 ton-h (70,376,801 MJ-h) annually, so the associated water savings is 11,117,978 gallons (42.32 ML). Water cost at the facility is

| Bin Data (Raleigh, NC) | | | 3 - 1,350 Ton VFD Chillers, Condenser Pumps, and Tower Fans | | | | | |
|---|---|---|---|---|---|---|---|---|
| Hours | DB °F (°C) | WB °F (°C) | Load Tons (MJ) | (1) KW/Ton | Electric (KW) | Mw-Hrs | Annual Cost $ | Annual Ton-h (MJ-h) |
| 119 | 90/99 (32/37) | 76 (24) | 3,800 (48,108) | 0.756 | 2,872.80 | 341.9 | $25,640 | 452,200 (5.72 X106) |
| 924 | 80/89 (27/31) | 72 (22) | 3,300 (41,778) | 0.706 | 2,329.80 | 2,152.7 | $161,455 | 3,049,200 (38.60X106) |
| 1,994 | 70/79 (21/26) | 68 (20) | 2,800 (35,448) | 0.650 | 1,820.00 | 3,629.1 | $272,181 | 5,583,200 (70.68X106) |
| 1,809 | 60/69 (16/20) | 59 (15) | 2,300 (29,118) | 0.599 | 1,377.70 | 2,492.3 | $186,919 | 4,160,700 (21.44X106) |
| 1,411 | 50/59 (10/15) | 49 (9) | 1,200 (15.192) | 0.540 | 651.60 | 919.4 | $68,956 | 1,693,200 (21.44X106) |
| 1,246 | 40/-49 (4/9) | 40 (4) | 979 (12,394) | 0.503 | 494.40 | 616.0 | $46,202 | 1,219,834 (15.44X106) |
| 904 | 30/39 (-1/3) | 31 (-1) | 912 (11,546) | 0.488 | 445.06 | 402.3 | $30,175 | 824,488 (10.44X106) |
| 310 | 20/29 (-7/-2) | 22 (-6) | 845 (10,698) | 0.470 | 397.15 | 123.1 | $9,234 | 261,950 (3.32X106) |
| 47 | 10-19 (-12/-8) | 13 (-11) | 778 (9,849) | 0.467 | 363.33 | 17.1 | $1,281 | 36,566 (462,926) |
| Notes: 1. Includes chiller, condenser water pumps (CS), and VFD cooling tower fans. | | | | | | **10,694** | **$802,042** | **17,281,298 (219X106)** |

Table C. Main VFD chiller energy cost without heat pump.

| Bin Data (Raleigh, NC) | | | | Heat Pump Data | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Load Data | | | Annual Data | | |
| Hours | DB °F (°C) | WB °F (°C) | Plant CW Tonnage (MJ) | Cooling Tons (MJ) | KW per Ton | Electric (KW) | Electric Energy (MW-Hrs) | Annual Energy Cost | Cooling Load Ton-h (MJ-h) |
| 119 | 90/99 (32/37) | 76 (24) | 3,800 (48,108) | 546 (6,912) | 1.329 | 726 | 86.4 | $6,480 | 64,974 (0.82X106) |
| 924 | 80/89 (27/31) | 72 (22) | 2,750 (34,815) | 566 (7,166) | 1.313 | 743 | 686.5 | $51,490 | 522,984 (6.62X106) |
| 1,994 | 70/79 (21/26) | 68 (20) | 1,700 (21,522) | 588 (7,444) | 1.297 | 763 | 1,521.4 | $114,107 | 1,172,472 (14.84X106) |
| 1,809 | 60/69 (16/20) | 59 (15) | 1,373 (17,382) | 610 (7,723) | 1.281 | 782 | 1,414.6 | $106,098 | 1,103,490 (13.97X106) |
| 1,411 | 50/59 (10/15) | 49 (9) | 1,046 (13,242) | 633 (8,013) | 1.266 | 801 | 1,130.2 | $84,766 | 893,163 (11.31X106) |
| 1,246 | 40/-49 (5/9) | 40 (4) | 979 (12,394) | 670 (8,482) | 1.242 | 832 | 1,036.7 | $77,750 | 834,820 (10.57X106) |
| 904 | 30/39 (-1/4) | 31 (-1) | 912 (11,546) | 755 (9,558) | 1.194 | 901 | 814.5 | $61,088 | 682,520 (8.64X106) |
| 310 | 20/29 (-7/-2) | 22 (-6) | 845 (10,698) | 800 (10,128) | 1.171 | 937 | 290.5 | $21,785 | 248,000 (3.14X106) |
| 47 | 10/19 (-12/-8) | 13 (-11) | 778 (9,849) | 778 (9,849) | 1,182 | 919 | 43.2 | $3,239 | 36,566 (462,926) |
| | | | | | | | **7,024.0** | **$526,803** | **5,558,989 (70.38X106)** |

