Application Guide

Electrifying Retrofit HVAC Systems

⚠SAFETY WARNING

Only qualified personnel should install and service the equipment. The installation, starting up, and servicing of heating, ventilating, and air-conditioning equipment can be hazardous and requires specific knowledge and training. Improperly installed, adjusted or altered equipment by an unqualified person could result in death or serious injury. When working on the equipment, observe all precautions in the literature and on the tags, stickers, and labels that are attached to the equipment.

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Preface

As a leading HVAC manufacturer, we deem it our responsibility to serve the building industry by regularly disseminating information that promotes the effective application of building comfort systems. For that reason, we regularly publish educational materials, such as this one, to share information gathered from laboratory research, testing programs, and practical experience.

This publication focuses on a holistic approach to electrification by starting with the fundamentals of electrified heating systems. It provides guidance for assessing the current state of an existing building—not limited to the HVAC system. Selection of the appropriate heat pump system is highly variable and depends on many factors.

We encourage engineering professionals who design building comfort systems to become familiar with the contents of this guide and to use it as a reference. Architects, building owners, equipment operators, and technicians may also find this publication of interest because it addresses system layout and control.

Trane® has a policy of continuous product and product data improvements and reserves the right to change design and specifications without notice. As such all data in this application guide should be considered for reference only, please consult with a Trane® sales associate for current equipment operating range and performance.

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Overview

Introduction

This manual is intended to provide guidance for design professionals tasked with electrification projects within existing buildings. It is organized into sections to help readers quickly find relevant information.

This manual takes a holistic approach to electrification, beginning with the fundamentals of electrified heating systems. Next, it provides guidance for assessing an existing building's current state—not limited to the HVAC system. Selecting the right heat pump system is highly variable and depends on many factors.

Architectural concerns and risk reduction are topics not often covered in existing literature today. Case studies are included to share outcomes and lessons learned. Even a well-designed system will not perform as expected if it is not properly maintained.

Cost of ownership and return on investment are factors that will be considered when the project budget is under scrutiny. Finally, the manual will address operation and control.

What are heat pumps and why are they beneficial?

A heat pump is generally defined as a refrigeration unit that produces heated fluid (either air or water) and also provides cooled fluid. Traditionally, the HVAC industry has considered a heat pump to be a unit with a reversible refrigeration circuit. In the context of this manual, the term "heat pump" may also refer to a non-reversible heat pump (i.e. a chiller or heat pump chiller) from which heat may be recovered. The HVAC industry has used chillers for decades to remove heat from buildings and processes. In typical cooling applications, this heat is rejected to the atmosphere; however, the same technology can be used to recover and repurpose the heat rather than discard it.

Commercial heat pumps provide cooling and heating using the vapor-compression cycle. The components include an evaporator, condenser, compressor, and expansion device. The technology used within any given piece of equipment varies. For further detail on vapor-compression refrigeration systems, refer to the Trane "Refrigeration Cycle" *Air Conditioning Clinic* (TRG-TRC003-EN).[22]

There are benefits to using heat pumps instead of traditional heat sources such as boilers or electric resistance heaters. Decarbonization is driving the design of HVAC systems in many locales, often through regulatory requirements. As a result, the use of natural gas or other fossil fuels to heat a building is to be avoided, or possibly even prohibited.

Coefficient of Performance (COP) is a dimensionless ratio of useful heat supplied (or removed) divided by the energy input. In heat-recovery applications, COP includes both the useful heating output and cooling output.

In addition, when compared with a gas boiler, heating efficiency can be significantly improved. A gas boiler may have a Coefficient of Performance (COP) in the range of 0.8 to 0.95. In contrast, heat pumps—reversible or non-reversible—often have a COP as high as 4.0 or 5.0, depending on operating conditions. Heat-recovery units may even achieve COP values of 7.0 or higher. The heating COP of a heat pump is always greater than its cooling COP due to the heat of compression. This is the heat transferred from the compressor to the compressed refrigerant, which is in turn transferred to the fluid being heated (or rejected).

Heat pumps are very beneficial in decarbonization efforts because they use electricity for heating and achieve high COPs. Additionally, reversible heat pumps may offer opportunities for installed cost savings, especially as the technology becomes more widely available, since they can provide both cooling and heating with the same piece of equipment.

A heat pump must get heat from a source. That source of heat may be from building or process cooling loads, a process commonly referred to as heat recovery. Heat recovery is very efficient, because heat removed from one location is reused elsewhere. Common uses of recovered heat include:

- Reheat
- Outdoor air (OA) preheat
- Industrial or commercial processes
- Service water heating
- Potable water heating or preheat

Although not limited to water-source equipment, heat recovery is frequently applied in such systems.

Air-source equipment uses ambient air to source heat. This equipment is most often placed outside of a building or on rooftops. The compressor in the unit sources heat energy from the ambient air and increases its temperature through the vapor-compressor cycle.

Ground-source equipment may either source or reject heat to a ground loop. The loop may connect to heat exchangers in the ground, such as those used in a geothermal system. Other configurations may use heat exchangers placed in bodies of water (lakes and rivers) or in aquifers. Regulations on water removed from these sources vary, so it is important that the designer is in early contact with regulatory officials to ensure a project's success.

Each type of equipment has performance and application limitations. The designer must ensure this is reviewed whenever equipment is selected for a project.

How do heat pumps work and what are their key performance characteristics?

A reversible heat pump is capable of changing the direction of refrigerant flow through the components of the vapor-compression cycle, reversing the function of the evaporator and condenser heat exchangers. Both air- and water-source equipment are available, producing either heated air or fluid. For more information on heat pumps, refer to the Trane Air Conditioning Clinic, *Water-Source Heat Pump Systems*, TRG-TRC015-EN.[25]

Location of components

In a hydronic heating system, pumps are often placed in a mechanical room. Their purpose is to create pressure to move fluid to where it is needed, typically a coil or other load. These coils may be located within air handlers—which may be large if air is ducted throughout a building. For example, a dedicated outdoor air system (DOAS) may be used to heat large volumes of outdoor air, which is then ducted to terminal units or directly to the building spaces. Localized coils may be used to reheat the supply volume of air at terminal units, as in a VAV reheat system. Alternatively, fan coils and unit ventilators may receive heated fluid and to heat air that is either recirculated or drawn into a space.

Like the hydronic system, fans are used to move air throughout the building. A large air handler or local units may have smaller fans dedicated to the zone or zones served.

Ductwork

Heat pump installation depends on the type of equipment installed. A water-to-water heat pump may function as a water-cooled chiller that is operating in heating mode. These units are typically installed indoors. An air-to-water heat pump is a unit that sources heat from ambient air to heat the fluid circulated in the unit, and these units are usually installed outside.

However, there may be installations in which equipment normally located outdoors is instead installed inside. This may be due to outdoor space constraints, noise considerations, or architectural or landscape design. In these circumstances, ducting is used to bring in outdoor air to maintain temperatures near the ambient conditions or to modulate the operational ambient temperature around the unit.

A heat pump operating in heating mode will lower the ambient temperature as it cools the air at its air coil. This may be undesirable inside the space because, although the unit's function is to provide heat, it can create a need to heat the area where the equipment is located. Therefore, air may be ducted into and out of the space in which the heat pump is installed.

Operational characteristics

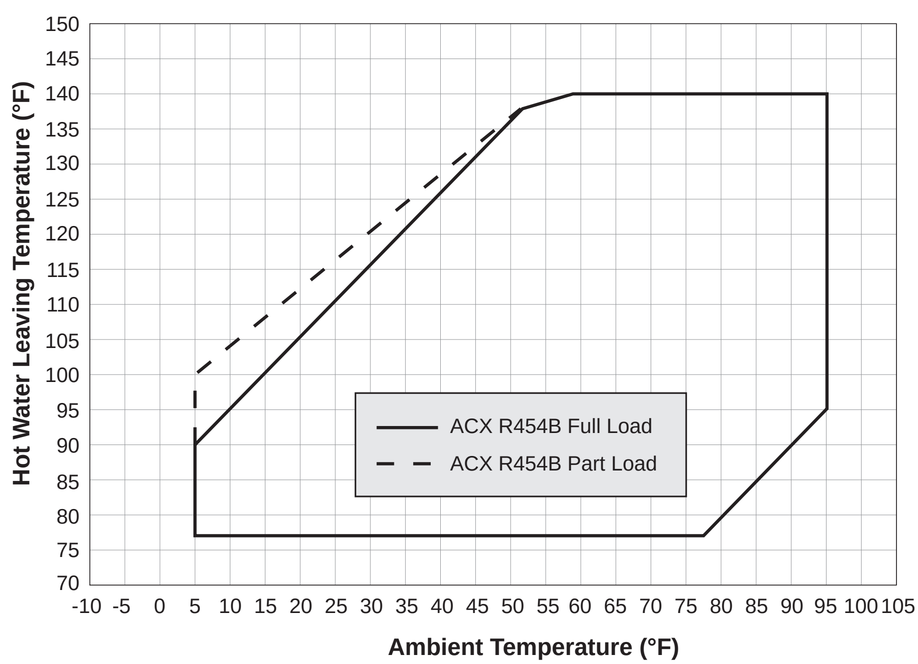
The operational characteristics of a heat pump can be determined by reviewing cataloged performance tables or through a certified selection from an equipment manufacturer.

Air-source equipment generally includes a minimum ambient operating temperature and a supply air or fluid temperature at a given flow rate. However, water-source equipment includes similar limitations because this equipment is often located inside the building, it is not bound by the outdoor ambient temperature.

Generally, as source temperature is reduced, the capacity and efficiency of a given heat pump also decrease. Additionally, the available heated fluid temperature—air or water—decreases with the source temperature. Shown below (Figure 1) is the operating map for the Trane ACX air-to-water heat pump (AWHP), using R454B.

While this unit can produce 140°F (60°C) fluid when the ambient temperature is mild, the available supply fluid temperature decreases as the ambient temperature drops. There is a knee near the rating point of 47°F (8°C), and as the outdoor air temperature drops further, the supply fluid temperature declines more rapidly. At part load, the slope is not as dramatic. In either case, the lowest ambient temperature at which this equipment can operate is 0°F (-18°C).

Figure 1. ACX R454B operating map (heating mode)



Controls

A heat pump of any type requires unit-level controls that receive information from the Building Automation System (BAS) or another system-level controller. The primary inputs are requests to heat or to cool. As with any hydronic system, development of the sequences of operation should be undertaken during the design phase. The designer must think through the system modes, and a table is typically generated to outline the expected modes of operation.

From there, sequences should be generated that describe the intended operation of the pumps, valves, and equipment used in the system. The heat pumps and other heating and cooling equipment used have unit-level control for their respective components.

Control of these systems will be discussed in "System Operation and Control," (p. 76) near the end of this guide.

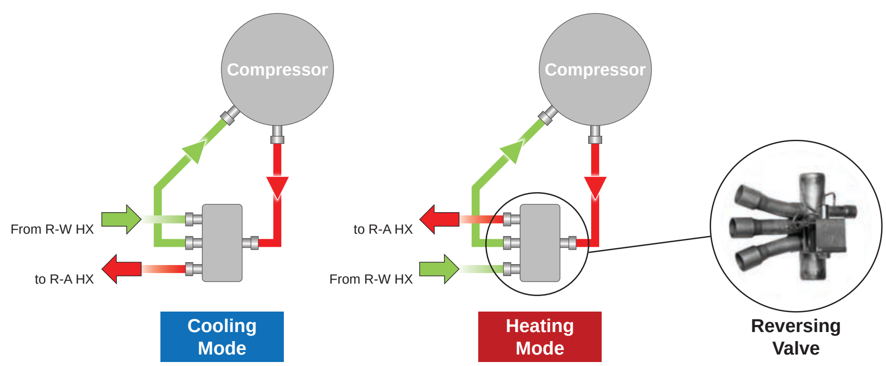
Reversing valves

For a reversible unit (Figure 2), the call for heating or cooling informs the heat pump of its operating mode. There are typically delays that occur during the switchover from heating to cooling mode.

For a non-reversible unit, a call for heating or cooling may determine the setpoint to which a unit is controlling. When operating in heating mode, for example, a non-reversible unit is likely to be controlled to a leaving-condenser temperature rather than the temperature leaving the evaporator.

The unit controls handle the unit operation.

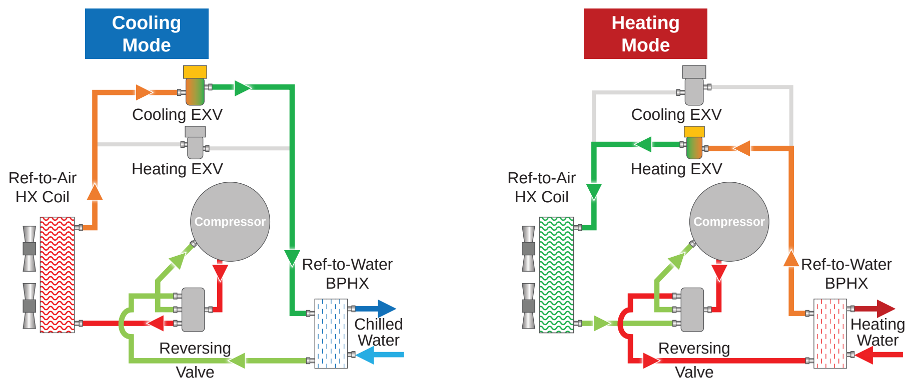
Figure 2. Reversible heat pump



The reversing valve is used only in reversible heat pumps. Aptly, its function is to reverse the flow of refrigerant. Refrigerant flow through the compressor and expansion valve is always in the same direction, but the evaporator and condenser heat exchangers switch roles. A four-way valve is common.

Reversible heat pumps (Figure 3) may include dual expansion valves, one for heating and one for cooling. In cooling mode, the cooling EXV is used; in heating mode, the heating EXV is used. This improves operational efficiency.

