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Electrified Water-Source Heat Pump (eWSHP) Systems

Water-source heat pump (WSHP) systems are available in several configurations, with varying installed costs and performance levels. Historically, system designs seeking to lower CO2e emissions typically used the ground as a heat source/sink. Today, new technologies have enabled alternative system configurations. This *Engineers Newsletter* will examine and compare several different "electrified" WSHP system configurations.

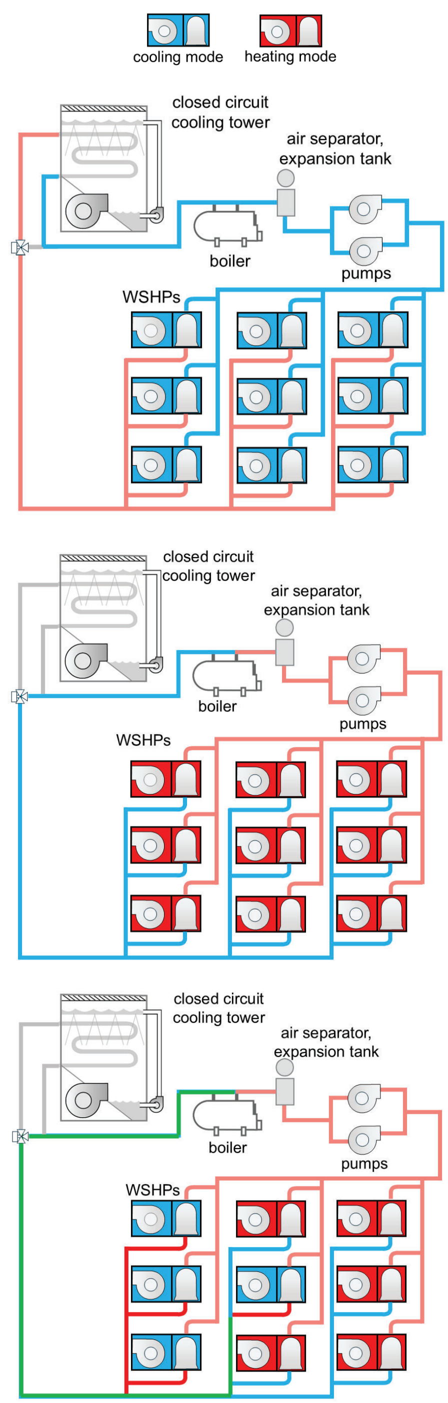
Traditional Water-Source Heat Pump Systems

WSHP systems are comprised of the following elements. (Details about WSHP systems can be found in Trane application manual SYS-APM010*-EN, *Water-Source and Ground-Source Heat Pump Systems*.)

- Multiple water-source heat pump units, each installed at the zone level
- A common water loop that provides a heat source or heat sink for the WSHP units
- A heat *rejection* device, such as a cooling tower, that removes heat from the common water loop in cooling dominant operation.
- A heat *addition* device, such as a boiler, that adds heat to the common water loop in heating dominant operation
- A control system that maintains the common water loop temperature within limits by activating the heat rejection and heat addition devices

A key benefit of WSHP systems is the ability to recover heat. Zones in cooling mode reject heat to the shared water loop, which is used as a source of heat for zones in heating mode. Heat recovery operation reduces demand on cooling towers and boilers, making the system more efficient.

Figure 1. Traditional WSHP system in cooling mode (top), heating mode (middle), heating dominant and recovering heat (bottom)



Terminology

Water-source heat pump (WSHP) unit: terminal unit that heats or cools a space using refrigerant compression.

WSHP system: consists of multiple WSHP units connected to a shared water loop that provides a heat sink and heat source.

Electrified WSHP system: WSHP system that does not use a gas boiler. This EN considers replacement of boilers with an air-to-water heat pump.