Table D. Heat pump energy cost.

$7.35 per 1,000 gallons ($1.94 per 1,000 liters.) Annual water savings is $81,717.

For changes in heating hot water generation costs, refer to Tables F and G. With a gas fired steam boiler and a steam to hot water converter, an 82% total thermal efficiency was estimated. The annual natural gas cost to generate the heating hot water is $740,151.

The natural gas cost is only $4,230 for the system fit out with the heat pump. Reduction in natural gas consumption is significant at $735,921 annually which exceeds a 99% reduction. Note that the electrical cost of generating heating hot water was already factored in when the entire kWh consumption of the heat pump was considered with respect to when looking at the chilled water side.

Total annual utility savings is estimated at gas savings plus water savings minus additional electrical power ($735,921 + $81,717- $216,905 = $600,733).

## Economics

Savings associated with annual utility reductions is well and good, but how does this stack up against initial capital outlay and additional maintenance cost associated with the additional equipment? There are capital costs for the additional equipment and reductions for reduced sizing of other equipment. Refer to Figure 4 for capital costs associated with the modified plant design to incorporate the heat pump into the design.

Capital cost of the installation is an additional $925,000 relative to a plant without the heat pump. The heat pump will run at a minimum chilled water load of 546 tons (6,912 MJ) per Table D. Since this is the lowest load the heat pump will operate, this is the amount the main VFD chiller capacity can be reduced without impacting planned system redundancy; therefore, it is deducted from the main chiller cost.

As in the case of deducting the excess capacity from the main chiller sizing, the same can be done for the heating hot water generators. In our case, this applies to sizing of the steam boilers. The boilers can be reduced by the minimum heat pump hot water generation load when limited by capacity on the chilled water side. This corresponds to 12,432,000 Btu/hr (13,147 MJ/hr) load per Table G. Therefore, the boiler siz-

| Bin Data (Raleigh, NC) | | | 3 - 1,350 Ton VFD Chillers | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Hours | DB °F (°C) | WB °F (°C) | Load Tons (MJ) | Condenser Water Temp °F (°C) | KW/Ton | Electric (KW) | Mw-Hrs | Annual Cost $ | Annual Ton-h (MJ) |
| 119 | 90/99 (32/37) | 76 (24) | 3,254 (41,195) | 83 (28) | 0.732 | 2381.9 | 283.4 | $21,259 | 387,226 (4.90X106) |
| 924 | 80/89 (27/32) | 72 (22) | 2,734 (34,612) | 79 (26) | 0.650 | 1777.1 | 1,642.0 | $123,153 | 2,018,016 (25.55X106) |
| 1,994 | 70/79 (21/26) | 68 (20) | 2,212 (28,003) | 75 (24) | 0.540 | 1194.5 | 2,381.8 | $178,634 | 2,217,328 (28.07X106) |
| 1,809 | 60/69 (16/19) | 59 (15) | 1,690 (21,395) | 66 (19) | 0.515 | 870.4 | 1,574.5 | $118,085 | 1,380,267 (17.47X106) |
| 1,411 | 50/59 (10/15) | 49 (9) | 567 (7,178) | 60 (16) | 0.508 | 288.0 | 406.4 | $30,481 | 582,743 (7.38X106) |
| 1,246 | 40/-49 (4/9) | 40 (4) | 309 (3,912) | 60 (16) | 0.505 | 156.0 | 194.4 | $14,582 | 385,014 (4.87X106) |
| 904 | 30/39 (-1/4) | 31 (-1) | 157 (1,988) | 60 (16) | 0.517 | 81.2 | 73.4 | $5,503 | 141,928 (1.80X106) |
| 310 | 20/29 (-7/-2) | 22 (-6) | 45 (570) | 60 (16) | 0.529 | 23.8 | 7.4 | $553 | 13,950 (176,607) |
| 47 | 10/19 (-12/-7) | 13 (-11) | 0 | 60 (16) | 0.529 | 0.0 | 0.0 | $0 | 0 |
| | | | | | | | **6,563** | **$492,251** | **7,126,472 (90.2X106)** |