Figure 3. Air-to-water heat pump unit examples

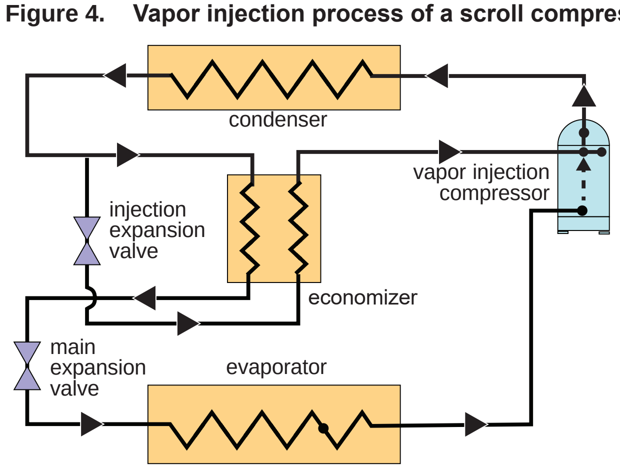


Enhanced vapor injection

Vapor injection is a mechanism used often in scroll compressors to enable higher hot-fluid temperatures, even at lower ambient conditions. This technology enables safe and reliable operation of scroll compressors by overcoming system limitations. It does this by extending the compressor operating map for heating applications. Essentially, it allows for an increased temperature/pressure differential between the evaporator and condenser.

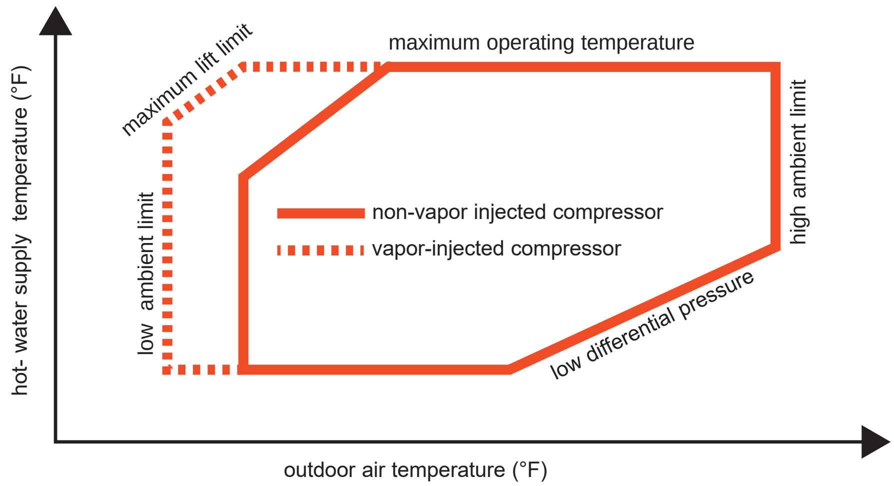
After leaving the condenser, a portion of the cooled liquid refrigerant is diverted through an expansion valve (Figure 4), where it flashes off. This relatively cool gas then passes through a brazed-plate heat exchanger, which is also carrying the remaining liquid refrigerant. This heat exchanger may be referred to as an economizer. The injection vapor mass flow is heated further in the heat exchanger, while the remaining flow of liquid exiting the condenser is cooled further. Because the evaporator receives cooler refrigerant, its capacity increases—resulting in increased heating capacity.

Figure 4. Vapor injection process of a scroll compressor



The injection gas is then brought into the compressor via an intermediate injection port, located midway through the compressing scrolls. By injecting the heated vapor refrigerant into the compressor, the compressor can do less work to achieve the desired discharge pressure and subsequent heating-fluid temperature. Reducing the work done inside the compressor results in reduced operational energy. Altogether, this leads to higher heating capacity, improved system efficiency, and a lower operational temperature (Figure 5).

Figure 5. Standard versus vapor injection operating map



Inverter-based systems

Equipment used in hydronic heating systems may have variable-frequency drives (VFDs) applied. VFDs are used to modulate the speed of compressors or pumps in the system. By slowing the speed of the heating or cooling equipment, they reduce energy consumption at part-load conditions.

For example, when valves in the system close, less flow is needed by the coils supplied through these valves. The differential pressure increases, the VFD slows the pump down to save energy in a system where pump speed is controlled to a differential pressure setpoint.

For a chiller, the purpose of the compressor is to increase refrigerant pressure in order to increase its temperature. This allows heat to be rejected either to ambient air or to a condenser water system, which subsequently rejects that heat to ambient air.

In a heating system, the compressor performs the same function. The only difference is that the equipment produces useful heat rather simply working to remove heat from the building.

Heat of compression—the heat energy added by the compressor that must be rejected by the heat rejection equipment—becomes advantageous when heating is the desired outcome. In the past, reducing condenser temperatures was used as a way to gain efficiency. Now, a reduced condensing temperature means a reduction in the hot fluid or air temperature being provided to the system, for a given leaving-evaporator temperature. While variances in load can allow for temperature reset, it is not necessarily tied to the ambient conditions. When outdoor temperatures are warmer, however, air-to-water heat pumps can heat more efficiently.

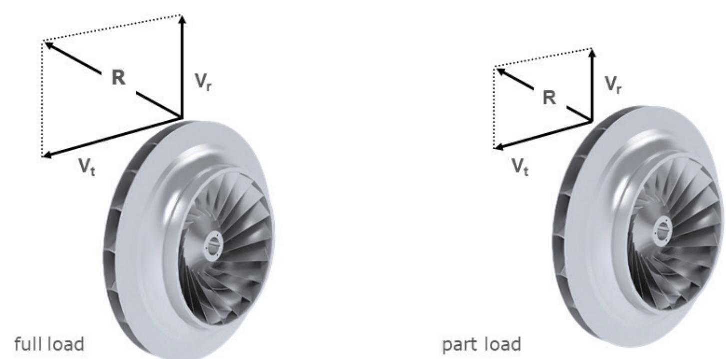
When using VFDs on centrifugal chillers, it is important to understand the compressor's unloading capabilities along with the minimum load the equipment must meet.

Centrifugal compressor part-load operation

When using a centrifugal chiller in a heating or heat-recovery application, it is extremely important to understand the compressor's part-load operation. The larger pressure differentials required for a heat-recovery design also tend to reduce the unloading capability of the compressor.

Consider a compressor impeller of a given diameter that rotates at a constant speed. As the load on the chiller decreases, the flow rate of refrigerant through the compressor drops. Radial velocity (Vr), which is proportional to refrigerant flow, decreases as well. Even though the speed of rotation and diameter of the impeller remain constant, the tangential velocity (Vt)—which is proportional to the product of impeller rotational speed and impeller diameter—drops because of the pre-swirling of the refrigerant caused by the inlet vanes.

Figure 6. Resultant-velocity vector (R) based on impeller rotational speed,



The result is a shorter resultant-velocity vector (R), which means that less static pressure is generated (Figure 6).

As the load and the corresponding refrigerant-flow rate continue to fall, the radial force eventually becomes smaller than the generated static pressure, letting the pressurized refrigerant vapor flow backward from the diffuser passages into the impeller. This instantaneously reduces the pressure within the passages to less than the radial force, and the compressor is able to re-establish the proper direction of refrigerant flow.

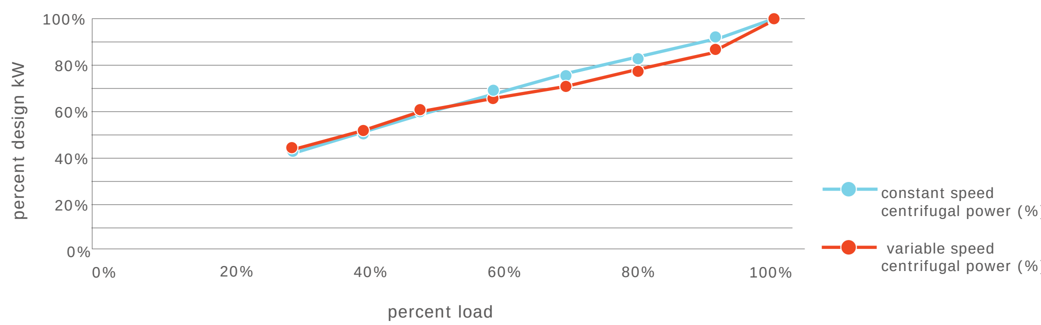
This condition is known as surge. As long as this unstable load condition exists, the refrigerant alternates between flowing backward and forward through the compressor impeller, generating noise and vibration. Prolonged surging is detrimental to the compressor and should be avoided.

Variable-speed centrifugal compressors

As compressor speed is reduced, both refrigerant flow (capacity) and pressure differential are initially reduced. However, if the compressor does not produce a high enough pressure differential, the compressor experiences surge. Prolonged operation in surge can significantly affect reliability and longevity. Thus, the compressor speed reduction is dependent on a reduction of the pressure differential between the condenser and evaporator refrigerant pressures. If that pressure differential is not reduced, compressor speed cannot be lowered. This situation occurs in climates that are always hot and humid, or applications where the condenser-refrigerant is not reduced—such as heat-recovery applications in which the leaving-condenser water temperature is constant. In such cases, variable speed drives provide little or no benefit.

Figure 7 compares variable- and constant-speed centrifugal compressors maintaining a constant condenser leaving water temperature. Some people think of a variable speed drive on a centrifugal chiller to be a “part-load” device. A VSD can only reduce its speed if the pressure differential is reduced. Thus, a VSD on a centrifugal compressor is a “part-lift” device, NOT a “part-load” device.

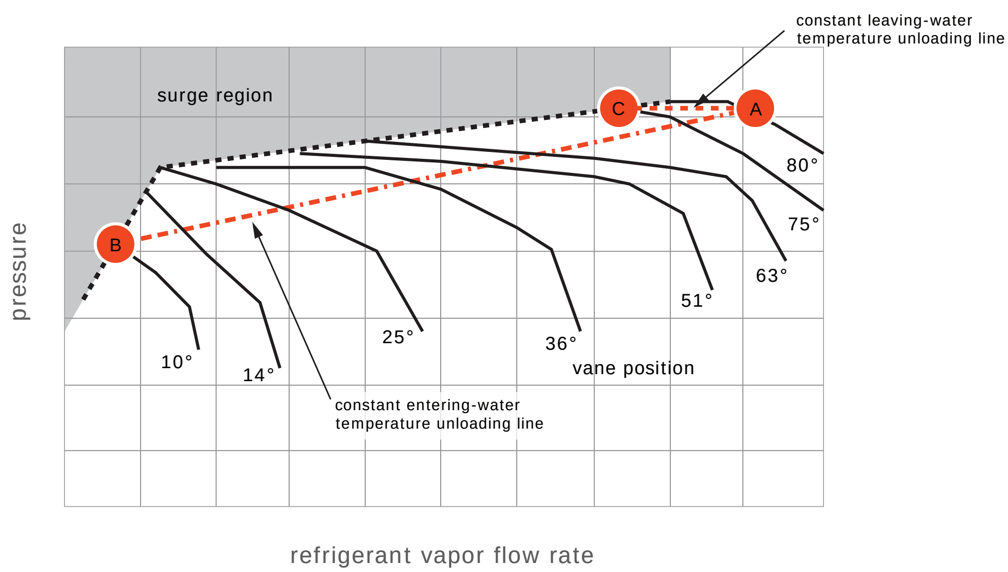
Figure 7. Performance comparison constant entering or leaving-condenser water temperature



[Figure 8](#) illustrates surge. In a multiple-stage compressor, each impeller delivers a portion of the total required pressure differential. As a result, a compressor with multiple stages has a greater ability to overcome the operating pressure differential in a heat-recovery application and, therefore, maintain stable operation over a wider range of conditions.

The curves in Figure 8 represent the performance of a typical two-stage compressor over a range of inlet-vane positions. The horizontal axis is refrigerant flow rate, which indicates chiller load. The vertical axis shows the pressure difference between the compressor inlet (evaporator) and outlet (condenser). The shaded area represents conditions that cause the compressor to surge. Any operating point that falls below and to the right of this area is satisfactory for stable operation.

Figure 8. Surge in a multiple-stage compressor

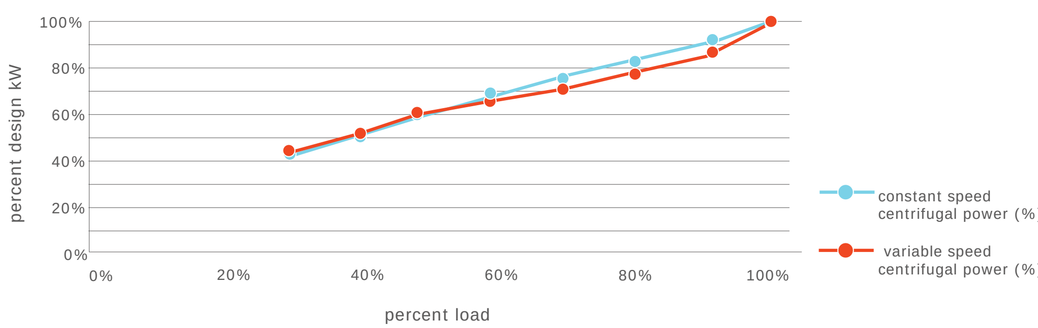


Heating/heat recovery and variable speed compressors.

Commonly, it is thought that a centrifugal chiller with a variable speed drive uses significantly reduced power at part-load conditions. For a centrifugal chiller with a variable speed drive to slow down substantially, the refrigerant pressure difference must be reduced. As mentioned previously, when the leaving-condenser (heating) water temperature remains constant, the refrigerant pressure difference remains almost the same. Figure 9 provides an example of constant-speed and variable-speed chillers. Note that their performance is almost the same and hard to distinguish. This is because the centrifugal compressor speed must be maintained to produce the necessary lift. If the leaving-condenser (heating) water temperature is to be held constant, a constant-speed centrifugal chiller is often much more cost effective.

On the other hand, a variable speed drive on a helical-rotary (screw) compressor saves energy when either load or pressure difference is reduced. Therefore, a screw compressor with a variable speed drive provides better performance at part-load conditions, even when the leaving-condenser (heating) water temperature is held constant. Thus, an economic analysis is warranted to determine the cost-effectiveness of adding a variable speed drive.

Figure 9. Performance at constant leaving-condenser water temperature



Impact of outdoor and supply temperatures on capacity, COP, and availability

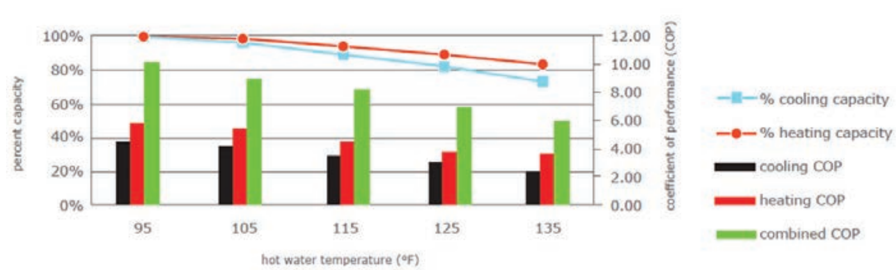
Positive displacement. Scroll and helical-rotary (screw) compressors are classified as positive displacement compressors. A unit with a positive-displacement compressor is selected to meet its specific capacities and both chilled and hot water temperature requirements. During the year, the unit may operate at many different combinations of chilled water and condenser water temperatures. However, as the heating-water (condenser leaving water) temperature rises, the capacity of the positive-displacement chiller is reduced. In addition to this capacity reduction, the power necessary to provide the compressor lift increases. Although the unit can operate in a heating or heat-recovery mode, one should evaluate whether the additional power required and the reduction in capacity justify the benefit.