Air-to-water heat pump (AWHP): refrigerant compression device that heats a water loop, using ambient air as a source of heat. AWHPs can also operate in cooling mode with the use of a refrigerant reversing valve.

Water loop: hydronic loop that is piped to the individual WSHP units and includes a means for heat addition and heat rejection, depending on operating conditions.

Note: ASHRAE® calls this "Water loop heat pump application". Often it's also referred to as a "hybrid heating/cooling loop" or "ambient loop".

In this EN, we need to differentiate between the distribution and production sides of the water loop.

Distribution loop: part of the water loop that connects to WSHPs.

Production loop: part of the water loop that connects to cooling tower, boiler, or AWHP

Cooling dominant: when more WSHP capacity is used for cooling than heating. Heat must be rejected from the water loop by a cooling tower or AWHP in cooling mode.

Heating dominant: when more WSHP capacity is used for heating than cooling. Heat must be added to the shared water loop by a boiler or AWHP in heating mode.

Electrified Water-Source Heat Pump System

Air-to-water heat pumps (AWHPs) may be used as both heat rejection devices and heat addition devices, replacing cooling towers and/or fossil-fuel boilers. Electrified WSHP systems offer reduced on-site CO2e emissions (by replacing fossil fuel boilers) and reduced water usage (by replacing evaporative cooling towers).

Figure 2 shows a conceptual diagram for an electrified WSHP system. The remainder of this EN is focused on design details that may arise when converting WSHP systems to "electrified" WSHP systems.

Capacity Sizing of Air-to-Water Heat Pumps

Trane application manual SYS-APM010*-EN provides detailed guidance for sizing the cooling tower and boiler:

The **boiler** is sized for the "heat extraction" value of WSHPs.

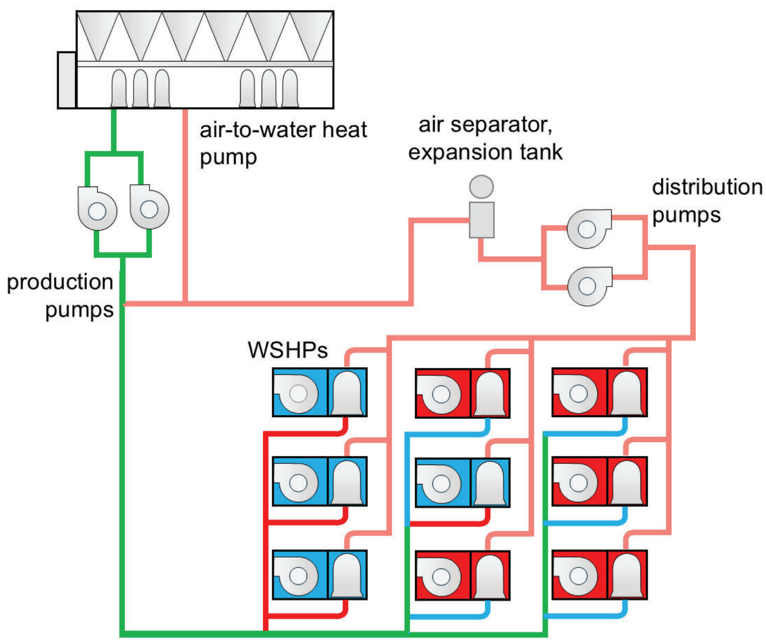
- If night setback is used, size the boiler for the sum of all WSHPs since they may all operate at rated heating capacity during morning warmup mode.
- If night setback is not used, the boiler size may be reduced by using load analysis software to determine the peak heating load.
- Additional reduction in boiler capacity may be achieved by considering other heat sources, such as computer room equipment, or by adding hot water storage tanks.

The **cooling tower** is sized for "heat rejection" value of WSHPs

- Start by adding heat rejection values for all WSHPs, then apply a "load diversity factor." The 2024 ASHRAE Handbook for HVAC Systems and Equipment (page 9.21) defines load diversity as "the maximum instantaneous cooling load of the building divided by the installed cooling capacity".