Table E. Main VFD chiller cost with heat pump.

| Bin Data | | Boiler Load/Plant Load Heating Hot Water | | Annual | |
|---|---|---|---|---|---|
| Hours | DB °F (°C) | MBh (MJ) | Boiler* (Dth) | Dth | Cost |
| 119 | 90/99 (32/37) | 8,710 (9.189) | 10.6 | 1264.0 | $8,532 |
| 924 | 80/89 (27/32) | 9,032 (9,529) | 11.0 | 10177.5 | $68,698 |
| 1,994 | 70/79 (21/26) | 9,389 (9,905) | 11.5 | 22831.3 | $154,111 |
| 1,809 | 60/69 (16/19) | 9,741 (10,278) | 12.5 | 22533.8 | $152,103 |
| 1,411 | 50/59 (10/15) | 10,112 (10,668) | 12.3 | 17400.0 | $117,450 |
| 1,246 | 40/-49 (4/9) | 10,685 (11,273) | 13.0 | 16236.0 | $109,593 |
| 904 | 30/39 (-1/4) | 12,056 (12,719) | 14.7 | 13293.2 | $89,729 |
| 310 | 20/29 | 13,358 (14,093) | 16.3 | 5050.0 | $34,087 |
| 47 | 10-19 | 15,112 (15,943) | 18.4 | 866.2 | $5,847 |
| MBh = 1,000 Btu/hr<br>* Boiler and heat exchanger at 82% total efficiency | | | | **109,652** | **$740,151** |

Table F. Steam plant energy cost without heat pump.

ing can be reduced 12,432,000 Btu/hr (13,147 MJ/hr) without impacting plant capacity/redundancy. Note that care must be taken to ensure the boiler capacity can handle the load with the heat pump down for redundancy purposes.

An additional annual cost to consider is maintenance associated with the heat pump. Heat pumps are more complicated than a typical chiller with higher lift so maintenance needs to be considered. Based on information obtained on the current maintenance contract, the heat pump portion of the maintenance contract is $25,000. Annual cost savings is reduced to $600,733 – $25,000 = $575,733.

*For the pharmaceutical manufacturing facility, the annual savings is $575,733 with a capital cost of $925,000 for the heat pump system. This provides a simple payback of less than 20 months. The majority of savings is associated with the more than 99% reduction in natural gas consumption. This also delivers a significant reduction in emissions.*

## Emissions Reductions

Another benefit of the heat pump is the associated reductions in emissions that inherently come with the reduction in energy consumption. From the electrical side, actual power consumption increases due to the additional power required by the heat pump to overcome the additional lift in generating the same amount of chilled water that is displaced by the lower lift main VFD chillers.

The difference in electrical energy consumption between the plant with the heat pump and the one without is 2,892 MWh referencing Tables C through E. Carbon dioxide emissions per kWh of electric generated is 1.334 lbm (0.605 kg) resulting in additional annual carbon dioxide production of 1,929 tons (1,754 metric tons).[3]

The reduction in natural gas consumption when using the heat pump verses a plant without is 109,025 Dth (115 X 106 MJ) referencing tables F and G. Carbon dioxide generated from natural gas is 120 lbm per Dth4. Based on the reduction in gas consumption, the carbon dioxide emission reduction is 6,541 tons (5,946 metric tons).