Figure 10 and Figure 11 illustrate how two positive-displacement compressor technologies react to elevated hot-water (leaving-condenser) temperatures and pressures. In all cases, the unit was originally selected at a “normal” condenser entering-water temperature. After selection, the condenser leaving water temperature was raised with the effect on capacity and power.

These figures are intended for comparative purposes only. All chillers have an upper operating limit, so always contact the chiller manufacturer for information on the specific chiller being considered.

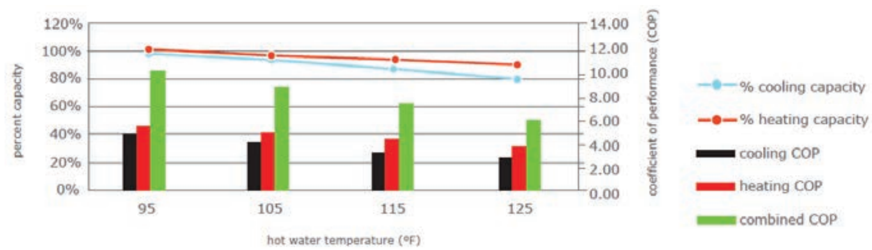
As shown in Figure 10, heat pump chillers utilizing constant-speed helical rotary compressors with slide valves experience a significant capacity reduction (15 percent in heating and 27 percent in cooling) as hot water temperature rises to 135ºF (57ºC) and the condenser water flow rate remains fixed. Along with this capacity reduction comes an increase in power.
Since power increases and capacity decreases, the change in COP reductions are 47 percent in cooling mode, 38 percent in heating mode, and 42 percent combined. These substantial reductions in both capacity and efficiency provide the importance of selecting the lowest hot water temperature that meets the application’s needs.

Figure 10. Effect of hot water temperature on capacity and COP, helical-rotary (screw compressor)



In Figure 11, the trends are similar, although the capacity reductions for scroll compressor units are not as steep.

Figure 11. Effect of hot water temperature on capacity and COP (scroll compressor)



As previously noted, all chillers have upper pressure limits for the range at which they are designed to operate. For example, in Figure 10 and Figure 11, the screw chiller could produce 140°F (60ºC) hot water, and the scroll chiller could produce 130°F (55ºC). These limits may be due to the need to remain below the design pressure of the shell, below the refrigerant relief-valve pressure, or within the tested envelope for the specific compressor. To remain within operating limits, a method of control must be available to keep the condenser pressure below these upper limits. This control can be accomplished by decreasing the condenser entering-water temperature, increasing the condenser water flow rate, or reducing compressor capacity, as discussed earlier in this section.

This performance highlights the importance of selecting lower heating temperatures. The lower the hot water temperature, the better the unit performance. Rather than specifying the hottest water temperature a unit can provide, select and specify the lowest hot-water design temperature that satisfies the application.

Domestic hot water heating and HVAC applications

Potable water heating can be provided either via heat recovery or a heating unit. When a compressor is used, there is a possibility that refrigerant could leak into the water stream. When a hydronic heating fluid is used to heat domestic hot water, there is also a possibility that fluid from the heating loop could leak into the domestic hot water stream.

As stated by the 2019 ASHRAE® HVAC Applications Handbook, Chapter 51[3]:

> *“When the heating medium is at a higher pressure than the service water, the service water may be contaminated by leakage of the heating medium through a damaged heat transfer surface.”*

In the United States, some national, state, and local codes require double-wall, vented tubing in indirect water heaters to reduce the possibility of cross-contamination. When the heating medium is at a lower pressure than the service water, other jurisdictions allow single-wall tubing heaters because any leak would be into the heating medium.

An additional heat exchanger must be used to isolate the refrigerant from the service (potable) water when medium- and high-pressure refrigerants are used. For chillers in which the water pressure is greater than the refrigerant pressure, (some centrifugal chillers using low-pressure refrigerant), single-wall tubing may be allowed. Local code requirements should always be met. If domestic hot-water storage tanks are used, a minimum temperature must be maintained to prevent the growth and spread of Legionella bacteria. Refer to ASHRAE standard 188-2021.[6]

Heat sources

With the advent of compressorized heating, it is important to recognize that compressor-based heating equipment does not generate heat. A boiler burns fossil fuels to release stored energy, generating heat that is transferred to the heating fluid. An electric coil in an air stream produces heat through the dissipation of electrical energy, which is converted to heat. This heat is conducted to fins that then transfer heat to the air passing over and through them. While the transfer of heat energy to the air or fluid uses the same mechanisms of traditional heating systems, the heat itself is not generated by the equipment.

For more information, refer to the Trane Engineers Newsletter, “Heating with Lower Temperature Hot Water,” ADM-APN084-EN. Visit Trane.com/EN.[16]

Rather, heat energy is moved from a lower temperature to a higher temperature. The vapor-compression cycle has been used for decades to increase the pressure and temperature of the refrigerant in a cooling system, allowing it to reject heat to a lower-temperature, readily available fluid (including air).

To start that cycle, however, the heat must come from somewhere. Sources of heat energy for electrified heating solutions include:

- Ambient air
- Cooling load (heat recovery)
- Process and commercial water loads
- Geothermal (ground source)
- Bodies of water
- Ground water
- Solar
- Exhaust air
- Wastewater
- Load-shedding economizer *(Not a source of heat, but can manipulate amount of heat available.)*

The type of building, climate and available sources of heat will help to identify appropriate equipment options for any given building.

Distributed versus centralized systems

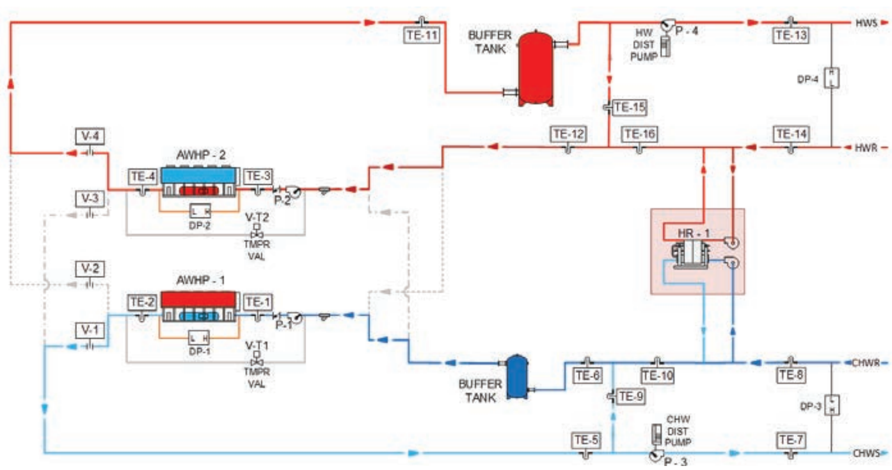
Distributed heating systems may include local WSHPs on a building loop. In an electrified system, rather than using a boiler as the heat source, an AWHP may be used to supplement the loop. While a cooling tower is often used to reject excess heat, a heat pump could perform both duties, but it is likely to use more energy than a properly controlled cooling tower. This type of system could be paired with a geothermal loop—with heat adders or rejectors—if the load is unbalanced.

Centralized cooling plants typically use air-cooled or water-cooled chillers and distribute chilled fluid through a cooling loop to serve building loads. Centralized heating plants may use heat pumps with a dedicated heating distribution loop. Centralized plants may also be designed as changeover systems that switch between heating and cooling modes or as systems with separate distribution loops for heating and cooling.

A centralized heating system may include water-to-water heat pumps (WWHPs) in a central plant and/or air-to-water heat pumps (AWHPs) placed outside. In either case, heat-recovery units—recovering heat from the return of the cooling fluid and injecting it into the heating fluid supply in a sidestream configuration—should be considered whenever a building has coincident heating and cooling loads.

The multi-decoupled, dual-feed system using only AWHPs is described in detail in the Application Guide “Air-to-Water Heat Pump System with Cascade Option” (SYS-APG003B-EN)[21], ACX Comprehensive Chiller Heat Pump Systems. It uses AWHPs in a primary-secondary configuration to allow for constant flow at the heat pumps. While variable primary flow has become common, the system design is simplified due to the limitations of heat pump condenser flow rates. A dedicated heat-recovery (DHR) unit can be placed in the sidestream position (Figure 12), and auxiliary heat can be included in the distribution to boost the heat pump fluid temperature during cold ambient conditions or to mitigate the impact of defrost cycles.

Figure 12. Dedicated heat-recovery unit option



Proper sizing of the DHR is critical to the cost-effective design and selection of the system. The amount of energy that can be transferred between the loops is limited to the lower of the two loops' loads at any given moment. As a result, the design capacity of a DHR unit is substantially less than that of the air-to-water heat pump units.

The proper method for sizing the DHR capacity is to perform an 8,760-hour load analysis for the heating and cooling loads, and then extract the minimum of the two loops' loads for each hour of the year in which heating and cooling loads occur coincidently. This hourly minimum coincident load data can then be evaluated to determine the appropriate DHR size (see *System Options* in SYS-APG003*-EN).[21]

For any installation, it is worth comparing the potential benefits of applying a DHR to those of investing in other competing efficiency measures, such as economizer cooling. However, heat recovery provides benefits beyond system efficiency. Incorporating a DHR into the system provides all the benefits of an air-source multi-pipe unit at lower cost and with better annualized efficiency.

A DHR can reduce the amount of time that two air-to-water heat pump units need to operate—one for cooling and one for heating. Table 1 shows a New York City school load example where heat pump operating hours are reduced by up to 1,600 hours per year. By recovering energy from one loop to the other, the DHR can fully meet one required load and partially meet the other. A single air-to-water heat pump unit meets the remainder of the dominant loop's load. This can help stabilize system operation and extend the operating life of the heat pump units.

Table 1. DHR impact on heat pump operation

fraction of design capacity		operating time without DHR	operating time with DHR	operating time reduction
annual		hours	hours	hours
NYC school	cooling	2,596	1,820	776
	heating	3,017	2,193	824

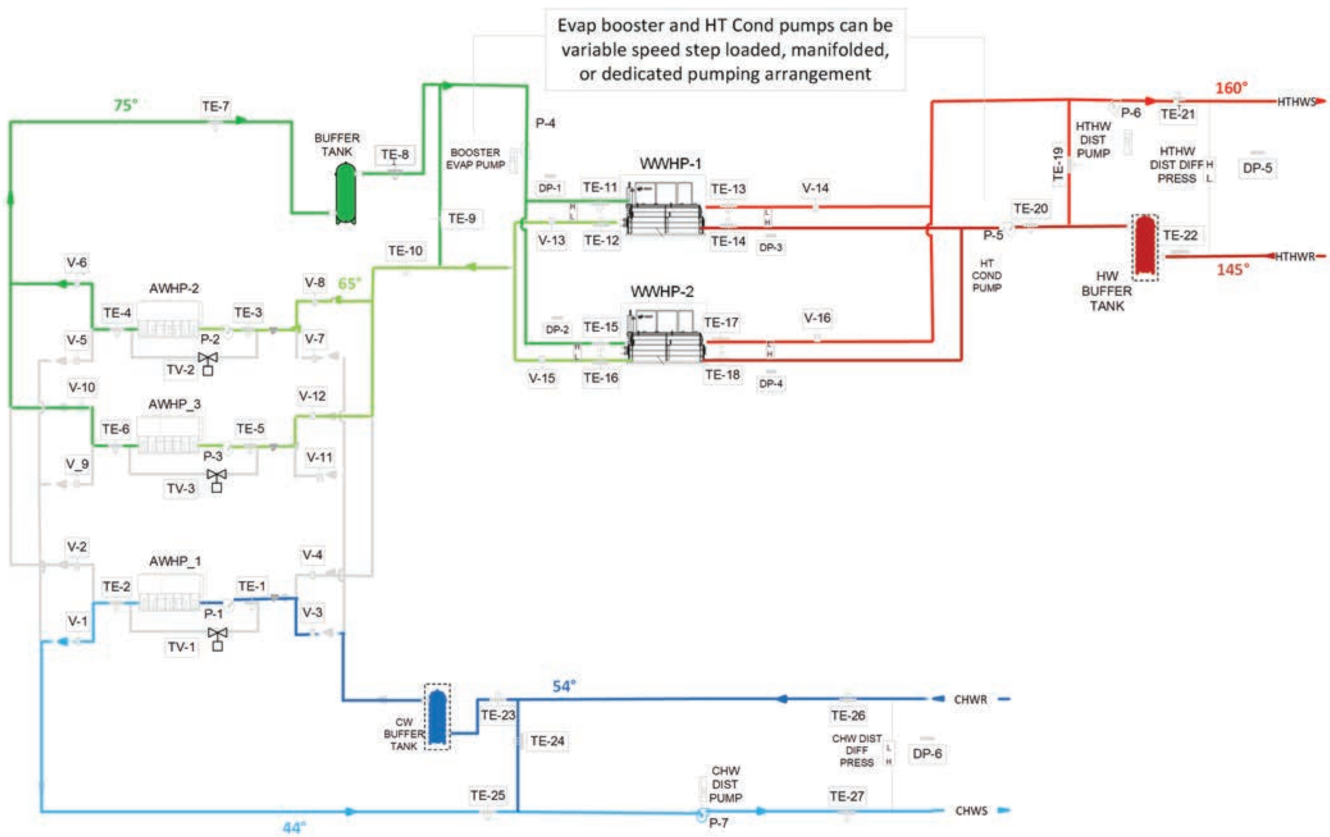
Other combinations of this system include thermal energy storage (TES) or a dedicated chiller for cooling-dominant climates. Refer to the *Thermal Battery™ Storage Source Heat Pump Systems* Application Guide (APP-APG022A-EN)[23] for more details, as these configurations will not be covered in this guide.