For an electrified WSHP system, the amount of heat extraction and heat rejection from WSHP units to the water loop is the same as in a traditional WSHP system. Therefore, the sizing criteria described in the Trane application manual can also be used to size the AWHP(s) in an electrified WSHP system. AWHP sizing should use manufacturer's selection software that also considers defrost and ambient temperature limitations. Auxiliary boilers should be considered if design day ambient temperatures are below AWHP operational limits.

Figure 2. Conceptual diagram of an electrified WSHP system in *heating dominant* mode



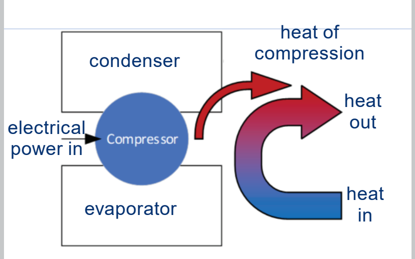
Heat of Compression

Heat pumps move heat from the evaporator to the condenser. The energy required to move heat adds to the condenser's capacity. This is called "heat of compression."

In cooling mode, the heat rejected to the water loop is equal to the heat removed from the space plus the heat of compression.
In heating mode, the heat pulled out of the water loop plus the heat of compression makes up the heat that is supplied to the space.

Heat addition devices and heat rejection devices must be sized for the amount of heat that WSHPs reject to and pull out of the water loop. WSHP product data sheets often label these values "heat rejection" and "heat absorption".

Some water-source heat pumps on the market are non-reversable. They achieve cooling with standard refrigerant cycle but rely on a direct water-to-air coil for heating. This means that heat of compression applies in cooling mode, but not in heating mode.
It also requires the water loop to operate at higher temperatures (e.g., >120°F) in heating mode.



Loop Temperature Control

Requirements for WSHP distribution loop temperature control are prescribed in ASHRAE® Standard 90.1, Section 6.5.2.2.3 (see excerpt below). This section includes a requirement for a temperature deadband between initiation of heat addition and heat rejection. The deadband ensures that the tower and boiler will not operate simultaneously and improves heat recovery potential in the system by allowing loop temperatures to drift.

> ***6.5.2.2.3 Hydronic (Water Loop) Heat Pump Systems.*** *Hydronic heat pumps connected to a common heat-pump water loop with central devices for heat rejection (e.g., cooling tower) and heat addition (e.g., boiler) shall have the following:*
>
> *a. Controls that are capable of and configured to provide a heat-pump water supply temperature dead band of at least 20°F between initiation of heat rejection and heat addition by the central devices (e.g., tower and boiler).*
>
> *b. For Climate Zones 3 through 8, if a closed-circuit cooling tower (fluid cooler) is used, either an automatic valve shall be installed to bypass all but a minimal flow of water around the tower (for freeze protection) or low-leakage positive closure dampers shall be provided. If an open-circuit cooling tower is used directly in the heat-pump loop, an automatic valve shall be installed to bypass all heat-pump water flow around the tower. If an open-circuit cooling tower is used in conjunction with a separate heat exchanger to isolate the tower from the heat-pump loop, then heat loss shall be controlled by shutting down the circulation pump on the cooling tower loop.*
>
> *Exception to 6.5.2.2.3: Where a system loop temperature optimization controller is used to determine the most efficient operating temperature based on real-time conditions of demand and capacity, dead bands of less than 20°F shall be allowed.*

These requirements were originally developed for traditional tower/boiler WSHP systems and may not have fully anticipated the use of electrified WSHP systems. Nevertheless, these requirements can still serve as a valuable framework for designing electrified WSHP systems. Understanding these temperature differentials is essential for effectively adapting the Standard 90.1 requirements to the design and implementation of electrified WSHP systems.