When combining the annual increase in carbon dioxide production from the additional electric consumption with the natural gas consumption reduction, the total carbon dioxide reduction is 4,612 tons (4,192 metric tons) per annum.

| Bin Data | | Total HTG Hot Water Load MBh (MJ) | HRC Heating MBh (MJ) | HHW Water Load | | Annual | |
|---|---|---|---|---|---|---|---|
| Hours | DB °F (°C) | | | MBh (MJh) | Boiler* Dth | Dth | Cost |
| 118 | 90/99 (32/37) | 8,710 (9,189) | 8,710 (9,189) | 0 | 0 | 0 | 0 |
| 924 | 80/89 (27/32) | 9,032 (9,529) | 9,032 (9,529) | 0 | 0 | 0 | 0 |
| 1,994 | 70/79 (21/26) | 9,389 (9,905) | 9,389 (9,905) | 0 | 0 | 0 | 0 |
| 1,809 | 60/69 (16/19) | 9,741 (10,276) | 9,741 (10,276) | 0 | 0 | 0 | 0 |
| 1,411 | 50/59 (10/15) | 10,112 (10,668) | 10,112 (10,668) | 0 | 0 | 0 | 0 |
| 1,246 | 40/-49 (4/9) | 10,685 (11,273) | 10,685 (11,273) | 0 | 0 | 0 | 0 |
| 904 | 30/39 (-1/4) | 12,056 (12,719) | 12,056 (12,719) | 0 | 0 | 0 | 0 |
| 310 | 20/29 | 13,358 (14,092) | 12,768 (13,470) | 1,302 (1,374) | 1.6 | 492.2 | $3,322 |
| 47 | 10-19 | 15,112 (15,943) | 12,417 (13,100) | 2,344 (2,473) | 2.9 | 134.4 | $907 |
| *Boiler plus HX at total 82% efficiency.<br>MBh = 1,000 Btu/hr | | | | | | **626.6** | **$4,230** |

Table G. Steam plant energy cost with heat pump.

## Special Design Issues

There are various design issues associated with the heat pump application that need to be given serious consideration that are not typical of plant design without a heat pump. Some of which are listed here:

1. Proper sizing of the heat pump looking at coincident chilled water and heating hot water load on an annual basis
2. Main chiller evaporator barrels need to be sized to accept the additional flow associated with a running heat pump and a lower delta-T across the main chiller(s).
3. Main chiller evaporator barrels are not so oversized as to adversely impact allowable minimum flow when installed in a primary variable pumping system.
4. Maintaining main heating plant in ready condition when in prolonged idle periods
5. Control valve/boiler sizing taking into consideration very low loading when heat pump is on relative to the entire design load with the heat pump off.
6. Time required starting the main chiller if the heat pump is carrying the entire chilled water load and the heat pump fails.
7. Consider summer demand charges and rate structure.
8. Proper control and sequence development
9. Provide means for start-up, testing and commissioning.

Proper sizing of the heat pump is critical to both operation and the economics. Not every central plant is a candidate for a heat pump installation. A coincident heating hot water and chilled water load is required. The heat pump pulls heat from the returning chilled water system and delivers it to the heating hot water side of the plant. Both demands are required simultaneously to make the installation of a heat pump applicable. Some means of determining both the heating hot water and chilled water load for a typical load cycle, which more often than not is on a yearly basis to capture all the seasonal HVAC loads. Once the loads are determined, they need to be overlaid to start the process of sizing the heat pump. Each application must be developed based on the required economic payback, utility cost structure, heat pump efficiency and performance constraints, and heating and chilled water demand overlay.

Not properly sizing the main condenser chiller barrels for the expected full flow rate when the heat pump is in operation can be an expensive error. When the heat pump is in operation, the main chillers see less than design delta-T through the barrel due to the lower return chilled water temperature being delivered from the running heat pump. If the main chillers are not sized for this additional flow, the plant capacity will be limited to the flow that can pass though the main chillers and the sequence of operations and associated controls will become more complicated to overcome this issue.

However, care must be taken as to not oversize the barrel so much that the flow through a VFD driven chiller cannot be reduced at low loads. If this is missed, savings from VFD pumping will be adversely impacted.