Cascaded heat pumps

For more information about cascaded systems, refer to the *Air-to-Water Heat Pump System with Cascade Option: Part of the Comprehensive Heat Pump Chiller System* Application Guide (SYS-APG003B-EN).[21]

Cascaded systems provide the opportunity to deliver higher fluid temperatures, even when the source temperature is low. A central cascaded system is comprised of two heat pumps with the low temperature condenser connected to the high temperature evaporator (Figure 13). This enables a wider range of operating temperature. The low temperature heat pump may be an AWHP or WWHP. The high temperature unit is a WWHP.

Figure 13. Two WWHPs in a cascade system



In this configuration, two chillers are used in a fluid cascade to provide warmer fluid than a single unit could provide. The low-temperature unit can also be used for cooling, as shown here with a split condenser bundle. This enables the unit to provide cooling and transfer that heat either to the high-temperature unit to heat the building or to reject it outdoors if the heat is not needed. The high-temperature unit then lifts the fluid temperature further.

This configuration provides turndown to 25 percent or lower, and is capable of operating under uneven heating and cooling loads due to the split condenser. Any water-cooled chiller can be used on the low side, and with proper piping, the high-temperature unit may be used for summertime cooling to increase operating hours.

Trane offers low global warming potential (GWP) refrigerants in both units.

Other configurations are possible.

Refrigerants

Similar to any chiller system, the designer must consider the impact of refrigerant choice within the system. Trane has transitioned its heat pump portfolio to low GWP refrigerants.

Climate-specific considerations

In cold climates, while AWHPs may be able to provide heating for many hours of the heating season, there may be periods of time in which the unit cannot operate. In these conditions, supplemental or backup heat is recommended.

There will be a minimum operating temperature, below which the unit cannot be guaranteed to operate reliably, nor can a unit be started below a certain temperature.

Furthermore, AWHPs will enter defrost cycles to melt frost off the air coil. This frost forms when water vapor in the air condenses and freezes on the cold coil. When this occurs, heating system efficiency is compromised. The air coil cannot transfer heat energy from the ambient air into the refrigerant inside the coil as effectively when a layer of frost or ice is insulating it. These units use the approach temperature between the air and the refrigerant vapor leaving the coil to initiate a defrost cycle.

During a defrost cycle, the refrigeration cycle is reversed and the outdoor coil becomes a condensing coil. The fans are turned off and the ice is melts from the coil. For this reason, several considerations apply to AWHP installations in cold climates, specifically when conditions are expected to fall below freezing. Even if such temperatures are not expected, if the extreme ambient drops below freezing, there are some best practices that should be applied.

The impact of defrost cycles has both design and operational implications. For more information about defrost cycles, refer to the Heat Pump Considerations for *Low Ambient Operation* Engineers Newsletter (ADM-APN095-EN).[12]

A drain pan should be included with the equipment to capture water coming off the coils during a defrost cycle. Manufacturers may provide these as an option, so be aware of whether they are included as standard or not. After installation, piping should be installed to divert condensate away from the unit and into a drain system. Heat trace must be installed to prevent freezing in the drip pans and in the piping systems.

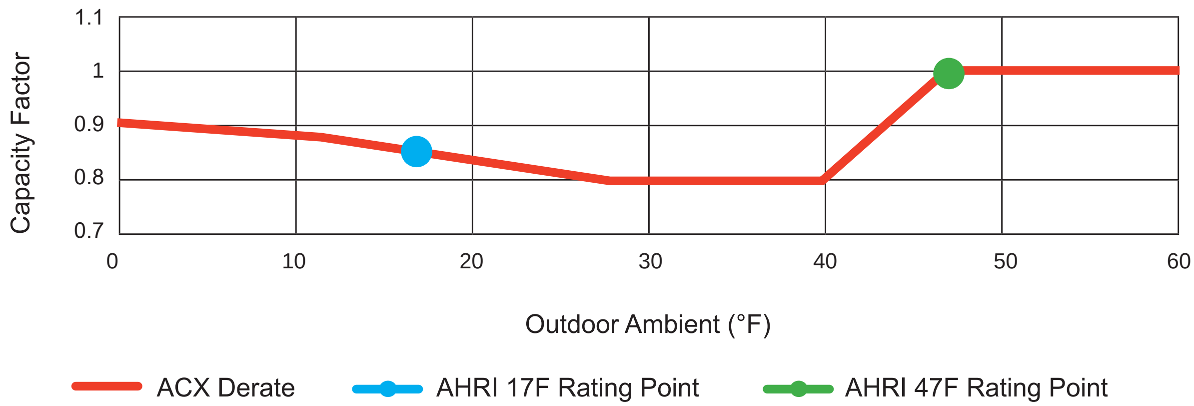
Defrost implications to sizing

Low outdoor air temperatures cause the outdoor coil temperature to drop below freezing, potentially resulting in frost accumulation. Defrost typically occurs only below 47°F (8ºC) outdoor air temperature (OAT). Air-to-water heat pump units will automatically enter defrost operation when required.

The Trane® ACX unit control has intelligent defrost management to minimize defrost while maximizing unit heating efficiency and capacity. The unit control limits defrost to one circuit at a time to minimize the temperature impact on the system.

Defrost operation results in a weighted performance derate to the equipment's heating capacity. Designer judgment is required because the frequency—and therefore impact—of defrost operation depends on actual operating conditions. Figure 14 provides a suggested range of heating derate capacity factors based on design outdoor air temperature. This derate capacity factor should be applied to the unit's required design heating capacity, and the equipment schedules and schedule notes should clearly indicate that this has been done. This helps ensure that equipment selections include the proper defrost impact.

Figure 14. AWHP unit heating defrost derate capacity factors at outdoor temperatures



Accounting for defrost does not always mean the equipment must be upsized. If the AWHP is sized for the heating design-day temperature, every hour below that temperature may provide surplus capacity, so the significance of defrost derate depends on how long those conditions persist. If the design-day condition occurs for only a few hours, the impact of defrost may be less significant than if those conditions last for an extended period. In many cases, accounting for defrost may lead to upsizing, but not always.

If the AWHP is used for both heating and cooling and the unit was sized for cooling, there may already be capacity available to account for defrost.

The number of units on site is also a factor in defrost derate impact. In a system with a single, dual-circuited AWHP, when one circuit goes into defrost, the unit loses 50 percent of its heating capability. However, in a system with two units, when one circuit goes into defrost, the heat pump system is only down 25 percent.

Note: Defrost derating curves may be affected by equipment configuration. Check the equipment installation and operating manual (IOM) for specific derating guidance.

Defrost implications to operation

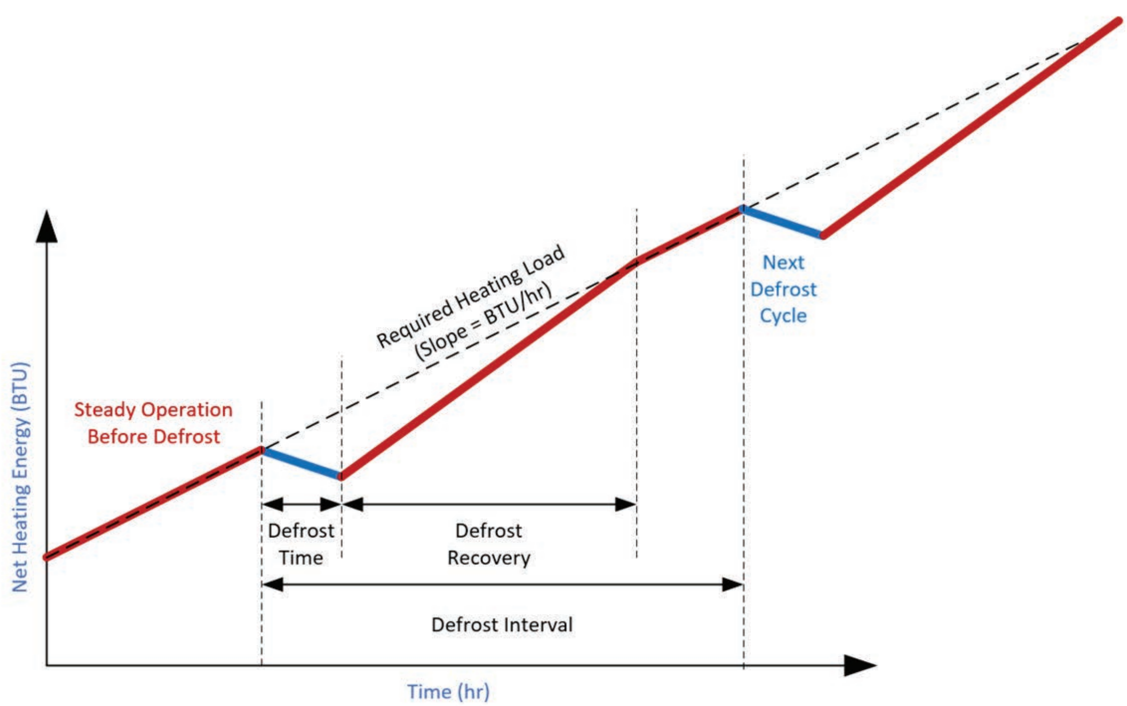
The operational impact of defrost cycles varies depending on system type.

AWHP direct. When AWHPs are used to directly heat the fluid used by the building coils, defrost becomes more important than in other system types. When the unit enters defrost mode, it acts as a chiller for the defrost period. Therefore, cold water may be supplied to the coils. Design and operational choices can mitigate this impact.

At design, options include the addition of loop volume or multiple units (or compressors). Typically, only one compressor per unit enters into defrost at one time. The impact depends on the number of circuits—for example, in a two-circuit heat pump, if one circuit enters defrost, the unit may become a net cooler depending on ambient conditions. For this reason, loop volume can be used. Another option may be to engage auxiliary heat when the supply temperature drops below a threshold, disabling it once temperature control is restored after defrost.

Figure 15 illustrates an example defrost cycle and its effect on cumulative heating output over time. The sloped dashed line represents the building heating load, while the heating produced by the AWHP changes during normal heating operation and during the defrost period. This example shows how short defrost events can temporarily reduce or reverse net heating, which is why system volume, unit configuration, and auxiliary heat strategy should be considered in the design.

Figure 15. Example defrost cycle time



Cascaded. In cascaded systems, where an AWHP feeds the evaporator of a water-to-water heat pump, similar concerns exist. However, because the defrosting unit's supply fluid is not sent directly to the coils, the overall system impact may be less. Regardless, there may be limitations on the upstream unit's ability to meet the heating setpoint if it is receiving cooled fluid from the AWHP. Similar strategies may be applied in scenarios where auxiliary heat is available to add to the distribution loop.

Storage-Source Heat Pump (SSHP). In this configuration, the AWHP does not directly heat the distribution stream. It adds heat only to the Energy Transfer loop when needed. For this reason, the impact of AWHP defrosting is reduced in this system. However, it may impact the net heat energy added to the system, which may require more run time during cold periods.

Ground Loop. An AWHP may be used to inject or remove heat into, or remove heat from, a ground loop. In this configuration, more run time may be required when units defrost.

Evaluating Existing Building Site Conditions

Upgrading or retrofitting an existing building is a difficult task. Unforeseen conditions, limited mechanical space and ceiling space, and a poor building envelope are just some of the issues designers must address. Adding electrification to the list of project requirements creates another incremental constraint that often compounds these issues.

Conducting proper site surveys, walk-throughs, interviews, and data logging helps the design team determine the project's unique requirements and identify potential issues that require additional attention during the design process and throughout construction. Multiple site surveys may be necessary throughout the design process. For example, once equipment has been preliminarily sized and selected, it may be necessary to revisit the site to confirm equipment locations, pipe and duct routing, or any coordination issues identified by the contractors.

Establish survey goals and assemble the ideal survey team

The goals of the on-site survey work must be clearly defined, and a team assembled to conduct the necessary survey tasks to achieve those goals.

Depending on the project size and scope of work, multiple site visits and surveys may be conducted throughout the course of design and construction. It may be tempting to bring as many people as possible to conduct the survey, but it is best to include only those necessary to achieve the goal of that specific site visit (Table 2). Those not included in any particular visit will have other opportunities to visit the site throughout the project timeline.

Table 2. Building survey team roles and responsibilities

Role	Responsibilities
Owner or owner's representative	Sets project goals
Facility maintenance staff	Knows the building's operational history, day-to-day operations, maintenance history and issues, and which areas of the building or equipment are currently having issues
General contractor or construction manager	Manages the construction process, and is responsible for contractor coordination and project scheduling
Commissioning agent	Responsible for ensuring the design and construction of the building renovation is functional and meets the owner's requirements
Architect	Designs the aesthetics of the building, including space planning, interior design, lighting, and building envelope
Mechanical engineer	Designs the mechanical systems in the building, and in some cases the plumbing systems
Electrical engineer	Designs the electrical systems in the building
Contractor(s)	Responsible for installing/constructing the project
Occupants	Ultimate end users of the building; critical for understanding how the building is used and its operating schedules

Assembling the proper site survey team is critical to achieving the survey goals. Early in the project, it is common for the team to include the owner (or owner's representative), architect, and mechanical and electrical engineers, with the goal of gathering specific information needed for the design to progress.

The design team should invite the facility's maintenance staff to participate in most, if not all, of the site survey work. Their knowledge of the building, its current operation, occupant or process needs, and any ongoing issues in different areas of the building will save the design team considerable time and may identify potential design concerns early in the design process, when they are much less expensive to correct.

As the design progresses, it is best to include contractors as soon as they are selected. Their knowledge of construction and buildability can steer the project and ensure the final design is practical to build, with minimal issues and impact on the construction timeline and project cost.

Once the survey team is selected, the site survey goals must be clearly communicated to all members of the team. A short on-site meeting to review the goals and all the information that must be gathered—before conducting the survey—helps ensure that all members of the team understand what must be accomplished. After the survey is completed, a similar meeting should be held to debrief and identify any items left incomplete.

Preliminary data gathering and review

Prior to arriving on site, a plan should be developed to identify which areas of the building must be surveyed, what equipment must be inspected, and what specific information must be measured or gathered.

A significant amount of time can be saved by gathering and reviewing as much information as possible prior to arriving at the site. Below are some items the team may find useful:

- Full set of drawings (architectural, structural, mechanical, and electrical) from the original building construction and any past renovations
- Design specifications from both the original construction and any past renovations
- Control drawings and sequences of operation
- Utility bills and power purchasing contracts
- Owner's design standards

In many cases, these drawings and specifications can be acquired from the owner or their operations or maintenance staff.

Drawings, in particular, can provide the team with significant information, especially regarding heating system loads, which support the eventual goal of electrification. A good place to begin the drawing review process is by studying the building layout (floors, wings, areas, etc.) to understand the intended use of each space, such as offices, classrooms, locker rooms, patient spaces, or product production areas.