A critical distinction to note is that AWHPs typically heat water to supply temperatures ranging from 105°F to 140°F (Table 1). In contrast, traditional WSHP systems enable heat addition at a significantly lower temperature, approximately 60°F. Similarly, AWHPs typically cool water to a supply temperature of around 44°F, whereas traditional WSHP systems enable heat rejection at about 90°F.

Allowable heating and cooling setpoint temperatures for an AWHP differ from one product to the next. Based on the example products listed in Table 2, there may not be enough overlap in the heating and cooling setpoint values to achieve the 20°F deadband requirement in Standard 90.1.

Since the deadband requirement is based on "initiation of heat addition or rejection," we do not need 20°F of setpoint overlap. Instead, we need 20°F difference between when the AWHP starts in heating mode versus in cooling mode. The following terminology is used for defining the loop temperature control:

- **Heating (cooling) setpoint:** The temperature that equipment controller attempts to maintain during operation. Heat pump capacity is modulated in order to achieve this value.
- **Differential to start:** The threshold for how far the operating temperature may deviate from setpoint before the heat pump starts.
- **Differential to stop:** The threshold for how far a heat pump may overshoot setpoint before it shuts off.
- **Initiate heating/cooling:** The temperature at which the heat pump turns on. This value may be used directly to enable equipment, or it may be the result of a setpoint value and differential to start.
- **Terminate heating/cooling:** The temperature at which the heat pump turns off. This value may be used directly to disable equipment, or it may be the result of setpoint value and differential to stop.
- **Setpoint overlap:** Common setpoint temperature values that are allowed as both heating setpoints and cooling setpoints.

Electrified WSHP loop temperature control must be configured to achieve the following outcomes. Table 3 illustrates electrified WSHP loop temperature control with these criteria and varying amounts of AWHP setpoint overlap.

1. At least a 20°F difference between the initiation of heating and initiation of cooling.
2. Terminate heating temperature must be lower than the Initiate cooling temperature.
   - Table 3 uses a minimum of 5°F between terminate heating and initiate cooling.
3. Terminate cooling temperature must be higher than the Initiate heating temperature.
   - Table 3 uses a minimum of 5°F between terminate cooling and initiate heating.
4. Heating and cooling setpoints within the allowable range for the specific equipment.

Table 1. Temperature comparison of traditional WSHP systems versus typical AWHP application

Operating mode	Traditional WSHP system	Typical AWHP application
Heating	~60°F (enable boiler)	~120°F (hot-water supply temperature)
Cooling	~90°F (enable cooling tower)	~44°F (chilled-water supply temperature)

Table 2. AWHP setpoint values for heating and cooling mode

Heating setpoint values	Cooling setpoint values	Heating/cooling setpoint overlap	Amount of setpoint overlap
50°F to 140°F	20°F to 75°F	50°F to 75°F	>20°F
55°F to 140°F	20°F to 65°F	55°F to 65°F	<20°F
75°F to 140°F	20°F to 65°F	n/a	no overlap

Table 3. Example setpoint values for electrified WSHP systems

Amount of setpoint overlap	Initiate heating	Heating setpoint	Terminate heating	Initiate cooling	Cooling setpoint	Terminate cooling
>20°F	48°F	50°F	55°F	77°F	75°F	70°F
<20°F	53°F	55°F	60°F	73°F	65°F	60°F
no overlap	58°F	75°F	77°F	82°F	65°F	63°F

Efficiency and Water Usage Considerations

Compressor power draw is proportional to lift (the temperature difference between condenser and evaporator). System efficiency is related to the total system lift, which is split between AWHP and WSHP units (Figure 3). When the loop temperature changes, the lift values shift from AWHP to WSHP, but the combined system lift is unchanged. Therefore, the water loop temperature does not directly affect system efficiency, it only affects which compressors draw more power.