The installation of a heat pump can cause long periods when the main heating plant has no load. This is especially true for installations where HVAC demands require high levels of dehumidification or there are sizable process loads that are continuous. Consideration needs to be given to the type of heating plant and how to maintain it in a "ready" state to pick up load when the heat pump capacity cannot handle the load. In addition, heat pump failure needs to be considered as to how quickly the main heating plant can convert from standby to active temperature control in a short period of time. For the Novartis project, the steam valves were always charged and the heating hot water was always passing through the steam to heating hot water heat exchanger to keep it in ready standby.

The main heating plant may need to run at very low loads, due to the load carrying capacity of the heat pump. The main plant also needs to be sized for the full system load, should the heat pump be out of service. Consideration needs to be given as to how the system capacity control will adequately provide for both large and small heating hot water loading. For the Novartis project, the steam control valves of several sizes were provided in parallel feeding the steam to hot water heat exchanger to allow for wide ranges in load control without excessive hunting or control valve wear.

Chilled water temperatures can fall out of acceptable range if the heat pump is carrying the entire chilled water load and the heat pump fails. The heat pump carrying the entire plant load translates into the main chillers being off line. Can the process or HVAC accept this loss in chilled water flow while one of the main chillers is converting from standby to active operation? Time is required to go through the start sequence for one of the main chillers. This same problem also exists if the plant is running with just one chiller online without the heat pump. Another important consideration is that heat pump reliability is not as good as that of a chiller and needs consideration. Novartis decided that they could not accept this loss of chilled water. To resolve this issue, the sequence was written such that the heat pump will automatically adjust load when needed to ensure a main VFD chiller stays on line. If the load drops to a level where both the main chiller and heat pump cannot stay on line, due to minimum load constraints, the heat pump shuts down. Load analysis indicates that this should not occur, but it was programmed in since the load profiles were modeled and not from actual load data.

**Capital Cost Variance with 800 Ton Heat Pump**

| Item | Cost/variance |
|---|---|
| 800 Ton (10,128 MJ) Heat Pump | $660,000 |
| Heating/Hot Water Pumps for Heat Pump | $76,000 |
| Associated Piping for Heat Pump | $194000 |
| Electrical Power/Control | $70,000 |
| Engineering | $75,000 |
| Start-Up/Commissioning | $75,000 |
| 500 ton (6,330 MJ) main chillers size reduction | -$150,000 |
| 12,400,000 Btuh reduction in heating plant | -$75,000 |
| **Total Capital Cost Increase** | **$925,000** |

Figure 4. Capital cost variance with 800 ton heat pump.

For simplicity, a blended annual electrical rate was listed in this article to show potential savings and economics of a heat pump installation. Using a blended rate is acceptable for the analysis, but variation in electric utility rates should be reviewed. As an example, demand charges can be substantial in summer. The additional power consumption associated with the heat pump system minus the reduced electrical load on the main chillers, condenser water pumps and tower fans need to be reviewed against actual "point in time" electric and natural gas costs to ensure that it makes sense to run the heat pump when electric rates are high. For the Novartis project, there was not a time the electrical rates where high enough to justify shutting down the heat pump.

Serious consideration needs to be given as to how the heat pump system will be controlled. The interaction of the heat pump needs to be considered for all loads, including all failure scenarios.

Start-up and testing of the heat pump can be challenging if not planned in advance. There needs to be enough simultaneous Heating Hot Water (HHW) and chilled water load to run the system. This can be a difficult hurdle in a plant start-up situation. The heat pump can be installed with cross connecting piping from/to the HHW and chilled water side of the unit to allow for false loading. Flow elements and temperature sensing devices are also needed to determine actual unit loading and for calculating unit efficiency verses manufacturers published data.

## Conclusion

A heat pump can be a very effective means of lowering natural gas consumption. The analysis of both heating hot water and coincident chilled water load is essential to justifying the economics and properly sizing the heat pump. The installation of a heat pump requires acceptance of lower than industry standard heating hot water temperatures to allow cost effective installation. Resistance, by both designers and operators, to lower heating hot water temperatures based on increased energy consumption, due to greater airside and water side pressure drops around the HVAC heating coils is unfounded. If a heat pump is properly sized, selected, and a well thought out sequence is developed, the annual savings can be significant. The economics of first cost verses annual savings can be very attractive along with the reduced emissions as compared to a central plant installed without a heat pump.