Once space utilization is understood, the building envelope can be investigated by the architecture team. Some things to look for include:

- Wall and roof construction and overall U-value (does the design comply with current energy standards?)
- Window type, U-value, SHGC, and quantity (do the windows comply with current energy standards?)
- Air and moisture barriers
- Thermal mass of walls and spaces
- Questions that need to be answered during the survey
- Potential areas for future improvement

Once the building envelope has been reviewed, the mechanical design team can determine which HVAC systems serve each area of the building. Some buildings have very consistent HVAC designs—for example, all areas may be served by two large VAV systems or all classrooms may be served by dedicated unit ventilators. Other buildings have a mixture of systems. Each system or equipment type should be reviewed on the drawings. Information that can be determined include:

- Airside capacity
- Ventilation airflow (or outdoor air percentage)
- Supply air temperature cooling and heating modes
- Humidification or dehumidification capacity
- Hot-water and chilled-water supply temperatures
- Perimeter heating systems (radiant, baseboard, window-washing fan coils, etc.)

For buildings with a central steam or hydronic heating system, it is beneficial to understand how the heating plant was sized. Airside coils are often oversized to account for some safety factor. Some central plants are sized by summing the capacities of the airside coils. Since the airside coils are oversized—and since it is unlikely that they are all at maximum load at the same time—the central plant is likely oversized as well. Hot-water distribution pumps are often subject to the same sizing practice, and therefore the same degree of oversizing. If this condition is identified (or suspected) during the drawing review, the plant data logs should be retrieved from the previous winter, if available, to quantify how much the heating equipment is oversized.

The electrical engineer should also review the electrical drawings. In many cases, the lowest-cost (but least efficient) electrification solution is electric resistance heat. One of the greatest limitations to adding electric resistance heat—or other electrified heating solutions—is the electrical capacity of the building. The electrical engineer should note what the main electrical service is sized for and if the electrical gear can support the significant electrical load required to retrofit the building to an electrified heating solution. At this point, the exact amperage needed is likely unknown. But the electrical engineer should be aware of how much supplemental capacity, if any, is available.

One method that many designers use is to scan drawings and documents into PDF editing software. The PDF can then be marked up to include the entire survey plan and the information needed in each space. This allows the survey team to record all data in a central, convenient location.

Conducting the site survey

Once the team arrives on site and has reviewed the goals, the actual surveying can begin. The initial building survey may resemble the process required to create a detailed energy model, since system sizing and a load profile will be necessary to properly analyze system options later in the design process.

The following is a short list of the information that must be collected; certain buildings may need additional information:

- Confirm room dimensions
- Confirm wall, roof, and window construction
- Gather lighting quantity and wattage, as well as operating schedule
- Note thermostat setpoints
- Identify additional space loads, such as computers, medical equipment, refrigerators, etc.
- Estimate air leakage infiltration and building pressurization
- Determine occupancy schedules

Once this space information has been determined, the mechanical engineer can survey the HVAC equipment. In many cases it is best to start at the central plant and work out to the smaller, zone-level equipment. The following information should be captured in the mechanical room:

- Equipment nameplate, model, and serial number for chillers, boilers, pumps, air handlers, etc.
- Pictures of current operating conditions for all major central plant equipment
- Steam boiler operating pressure
- Chilled-water system supply and return temperatures
- Hot-water system supply and return temperatures
- Cooling tower fan speeds and condenser water supply and return temperatures
- Refrigerant monitors and sensors
- Refrigerant venting and exhaust systems
- Confirmation that plant piping layout matches drawings previously reviewed
- Available space in and around the mechanical room

From the central plant, the next areas to survey are smaller mechanical spaces with air-handling units (AHUs), as well as the roof with existing AHUs or rooftop units. In many cases, existing packaged rooftop units can be replaced with heat pumps models; so unit data and curb dimensions should be recorded. AHUs are a bit more complicated. First, check if the unit installed matches the unit on the drawings. If it does, much of the survey work is already done. If not, more information will be needed. Either way, additional coil information will be required in order to determine coil capacity at fluid temperatures other than design. Following is the AHU and coil information that should be recorded:

- AHU tag information, model number, serial number, etc.
- AHU layout and components; confirm that they match the drawings
- AHU fan CFM
- Heating coil dimensions, rows, fin spacing, and circuiting

For more information, refer to the Trane Engineers Newsletter, “Heating with Lower Temperature Hot Water,” ADM-APN084-EN. Visit Trane.com/EN.[16]

The ASHRAE guide, “Decarbonizing Building Thermal Systems: A Guide for Applying Heat Pumps and Beyond,”[14] explains the importance of documenting equipment, coil performance, and hot-water needs to support effective building electrification.

Once the major mechanical spaces have been surveyed, the zone-level terminal units (VAV boxes, fan-coil units, unit ventilators, etc.) must be reviewed. In many cases, it would take too much time to investigate all of these terminal units. In that case, identify a handful of terminal units that represent the majority of terminal unit types. In buildings that were constructed or renovated in phases, it is common for terminal units to be different brands, type, and age. Each vintage and type of terminal unit should have a representative sample surveyed. During these surveys, the designer should pay special attention to identifying perimeter heating systems—such as radiant panels, baseboard convectors, or window-washing fan-coil units—since they are often the most difficult types of equipment to convert to an electrified, low-temperature heating system. The following are some of the things that should be recorded when looking at zone-level terminal units:

- Terminal unit tag information, model number, serial number, etc.
- Confirm that terminal units match the drawings
- Controls, sensors and valve actuator vintage and condition

Domestic (or service) hot-water systems are one of the more difficult building systems to electrify due to the required supply-water temperature. Traditional domestic hot-water systems use a boiler, or a heat exchanger connected to a central heating system, to supply hot water to the building. In many cases, this system is not sized to handle the peak hot water demand, so a hot-water storage tank is included to meet the peak demand. Storage tanks must be maintained at or above 140°F (60ºC) to prevent microbial growth, specifically Legionnaires disease. A mixing valve ensures that 140°F (60ºC) water is not supplied to plumbing fixtures such as showers or hand-washing stations to prevent scalding, but this higher-temperature water may still be supplied to other devices, like dishwashers.

One way to avoid the 140°F (60ºC) temperature requirement is to eliminate hot water storage and pump a continuous flow of hot water to the building fixtures, allowing unused hot water to be bypassed back to the domestic hot-water system. In this case, the hot-water supply temperature can be lowered to around 120°F (49ºC), provided no appliances require hotter temperatures.

Interviews with key stakeholders

Once the site survey work is completed, interviews with key stakeholders for the project will provide insights into building operation, maintenance, and the load profile. Starting with the occupants, it is critical to understand the building's operating schedule and how different spaces are used. In addition, a building load profile is key to properly sizing electrified heating systems.

The owner and also the operations and maintenance staff should be able to answer many of the critical questions:

- What time is "X" area of the building occupied?
- Are the lights turned off and thermostats reset during unoccupied hours?
- When are special spaces (production areas, kitchens, large meeting rooms, auditoriums, etc.) used and what equipment is typically on?
- Are there any areas of the building that have trouble maintaining temperature setpoint?
- Are there any plans to change the use of any spaces/areas of the building?

BAS and standalone data logs

Using an existing building automation system (BAS) to log how existing systems are operating can provide an unbiased view of equipment sizing and operation. Data logs can be reviewed or set up to verify building cooling and heating loads and to calibrate any load calculations or energy models. Some items to consider data logging include:

- Building heating and cooling loads
- Chilled-water and hot-water supply and return temperatures
- Outdoor airflow rate
- Lighting and occupancy schedules, which may be different than actual use

If the BAS is not capable of logging certain data points, or equipment is not connected to the BAS, or pneumatic controls are used, it may be beneficial to find other ways to log building data. Small circuit transformers (CT's) can be installed—by a licensed electrician with the proper safety gear—in electrical panels to monitor equipment schedules and energy use. Temperature and humidity sensors can be used to verify thermostat control and night setback. Remote temperature sensors can be installed under the piping insulation to gather temperature data when those points are not available in the BAS. Both BAS trends and data logs require time to setup and gather information. Therefore, they should be implemented as early in the design process as possible to ensure that the important data is captured.

Selecting the Right Heat Pump for the Project

Identifying available heat sources

When deciding what type of heat pump best fits the needs of a specific project, one of the first tasks is identifying the available source(s) of heat. Recall that when using a chiller or heat pump, heat is being moved from one place to another, and that source of heat can be a fluid or air. Several common examples—such as cooling loads, exhaust air, geothermal, or wastewater—are discussed further below.

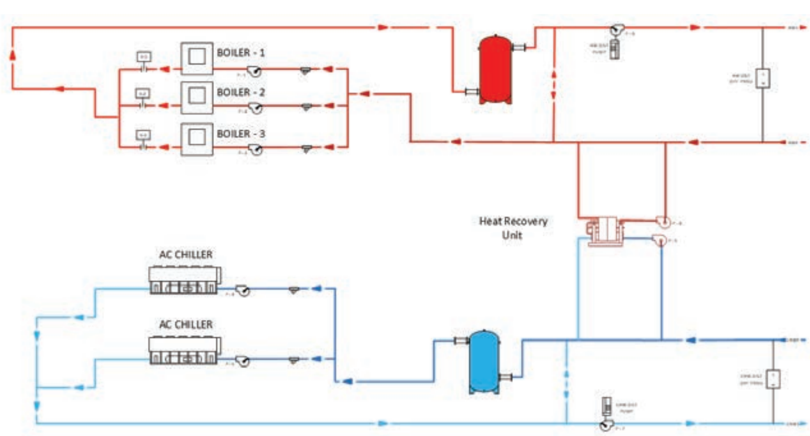
Often multiple sources of heat may be required to satisfy a building's heating load. Multiple sources may be required simultaneously to satisfy a peak heating load or may be used at different times due to varying loads and ambient conditions. For example, at extreme low ambient conditions, AWHPs are unavailable to heat, so another (backup) source of heat needs to be considered. In many cold climates, the most cost-effective and practical solution may be a fossil-fuel-based boiler in a hydronic system or a gas-fired burner in a packaged rooftop unit.

Evaluating all available heat sources is necessary to help select the correct type of equipment for the project.

Cooling load as a heat source (heat recovery)

The concept of heat recovery involves using a building's cooling load as a source of heat to help satisfy some or all of the heating load. When a chiller operates to remove heat from the building, that heat is typically rejected to ambient air through a cooling tower or an air-cooled condenser. Heat recovery instead uses that would-be rejected heat and to satisfy the heating load. When there are concurrent (simultaneous) cooling and heating loads, using a heat-recovery chiller can improve system efficiency by simply moving BTUs from one loop to another, aided by the vapor-compression refrigeration cycle (Figure 16).

Figure 16. Example heat-recovery chiller in a chiller/boiler system.

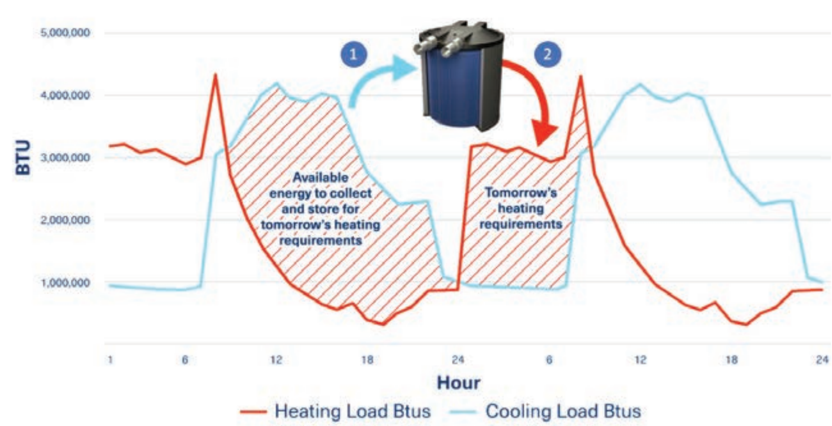


Thermal energy storage (TES)

TES allows heat from the building's cooling load to be stored for instantaneous or future use instead of rejecting it outside (Figure 17). This is referred to as a Storage-Source Heat Pump (SSHP) system. If the building's cooling load is not sufficient to recover enough heat (i.e., cooling and heating loads are non-coincident), the heat pump chiller uses the storage tanks as the heat source to satisfy the building's heating load.

In this manner, TES allows the cooling and heating loads to be decoupled, that is not equal and not coincident. Heat stored in the TES tanks is recovered from the building's cooling load, sourced from ambient air by operating an AWHP, or added by a trickle-heater boiler when ambient conditions are cold and the AWHP is unable to operate.

Figure 17. Building cooling and heating loads with ice-based thermal energy storage



Exhaust air as a heat source (exhaust-air heat recovery)

Another way to provide cooling load to the chiller is to create a "false load" by mounting a coil in the exhaust air stream. Since the exhaust air temperature is close to the space air temperature, cooling load is available anytime the exhaust air system operates. When the rest of the building's cooling load drops to zero, water may be passed through this coil and heated. This warmer water provides a cooling load from which heat can be efficiently extracted due to the relatively high exhaust air temperature. To reduce ancillary fan consumption the coil may be bypassed when it is not in use.

It is important to understand that if air is being exhausted, outdoor air must be brought into the building to avoid negative building pressurization and infiltration. Using an air-to-air heat exchanger reduces the amount of energy needed to preheat any additional outdoor air being brought into the building.