When retrofitting a traditional WSHP system to be an electrified WSHP system, it may be necessary to consider changes in system efficiency. In heating mode, the electrified WSHP system will achieve higher COP values due to replacing a boiler with a heat pump. In cooling mode, the system efficiency will be lower because the AWHP requires more electrical power than a cooling tower.

The total system efficiency is inversely proportional to system lift. Figure 4 illustrates the difference in system lift for a traditional WSHP system (rejects heat to the ambient wet-bulb temperature using an evaporative cooling tower) versus an electrified WSHP system (rejects heat to the ambient dry-bulb temperature using an air-cooled condenser in the AWHP).

Cooling towers require substantial amounts of makeup water due to evaporation loss, as well as "blowdown" operation (draining of cooling tower water to manage chemistry and impurities). Cooling tower water usage is eliminated in an electrified WSHP system.

Figure 3. Compressor lift in an electrified WSHP system

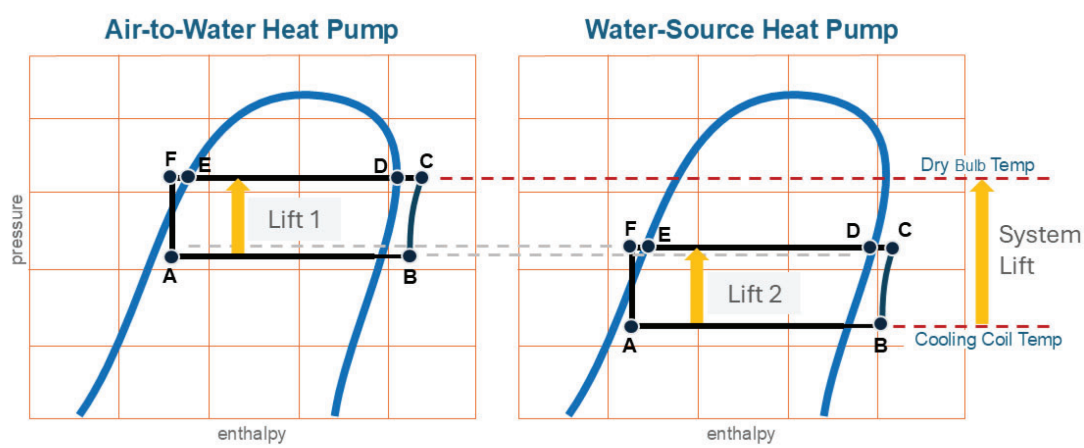
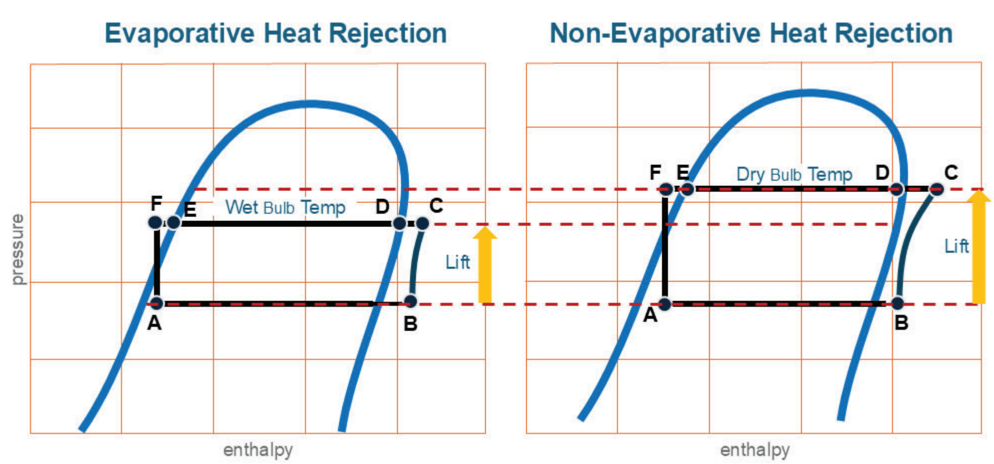


Figure 4. Lift comparison for traditional WSHP system vs. electrified WSHP system



Pumping and Flow Management

The electrified WSHP system includes a production loop connected to AWHPs and a distribution loop connected to the WSHPs. Figure 5 shows a decoupled pumping arrangement where P-1(x) are the distribution loop pumps, and P-2(x) are the production loop pumps.