## References

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4. U.S. Environmental Protection Agency, October, 2009, AP 42, Fifth Edition, Volume 1, Compilation of Air Emissions Factors, Volume 1, Stationary Point and Area Sources, Chapter1, Section 1.4, Natural Gas Combustion, page 1.4-6.

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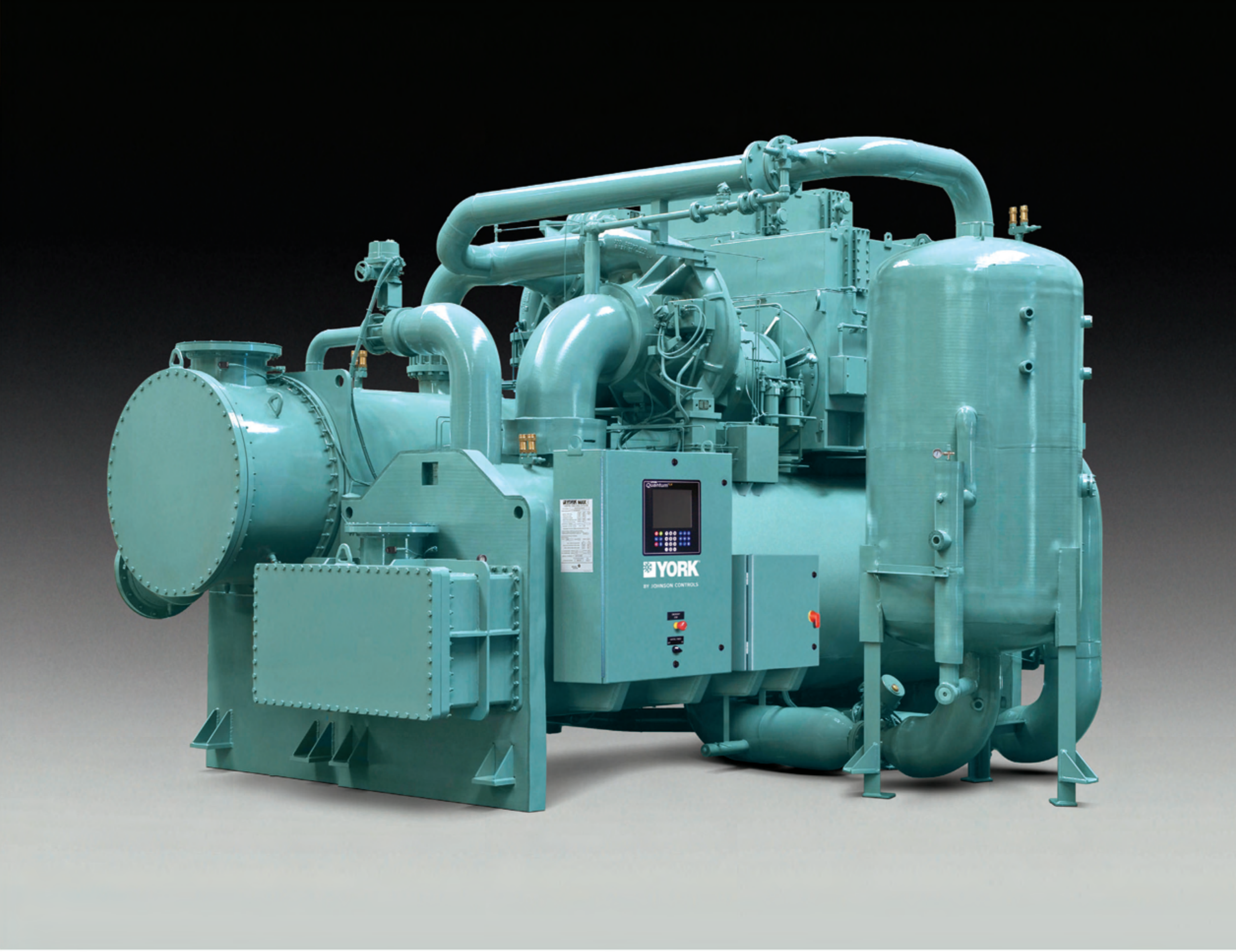


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