Ground or groundwater as a source (geothermal)

For more information about geothermal systems and borefields, refer to the Central Geothermal Systems Application Manual, (SYS-APM009D-EN)

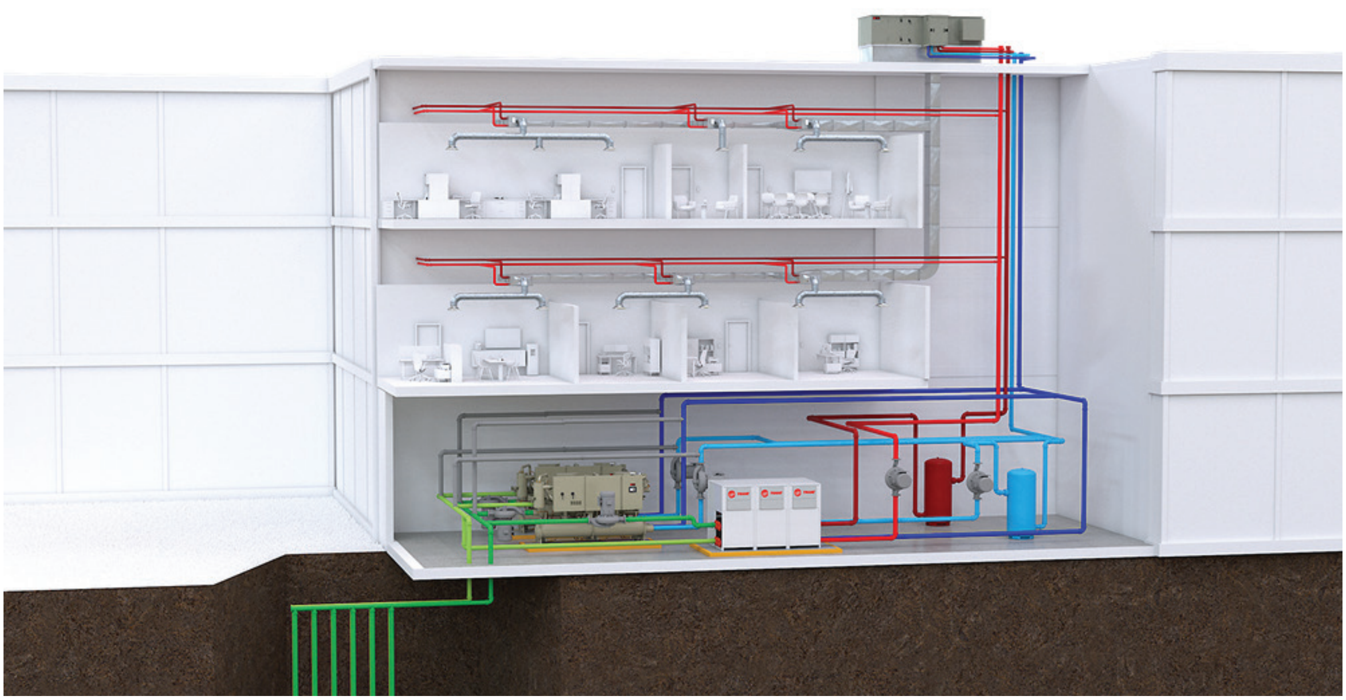
A geothermal (or ground-source) system uses the earth as a heat sink when the building requires cooling and as a heat source when it requires heating. In other words, heat removed from the building during the cooling season is stored in the earth and then retrieved during the heating season. Because the ground temperature is generally more moderate than the outdoor air temperature, a geothermal system can typically operate more efficiently than a comparable conventional HVAC system.

A geothermal system consists of a ground-source (geothermal) loop coupled to the building's HVAC system in order to reject heat from, or add heat to, the building as required. The ground loop may be:

- a closed-loop borefield of pipe buried in the ground (Figure 18)
- a closed-loop pipe submerged in a large body of water
- water pumped from the ground and returned back into the ground

Each type of ground loop has its own equipment implications.

Figure 18. Example of a borefield used as a ground-source loop



Choosing distributed versus central system architectures

Both distributed and central geothermal systems offer unique benefits beyond their geothermal efficiency. Table 3 provides a comparison of system characteristics for distributed heat pump and central geothermal systems for consideration by the system designer and building owner.

Table 3. Distributed and central geothermal system comparison

System characteristic	Distributed system	Central system
Number of vapor compression HVAC units	Many	Few
Heat pump enabling technology	Reversible refrigeration circuits	Hydronic system or reversible circuits
Location of vapor compression units	In each space	In central mechanical space
Method of conditioning the space	Terminal units (heat pumps located in or near the space)	Central air handlers and VAV boxes (and/or fan coil terminal units)
Geothermal loop temperatures	25ºF to 90ºF (-4ºC to 32ºC)	40ºF to 140ºF (4ºC to 60ºC)
Number of distribution loops within the building	One (ground loop)	Changeover systems have two loops (ground loop and distribution loop) Heating/cooling systems have three loops (ground loop, heating loop, and cooling loop)

A central system is typically viewed as having the following advantages when compared to a distributed system:

- **Maintenance:** A central system uses fewer compressor and fan bearing pieces of equipment and therefore will have reduced maintenance. Also, the maintenance of central refrigeration and air-handling systems takes place away from occupied spaces, reducing the impact on building users. Centralized air handling also eliminates the need for unit drain pans and filters within the occupied spaces. This not only eases maintenance and cleaning, but also allows for more flexibility in air-handling configurations and options such as high-efficiency filtration, fan operation, and condensate collection.
- **Acoustics:** Central systems using both chillers and air handlers have many options available for sound attenuation. In addition, locating the HVAC unit sound sources away from occupied spaces may have an immediate benefit to space acoustics.
- **Airside economizer:** Central air handlers with integrated airside economizers can be intelligently controlled to save cooling energy by rejecting it to the atmosphere or by preserving cooling energy for storage in the geothermal borefield. This is known as “load shedding” economizer control and raises the efficiency of the system.
- **Air filtration flexibility:** Central air handlers can be equipped with a variety of high-efficiency filtration options to improve building IAQ. Many of these filtration options are not available for distributed water-source heat pump terminal units.

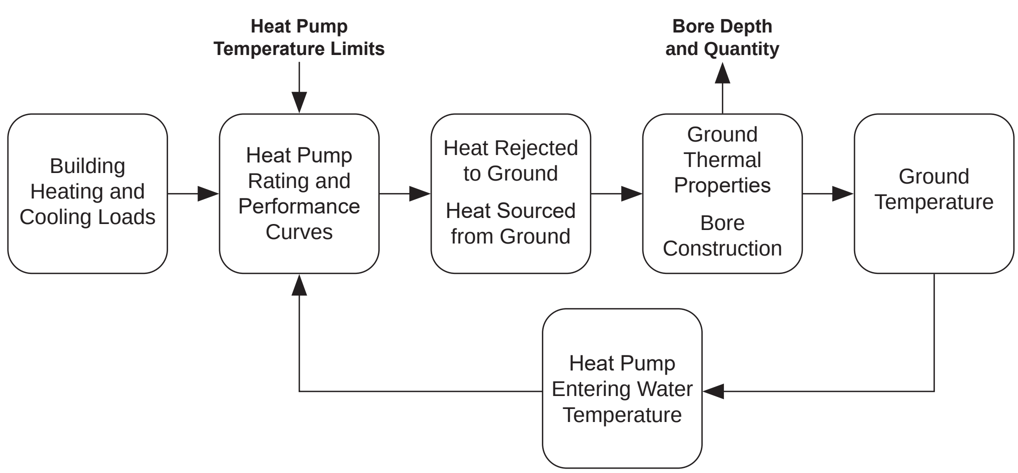
Borefield

Ground-Coupled Heat Pump (GCHP) systems use a ground heat exchanger, or “borefield,” as the heat sink and heat source for the system. This is the costliest part of a geothermal system. Ground heat exchanger sizing requires many assumptions, posing a risk that some assumptions are wrong. If the borefield size is too large, the project budget may not be approved. On the other hand, if the borefield size is too small, system performance is likely to be impacted. Proper borefield sizing requires special software capable of modeling the thermal characteristics of the earth and the material properties of the bore. Borefield sizing should be done by a certified professional, such as a Certified Geo-Exchange Designer (CGD) or a GSHP Commercial System Designer (GCSD). A directory of certified professionals is available on the International Ground-Source Heat Pump Association (IGSHPA) website (www.igshpa.org/business-directory).

The process of sizing a borefield may include the following steps (Figure 19):

1. Calculate the hourly heating and cooling loads with energy modeling software, such as Trane TRACE™.
2. Estimate the heat pump ratings and performance. The most important factor for this step is the heat pump operating temperature since it has a direct impact on heat pump performance (compressor lift).
3. Calculate heat rejected to and sourced from the ground, including the heat of compression from the heat pumps.
4. Use ground loop modeling software to estimate the operating temperature of the ground heat exchanger, given the heat load values and bore construction specifications. The ground loop software calculates the depth and quantity of bores needed to keep heat pump entering fluid temperature within the specified range. The ground loop software also considers year over year temperature drift for a target design life. A 20-year design window is often used.
5. Borefield sizing may require multiple iterations to find the optimal balance between bore depth, bore count, bore materials, and heat pump selections.

Figure 19. Borefield sizing workflow



Large body of water considerations

- Oceans and the Great Lakes have vastly different temperatures at the surface compared to their deeper depths.
- The deeper the source is, the more likely the temperature will remain relatively constant throughout the year.
- Surface temperatures can vary greatly with the seasons in regions between the tropics and the poles.
- Understand the temperature range of the source and how it will affect the performance of the equipment.
- Consider using an intermediate heat exchanger, or robust chiller tubes, and corrosion protection to maintain the life of the equipment.
- River water may contain significant sediment that can clog and foul heat exchangers.
- Salt water is corrosive, so precautions should be taken when in contact with equipment.
- Consider any applicable environmental regulations or laws; often there will be limits on how much a user can raise or lower the temperature of the water being returned.

Water pumped from the ground

- Water is pumped from an underground source and sent through the heat pump, where heat is extracted or rejected, before being returned to the ground.
- These systems may also be referred to as “once-through,” “pump-and-dump,” or “supply and re-injection” systems.
- Similar to large bodies of water, the temperature of ground water depends on geographical location and the source’s depth. Some groundwater sources may remain at a relatively-consistent temperature throughout the year, while others may be subject to seasonal variations.
- Consider any applicable environmental regulations or laws; often, there will be limits on how much a user can raise or lower the temperature of the water being returned.

Wastewater as a Source

- Water from sink and shower drains can provide heat to the system.
- A heat exchanger can be used to extract that head and it can be used a source for WWHP in the system.
- Wastewater (black water) provides a relatively consistent temperature source from which to draw from.
- Specialized self-cleaning heat exchangers exist for this purpose.

Choosing the method of heat distribution (air, water, or refrigerant)

There are several methods that heat can be delivered to a space, and each delivery method has implications for the system design. This section assumes that air will eventually be heated using one of the methods described below and then delivered to the conditioned space. The one exception is radiant heating.

Air

Air can be directly heated by a furnace or unit heater. This type of equipment includes a burner and a fan inside an enclosure. The most common fuel used by the burner is natural gas. Unit heaters are available in a range of capacities (from less than 100 MBh to several thousand MBh), in various configurations, and in either indoor or outdoor construction based on installation needs (Figure 20). These products may also be available with electric heaters rather than gas burners, which might be considered for electrification. Unit heaters are cost effective and easy to install and maintain, but they may not be the most efficient way to heat a space.

Figure 20. Examples of gas-fired unit heaters

Water

Water is a common means of delivering heat to a device that uses hot water to heat air, which is then delivered to the space (Figure 21). Heat is typically added to the water by a boiler in a central plant, which may consist of one or multiple boilers. Boilers can use natural gas, coal, fuel oil, wood, waste, or compost. Electric boilers are also an option.

The heated water is pumped through a piping network that includes terminal devices that regulate the amount of heat being added to the space. Terminal devices typically include fan coils, coils in air-handling units, VAV boxes, in-floor heating, or radiators (Figure 22). These systems can be designed for applications ranging from single-family homes to large skyscrapers and stadiums.

Hydronic-based heating systems offer high levels of flexibility and can be very efficient. However, they require more design work—often by a professional engineer—as well as more sophisticated controls and maintenance requirements.

Figure 21. Example of a hydronic heating system

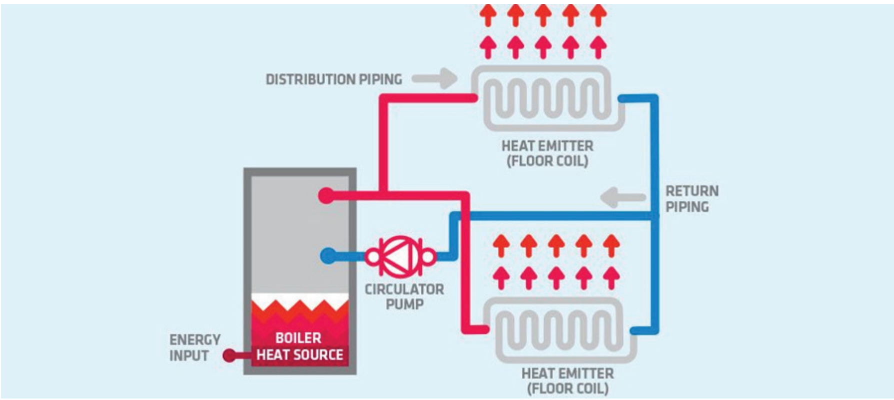


Figure 22. Examples of a fan coil and a baseboard

Refrigerant

Refrigerant is another means of moving heat. These systems use the vapor-compressor refrigeration cycle to extract heat from a source and deliver it to where it is needed. Air is blown over an air-to-refrigerant heat exchanger (referred to as a “condenser” when used for heating), where the air is heated and then delivered to the conditioned space.

Refrigerant-based heating systems include heat pump rooftop units (Figure 23), VRF terminals, water-source heat pumps, and DX coils inside AHUs. These systems can be configured for small residential applications all the way up to large commercial buildings. Some VRF systems offer a heat-recovery option which can increase system efficiency. With VRF systems, a separate air system for ventilation (a dedicated outdoor air system, or DOAS) is included (Figure 24). With many sizes, options, and configurations available, these systems can be very versatile. Consideration of numerous refrigerant runs and having refrigerant in occupied spaces is recommended.

Figure 23. Rooftop heat pump serving a multiple-zone VAV system

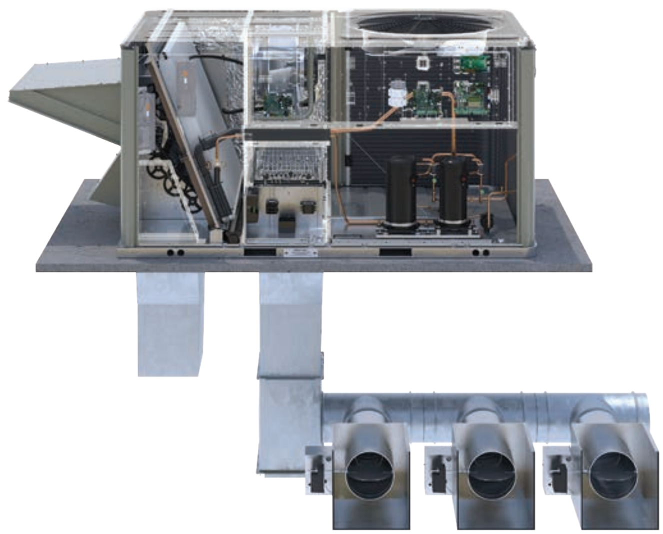


Figure 24. Variable refrigerant flow (VRF) system with dedicated outdoor air (DOAS)

Planning for backup heat

The climate in which a building is located determines the type and criticality of a backup heating system. In a cold climate, a reliable source of backup heat is very important; in a warm climate, a backup system may be less critical.