The production and distribution loops are hydraulically separated, allowing their individual flow rates to differ, and therefore be optimized to reliably and stably meet the operating requirements of the AWHPs at any load point. This is particularly important in this electrified WSHP system for the following reasons:

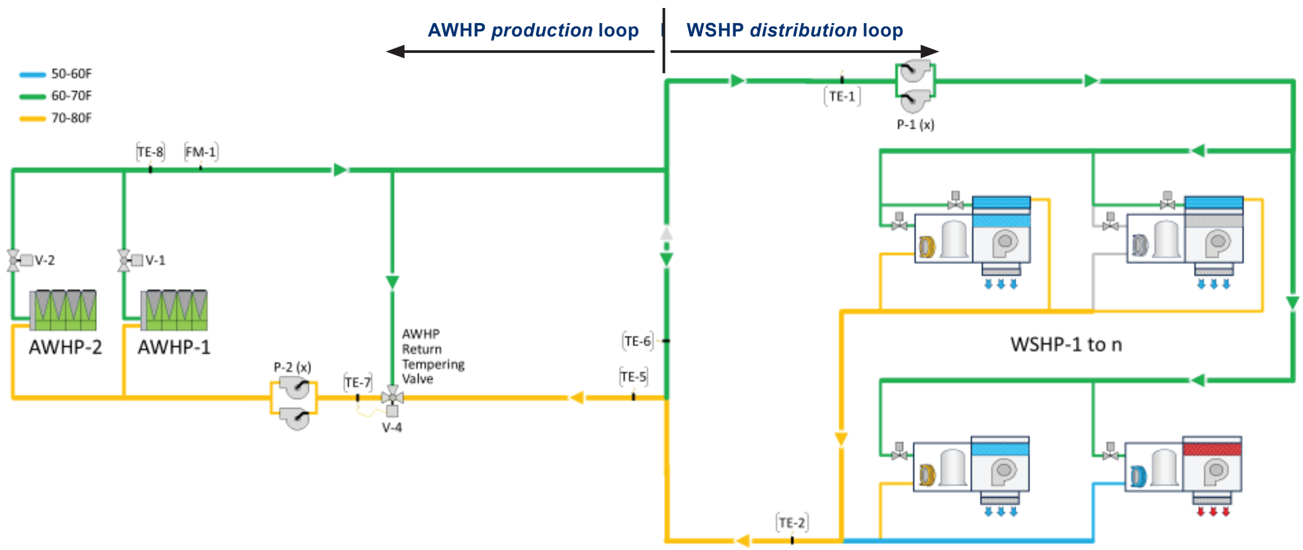
- There will be a wide range of flow rates in the distribution loop, from very low to full design flow.
- The AWHPs likely allow for a relatively narrow range of flow rates in the production loop, particularly in heating mode, depending on how many units are operating at any point in time.
- There may be two different design flow rates for the AWHPs, one for the heating mode and a different flow rate for cooling mode.
- The design flow rates for an AWHP may be near its minimum allowable flow rate, prohibiting or limiting reduced (variable) flow. This is particularly likely in heating mode.

The distribution pumps may be controlled as constant flow or variable flow. Trane application manual SYS-APM010*-EN provides more details about these two pumping configurations. The distribution loop in Figure 5 is configured as variable flow, with pump speed controlled to maintain a constant distribution loop supply pressure.