How much heat does the building need to stay comfortable during cold weather? Knowing this helps determine the capacity of the backup heating system.

Consider the cost: The installed cost of a backup heating system can range from very low (if existing heating equipment is reused) to very high (if a full-capacity backup heating system is required). It is also important to factor in the cost of maintenance when making this decision.

Consider reliability: The backup heating system should be reliable and able to provide adequate heat when it is needed. This requires proper preventative maintenance and regular inspections.

Consider the design temperatures: If an existing hydronic heating system was designed for 180°F (82ºC) hot-water supply (HWS) temperature and 160°F (71ºC) return temperature, the ability to use a heat-recovery chiller or heat pump may be limited. If the system was designed for less than 120°F (49ºC) HWS, then the use of compressor-based heating equipment becomes more feasible.

Adding an auxiliary or supplemental heating system

Auxiliary heat is defined as an alternate source, other than the AWHPs, which operates only when the AWHPs cannot operate due to ambient conditions or equipment failure. If outdoor conditions are cold enough, AWHP units may not be able to operate. In northern climate zones, this can occur with normal variations in weather. In other climate zones these temperatures may be abnormal, but could be 20- or 50-year extreme conditions. Regardless of climate fluctuations, planning for an auxiliary heat source is prudent given the operating limitations of AWHP equipment. If a full-capacity auxiliary heating system is to be provided, sizing for climate fluctuations (and extremes) would be a good design strategy. Since the auxiliary system is used infrequently, its impact on annualized carbon emissions is limited, so the use of high-efficiency fossil-fuel boilers should not be ruled out.

Supplemental heat is defined as an alternate source other than the AWHPs, which operates at the same time as the AWHPs in order to meet the total heating load. This concept enables further design optimization. Sizing AWHPs for the design heating capacity can lead to substantial oversizing in cooling mode, higher installed costs, and excessive compressor cycling at low loads. An alternative is to use a separate heating system to supplement the heating capacity of right-sized AWHPs to offset the peak heating load. This approach makes particularly good sense if an auxiliary heating system will already be required to address 20-, 50- or 100-year extreme weather episodes.

Maintaining existing gas equipment for backup heat

Another option is to leave existing heating equipment in place and use it only when the heat pump system cannot meet the required capacity or is unable to operate due to ambient conditions, maintenance, or equipment failure.

This approach likely has the lowest installed cost but not the lowest carbon emissions. However, it is important to understand utility grid emissions when deciding on backup heat sources, if carbon reduction is the goal. For instance, if the electricity provided to the building is from a “highly emissive” source (such as a coal-fired plant), electrifying the system today may not yield an immediate reduction in carbon emissions. Ideally, the new electrified heating system would be able to heat the building for all (or most) of the heating season, except maybe during 20- or 50-year extreme weather conditions, meaning the use of existing gas-fired equipment would be rare.

Adding electric resistance heat backup?

When seeking to reduce fossil fuel consumption, electric heat is another way to electrify a heating system. Electric boilers come in various sizes, can be applied in small to large systems, and are generally simple to operate and maintain.

Two major considerations when using electric resistance for backup heat are:

1. power available at the site, and
2. grid emissions.

For an existing building that used a fossil fuel for heating, the building site’s electrical infrastructure was likely not sized for electricity-based heating. In a cold climate, this could require a significantly larger electrical supply to serve the electric heaters—a significant cost the owner may not be willing to incur.

If decarbonization is a driving goal of the project, understanding the emissions related to the grid is very important. If the electricity supplied to the building is from a highly emissive source (such as a coal-fired plant), electric resistance heat may not be the best option—at least until the grid becomes cleaner.

Designing a system without backup heat

Some systems may not require backup heat, depending on building requirements or climate. In cold climates, the designer must consider conditions that might cause water pipes to freeze and burst, damaging the building. In hot climates, this is typically not a concern. When designing a system without backup heat, the system must be reliable. Consider systems with multiple circuits for built-in redundancy or adding additional equipment to provide some level of redundancy. For more details on using backup or supplemental sources of heat, refer to section "Sizing Heat Pumps," (p. 45).

Using storage technologies

Adding storage technologies to the system is another method of planning for backup heating. Historically, thermal storage has been in the form of ice or water. Ice tanks are often frozen overnight and then melted during the daytime to offset cooling loads. They do this in an effort to reduce on-peak electrical demand or to shift operation of cooling equipment to off-peak periods. However, these thermal storage tanks can also be used to base-load a heat-recovery chiller or act as a source of heat for a heat pump chiller.

Two major benefits of using ice for storage are:

1. the ability to store lots of energy due to phase change, and
2. the relatively compact size of the tanks compared to water storage tanks.

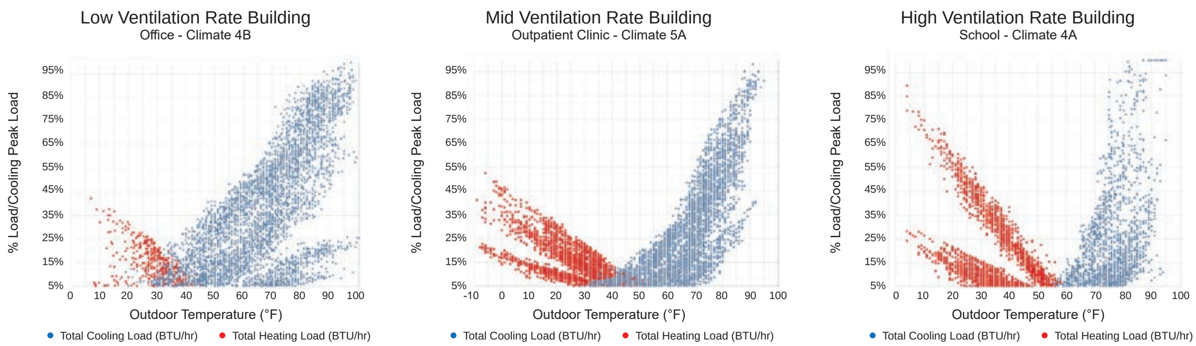
Ice storage systems can range from small to large sizes, while water storage is often only used in larger systems.

Thermal storage tanks can also be used as a source of heat or cooling in an emergency or backup situation. For example, if the building requires cooling and there is an inventory of ice inside the tanks, the pumps that move glycol from the tanks to the airside equipment would be the only power required to provide cooling. Alternatively, if the building requires heating and the water inside the tanks is not frozen, they can be used as a heat source for a heat-recovery chiller.

Evaluate cooling and heating load profiles to minimize electric infrastructure upgrade costs

Figure 25 shows an example plot of cooling and heating loads load versus outdoor dry-bulb temperature for three building types with varying ventilation requirements and in different climate zones. These building models are used as the basis for modeling proposed addenda to ASHRAE Standard 90.1-2022.[5] Hourly load data was extracted from TRACE® 3D Plus. Each point on the plot represents an hour over a typical calendar year (8,760 hours in total). The points in blue represent cooling loads, and the points in red represent heating loads.

Figure 25. Hourly heating and cooling loads plotted versus outdoor (ambient) temperature



Several observations can be made from these plots (Figure 25):

- The higher grouping of red points are occupied heating loads and the lower grouping are unoccupied heating loads. The difference is hard to discern in the office building due to the lower ventilation rates, which drive the difference between occupied and unoccupied heating loads.
- Notice the difference between the peak cooling load and the peak heating load in these three plots. The magnitude varies primarily with ventilation rate and secondarily with building type and climate zone.
- While this is generally well understood, 100 percent cooling or heating capacity is not often needed—especially for heating. Notice the density of red points nearest the peak heating load (yellow circles). There are few hours when the heating load is near peak load, and even less than for cooling.
- It is important to note that ventilation rates impact loads more so than building type or climate zone. (In addition to the three building types shown here, hotels have moderate ventilation rates, while large hospitals have high ventilation rates.) Effective use of exhaust-air energy recovery can substantially reduce the ventilation-driven heating load during occupied hours, bringing it closer to the much lower unoccupied heating loads.
- Commercial buildings, with primarily comfort heating and cooling loads (no data center or process loads) have limited hours with simultaneous heating and cooling loads, and may occur when outdoor conditions are well suited for air or water economizing. When simultaneous cooling and heating loads do occur the cooling load is small, which reduces the benefit of waterside heat recovery. However, there are other benefits to properly-sized heat recovery (“Sizing Heat Pumps,” p. 45).

By analyzing the annual cooling and heating loads of the building, better decisions can be made when sizing equipment. Oversizing equipment needlessly increases the budget and can lead to operational issues such as excessive cycling and large temperature swings.

Figure 26 shows the annual cooling and heating load profiles for a hospital. Figure 27 rearranges this data by sorting the cooling load from largest to smallest and the heating load from smallest to largest.

Figure 26. Annual heating and cooling loads for an example hospital

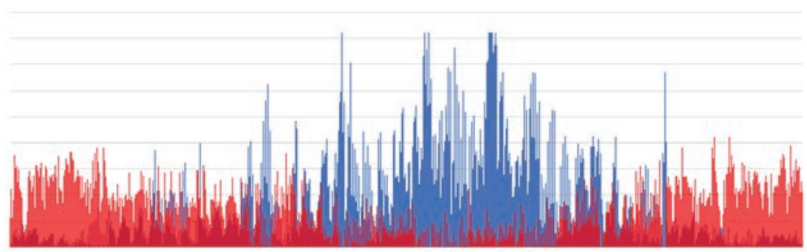
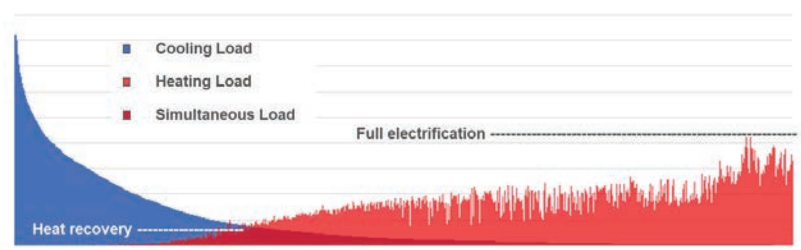


Figure 27. Rearranged load profiles for an example hospital



If the primary intent of equipment sizing and selection is to recover heat, sizing the equipment for a capacity near (or just below) the peak simultaneous heating and cooling loads is recommended. Ideally, the equipment can satisfy a base cooling load and recover heat all (or most of) the time. Upsizing beyond this will increase installed cost and result in more hours where the equipment is not fully loaded.

If the primary intent is to fully electrify the system, then the equipment must be sized to meet the peak heating load.

Without heat recovery, the cooling and heating systems would need to operate at the same time, adding heat while also removing heat from the building. System efficiency increases whenever heat recovery is used, as recovering the available heat reduces the runtime required by the primary heating system.

Explore practical heat pump system alternatives

There are nearly unlimited ways to configure a system, so the following examples are options to consider that are as simple as possible, efficient, and reliable.

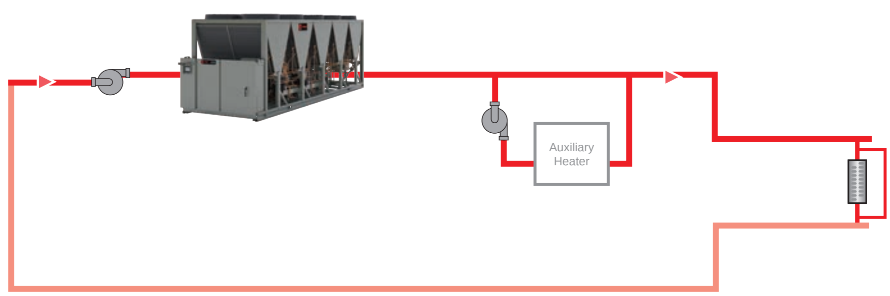
This section is organized based on the type of heating system that currently exists in a building (e.g., central hot-water boiler, forced-air gas furnace, packaged unit) and then describes options for an all-electric retrofit.

Existing central hot-water boiler (<140°F (<60°C) HWS)

Air-to-water heat pumps (AWHP) can be a practical and simple solution for an existing low-temperature hot-water system (Figure 28). Many AWHPs are capable of producing up to 140°F (60°C) hot water. However, this type of equipment may have limitations related to compressor lift (the difference between the HWS temperature and the ambient air temperature) which must be evaluated on a unit-by-unit basis. Therefore, AWHPs are best suited for:

1. Moderate climates where the outdoor air temperature is not expected to drop below the equipment minimum operating ambient temperature.
2. Systems with a HWS temperature less than 140°F (60ºC).

Figure 28. AWHP supplying low-temperature hot water



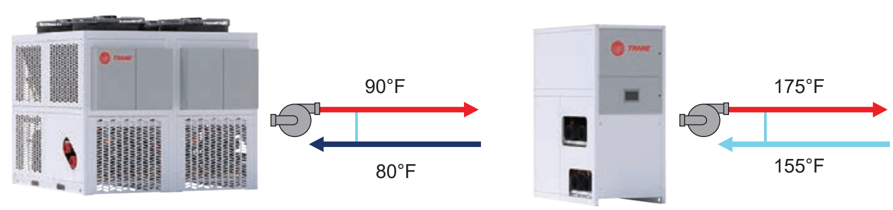
Existing central hot-water boiler (150°F to 180°F HWS (66°C to 82°C))

Existing systems that require higher HWS temperatures often involve more complexity. This is because AWHPs cannot typically provide HWS temperatures in this range, so water-to-water equipment must be considered. When using water-to-water equipment, there needs to be a sufficient cooling load (or another source) to provide the amount of heat needed. To produce a higher HWS temperature, the water-to-water unit may need a source that is warmer than the chilled-water loop (the source of the cooling load). Sources like geothermal, exhaust air streams, or wastewater may be needed.

Odyssey Split Systems are ideal for small- to medium-size buildings and for applications where rooftop unit installation is not possible or practical due to design, safety, or structural limitations. They provide both heating and cooling in a split configuration know for its unique versatility. Split systems are comprised of an indoor section that includes a fan, indoor cooling coil, heating section, and filter, while the compressor and condenser remains outdoors. Trane's broad line of split system components provides a mix-and-match, customizable design.