Production loop pumps are controlled to maintain design flow rate through the AWHPs. Design flow rate for AWHPs is typically different in heating mode versus cooling mode. Pumps may be operated with one speed for heating mode and another speed for cooling mode. Or the pumps may be left at the higher flow rate value (typically cooling mode flow rate). If dual-speed pump control is used, ensure that pump selections can achieve the full range of flow rates. Trane application guide SYS-APG003*-EN, *Air-to-Water Heat Pump System with Cascade Option*, provides more details about pump control for AWHPs. The production loop in Figure 5 is configured for constant flow, with separate pump speeds for heating mode and cooling mode.

AWHP tempering valve V-4 provides for recirculation of AWHP leaving fluid to keep the AWHP entering/leaving water temperature within the acceptable range when the production loop return temperature is unacceptably high or low.

Figure 5. Basic electrified WSHP system diagram



Optional System Features

Figure 6 depicts several optional features that could be added to this electrified WSHP system.

Dry coolers may be added to the system to reject heat directly to the atmosphere, without needing to operate the AWHPs. Closed-circuit cooling towers may also be used to improve annualized system efficiency by reducing the combined system lift (rejecting heat to the ambient wet-bulb temperature instead of dry-bulb temperature). For a building with a peak cooling load higher than the peak heating load, this may reduce the system installed cost by reducing the required AWHP capacity.

Diverting valve V-6 in Figure 6 can be positioned to send distribution loop flow through the dry cooler. The dry cooler could also be piped with its own separate pump(s).

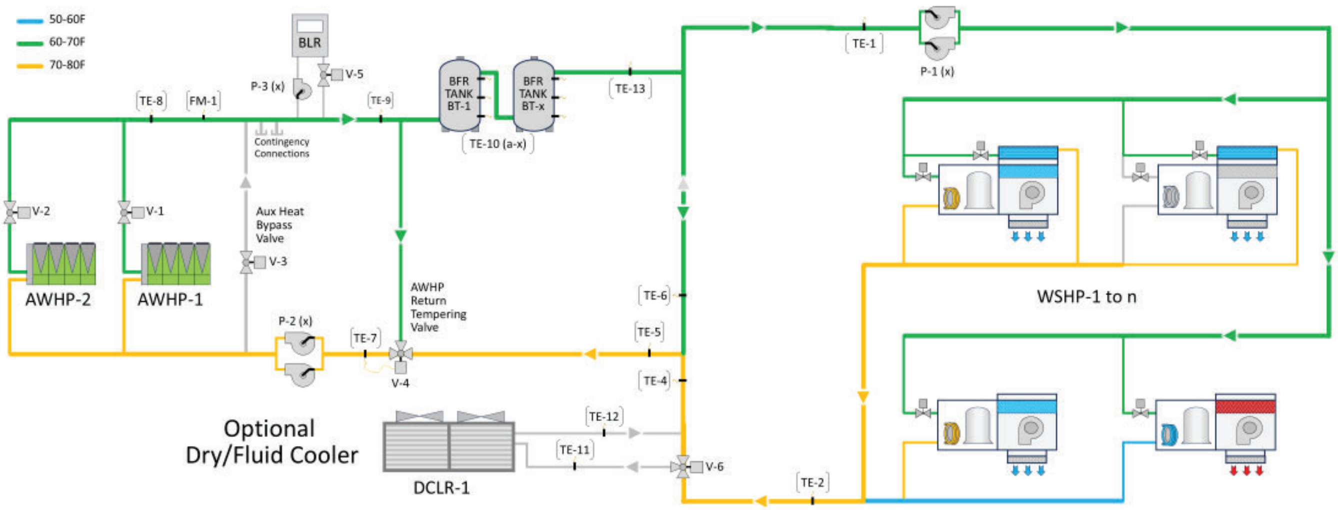
Auxiliary or backup boilers may be used to add heat to the water loop, satisfying high peak heating loads without needing to size AWHPs for peak load. In many cases, AWHPs sized for half of the peak heating load can still satisfy the majority of heating hours in a year, maybe as much as 90 percent of the hours.

Backup boilers are also needed if the design ambient temperature is lower than the AWHP temperature rating (see “Capacity sizing of Air to Water Heat Pumps” p.2).

Waterside economizers may be added to the WSHP units, enabling direct cooling of air from the water loop (WSHP compressor is turned off). The WSHP unit controller positions valves to direct water flow through the waterside economizer coil, which is located upstream of the water-to-refrigerant HX, based on the water loop temperature and a threshold temperature value.

Buffer tanks may be added to ensure adequate system volume (see “Operational Considerations” p.7).

Figure 6. Electrified WSHP system diagram with optional features



Operational Considerations

Defrost Operation of AWHPs

Frost may build up on the outdoor coil of an AWHP when the ambient temperature is 47°F or lower. Defrost mode melts this frost by temporarily reversing the refrigeration cycle, which causes the outdoor coil to heat up. The defrost cycle takes about 5 minutes. During this time, the hot-water supply temperature setpoint may not be met.

Fortunately, WSHPs are designed to handle a wide range of entering water temperatures. Many WSHPs can operate in heating mode with an entering water temperature of 30°F or below. Consult the manufacturer's product data sheet for operational limitations.

Loop Volume

The minimum loop volume for an AWHP system is based on limiting disturbances to the hot-water supply temperature during defrost mode. Consult the manufacturer's recommendations or Trane application guide SYS-APG003*-EN for detailed calculations of minimum loop volume.

A good rule-of-thumb is to ensure that the loop time is longer than the defrost time of 5 minutes. The loop time value is calculated as loop volume divided by design flow rate. For systems that use multiple AWHPs, use the design flow rate of one AWHP unit (assuming that only one AWHP will be in defrost mode at any given time).

Antifreeze/Glycol

This system fluid will require a minimum of 25 percent glycol concentration because the AWHP must continue operating during cold winter, unlike a cooling tower that could be drained. Higher concentrations may be required depending on the expected winter outdoor air temperatures and other system design features.

Note that the antifreeze concentration in an electrified WSHP system may need to be sufficient to provide full fluid "freeze" protection. A lower concentration that provides only "burst" protection will impede system pumping and heating operation.

The volume of glycol in the system can be reduced by placing a heat exchanger between the indoor distribution loop and the outdoor production loop. This heat exchanger would also decouple flow between production and distribution loops, providing greater operating stability. The tradeoffs are the added equipment cost of the heat exchanger and lower system efficiency due to added pumping energy and approach temperature of the heat exchanger.

Conclusion

WSHP systems can be "electrified" by replacing fossil-fuel boilers and cooling towers with AWHPs. Electrified WSHP systems reduce on-site CO2 emissions and water usage compared to traditional WSHP systems.

This *Engineers Newsletter* addressed design considerations for electrified WSHP systems, including the following:

- Sizing of AWHPs
- Loop temperature control, including ASHRAE 90.1 deadband requirements
- Pumping strategies
- Efficiency and water use considerations
- Optional system features, such as dry coolers, auxiliary/backup boilers, waterside economizers, and buffer tanks
- Operational considerations, such as defrost mode, loop volume, and glycol

By Ben Sykora, applications engineer, Trane. You can find this and previous issues of the Engineers Newsletter at www.trane.com/EN. To comment, send e-mail to ENL@trane.com.

References

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Trane *Air-to-Water Heat Pump System with Cascade Option* application guide SYS-APG003*-EN.

Trane *Thermal Battery™ Storage Source Heat Pump Systems* application guide APP-APG022*-EN.

ASHRAE® Standard 90.1-2022: "Energy Standard for Sites and Buildings except Low-Rise Residential Buildings".

ASHRAE 2024 Handbook: "HVAC Systems and Equipment", chapter 9 "Applied Heat Pump and Heat Recovery Systems".

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