A cascade system is one way to achieve higher HWS temperatures. In the example shown in Figure 29, an AWHP extracts heat from the ambient air and produces 90°F (32ºC) fluid, which is then used as the source for a water-to-water unit is capable of producing the desired HWS temperature (175°F (79ºC) in this case). This concept could take several iterations. In this configuration, the AWHP could also be replaced with a condenser water loop or other source of heat.

Figure 29. Cascade system supplying medium-temperature hot water



Existing central hot-water boiler (>180°F HWS (>82°C))

Some existing heating systems (or process applications) require very high temperature hot water or steam. Some water-to-water heat pumps are capable of producing hot water above 180°F (82ºC), making them a potential solution for an electrification retrofit. As explained in the previous section, the source of heat must be evaluated to ensure that the heat pump is capable of producing the required HWS temperature. Typically, the leaving-evaporator temperature is limited roughly 80°F to 120°F (27ºC to 49ºC), meaning a relatively high-temperature source will be required. Energy recovery or an AWHP may be needed as a source of heat for this application.

Existing split system (AC and forced-air gas furnace)

When retrofitting an existing DX split system that contains a gas furnace, a Variable Refrigerant Flow (VRF) system may be a good choice for an electrification retrofit. Trane® / Mitsubishi CITY MULTI VRF products feature an innovative two-pipe system that provides greater flexibility in design and application. There are options for air-source and water-source heat pumps, as well as simultaneous heating/cooling systems to maximize efficiency. Various ventilation solutions and multiple control options round out the complete system to meet unique building needs.

Trane® / Mitsubishi Electric HVRF is a two-pipe Hybrid VRF system that exchanges heat between refrigerant and water using a unique Hybrid Branch Controller (HBC). This system reduces refrigerant use on the outdoor side and keeps the piping inside the building refrigerant-free.

Existing packaged rooftop unit

When retrofitting an existing packaged rooftop unit that contains a gas furnace, Trane Precedent® heat pump and dual fuel models are available from 3 tons to 25 tons (11 kW to 88 kW), in either standard or high efficiency configurations, to maximize energy efficiency and help reduce a building's direct carbon emissions by providing electric heating and cooling with a single piece of equipment. This product line includes options for all-electric cooling and heating (heat pump) for temperate climates or a hybrid dual-fuel system that can heat with natural gas only when needed. Low-NOx burners are also available.

Dual-fuel units provide a hybrid approach, using the electric heat pump as the primary heating method, while an auxiliary natural gas burner is activated only on the coldest days. The changeover temperature from heat pump to natural gas can be adjusted to occur between 45°F and 15°F (7ºC and -9ºC), depending on the customer's goals for balancing comfort, payback and emissions reduction.

Sizing Heat Pumps

Right-sizing heat pumps is critical for project success. Undersized heat pumps may not satisfy the heating load during extreme conditions, while oversized heat pumps increase installed cost and may lead to unloading issues and excessive cycling.

This chapter discusses sizing the following:

- Air-to-water heat pump (AWHP)
- Water-to-water heat pump (WWHP)
- Dedicated heat-recovery (DHR) unit
- Example system that uses a heat pump and heat recovery together

The sizing analysis presented later in this section uses hourly load data from a building energy model. The basic principles for sizing can also be applied to projects where hourly load data is not available. Those sizing strategies include:

- Reduce the required heating loads
- Add a heat-recovery unit
  - Heat-recovery units produce both hot water and chilled water at the same time.
  - Heat-recovery units are often lower in capacity than heat pumps, improving the system unloading capability.
  - Heat-recovery units can be sized significantly smaller than the peak simultaneous load and still recover most of the available heat energy.
  - Pipe heat-recovery units in a sidestream of the hot water and chilled water return.
- Add sufficient heat pump capacity to meet the project's electrification goals
  - Closely examine capacity of air-to-water heat pumps that operate with outdoor air temperature <47ºF (<8ºC) (defrost operation is required)
  - Sizing heat pumps for partial electrification of heat is based on cost vs. performance tradeoffs.
  - Sizing heat pumps for full electrification requires significantly higher heat pump capacity to satisfy a small number of operating hours per year.
  - Ensure that heat pump electrical demand is within the electrical demand limits
- Use backup or supplemental sources of heat
  - If outdoor air temperature is below the rating of air-to-water heat pumps, then backup heat must be sized for peak heating load.
  - If outdoor temperature limits are not a concern, supplemental heat can be sized to make up the difference between heat pump capacity and the required heating load.
  - If the project has redundancy requirements, a backup boiler is often a less expensive solution than a backup heat pump.
  - If a functioning boiler already exists in a retrofit project, consider keeping it as a supplemental or backup source.

Reducing the building heating load

When sizing heat pumps for an existing building, closely analyze the building's design heating load. Any reduction in the design heating load allows for the installation of smaller heat pumps and a reduced installed cost. Reducing short-duration peak heating loads specifically allows for more consistent heat pump operation and more manageable sizing requirements.

Consider the following strategies to reduce building heating loads:

- Improvements to the building envelope (walls, roofs, glazing) directly affect annual building heating energy use. ASHRAE Standards 90.1 and 189.1, and the ASHRAE Advanced Energy Design Guides[2] can help identify and prioritize building envelope improvements.
- Adding exhaust-air energy recovery allows heat from exhaust air to be recovered for use in preheating entering outdoor air. This may significantly reduce heating energy use, while also reducing the peak heating load. Some energy-recovery devices require outdoor and exhaust air streams to be in close proximity, while coil loops can be used even when exhaust air streams are located far away from the outdoor air stream.
- Ventilating a building with cold outdoor air can significantly increase the heating load. Demand-controlled ventilation reduces intake airflow—and therefore heating energy use—when the building is not fully occupied.
- Nighttime setback may result in high peak heating loads during morning warmup. In the ASHRAE Journal *Optimal Control of Energy Consumption for Heating,* Tabunschikov and Brodatch mathematically demonstrate that the benefits of nighttime setback are maximized "if the absolutely maximum power capacity of the given heating source is used during the warmup period".[7] Consider eliminating nighttime setback in buildings equipped with heat pumps, since morning warmup (recovery) can drive peak heating loads and increase the required heat pump capacity.
- Resetting the supply-air temperature and/or HWS temperatures during milder weather can reduce compressor lift and improve system efficiency when heating loads are lessened and lower HWS temperatures is acceptable. ASHRAE Guideline 36 recommends a control sequence for this.

Importance of energy models and load profiles

Detailed energy models, or 8,760-hour load profiles, greatly improve the engineer's ability to size heat pumps correctly. The traditional method of sizing for peak load plus some safety factor often results in oversized heat pumps. This section demonstrates the value of hourly load data, while also providing guidance for heat pump sizing when detailed load data is not available.

Reference energy models are available from the Department of Energy (DOE)[26] and Pacific Northwest National Labs (PNNL).[18] These models include several building types located in each ASHRAE climate zone, ranging from tropical to arctic. PNNL updates the building models regularly based on changes to ASHRAE Standard 90.

This chapter uses the PNNL hospital model to demonstrate heat pump and heat-recovery equipment sizing. Climate zone 6A (Rochester, MN) was selected to demonstrate the combination of high heating loads and cold ambient temperatures. The 2016 reference building model is used as the baseline because the 2019 version of ASHRAE 90.1 added a new requirement for heat recovery in inpatient hospitals (Section 6.5.6.3). Comparisons between the 2016 and 2019 models provide a good example of potential energy savings from adding heat recovery.

The chronological load data in Figure 30 shows that the largest heating loads occur during winter (depicted in red) and the largest cooling loads occur in summer (depicted in blue). Simultaneous heating and cooling loads occur predominantly during the shoulder seasons.

Figure 30. Annual hourly heating and cooling loads for an example hospital in Rochester, MN

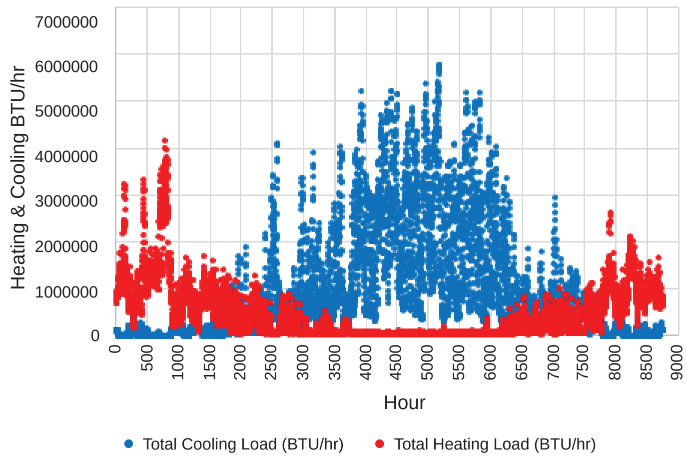
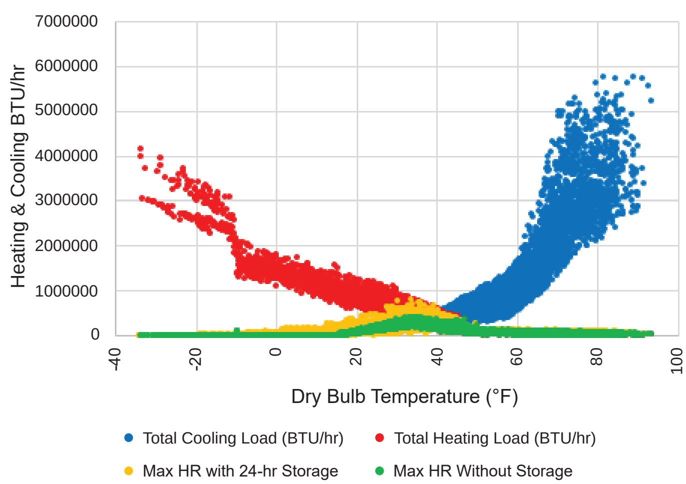


Figure 31 plots the same load data versus outdoor dry-bulb temperature on the x-axis, which shows the correlation between load and outdoor air temperature. The highest heating load correlates to the coldest outdoor temperature.

Figure 31. Annual heating and cooling loads versus outdoor air temperature



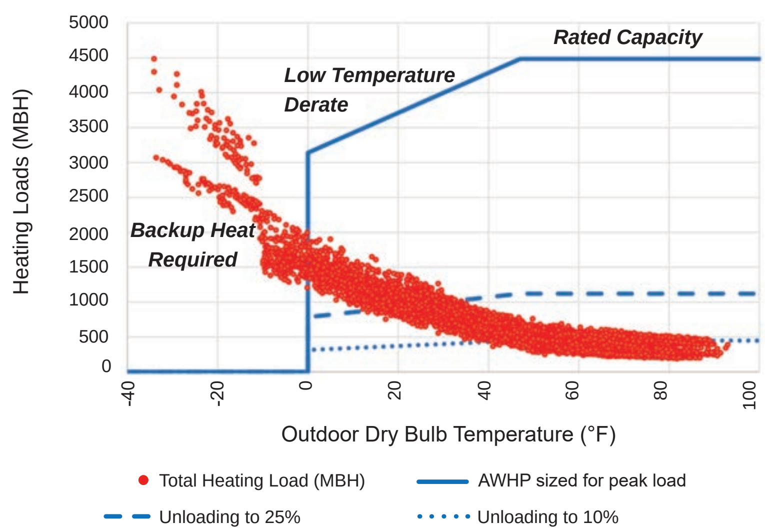
Sizing an air-to-water heat pump (AWHP)

An air-to-water heat pump (AWHP) uses outdoor air as the source of thermal energy and transfers that energy into a water loop. The capacity of an AWHP changes with the outdoor (source) temperature. This type of equipment may also have a low-temperature cutout (limit), below which it cannot operate.

Figure 32 includes only the heating loads for the example hospital building. It can be used to illustrates problems that may occur if an AWHP is sized using the traditional method of peak (design) heating load plus some margin of safety:

- Backup heat is required for any heating loads that occur when the outdoor temperature is colder than the low-temperature cutout (0°F (-18°C) in this example). Since the peak heating load occurs when it is coldest outdoors, the backup heating system must be sized for the peak heating load.
- The capacity of an AWHP is less than its rated capacity (derated) whenever the outdoor temperature is colder than 47°F (8°C). This is also when defrost operation may be required.
- The AWHP is able to achieve its rated capacity whenever the outdoor temperature is 47ºF (8ºC) or warmer, but at these conditions the building heating loads are low. As a result, the AWHP does not operate near its rated capacity.
- Excessive cycling may occur due to low heating loads. The heat pump's minimum capacity (turndown) depends on AWHP selection and system design. For reference, the dashed lines indicate 25 percent and 10 percent capacity corresponding to outdoor air dry bulb temperatures.

Figure 32. AWHP capacity versus building hourly heating load



balance point: the outdoor temperature at which a building's heat loss to the environment is equal to internal heat gains from people, lights, and equipment.

heat pump balance point: temperature at which the heat pump capacity and the building heat requirement are equal.

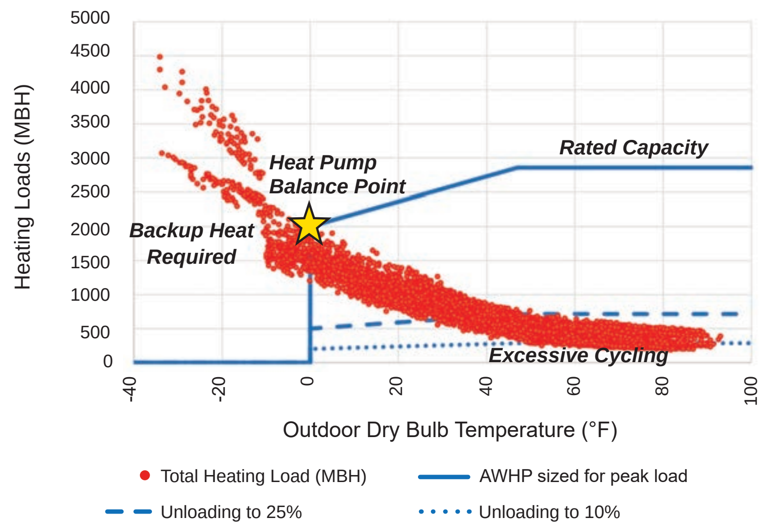
heat pump balance point temperature: the temperature at which the installed heat pump capacity is equal to the building's heat requirement.

- For a geoexchange system, it is the temperature below which the supplemental heating or cooling is required.
- For an air-to-air system, it is the temperature at which supplemental heating is required.
- For a water loop system, it is the temperature at which heating and cooling requirements are equal.

A better method for sizing an AWHP is to identify the heat pump balance point, which is the point at which the heat pump's capacity matches the heating load (Figure 33).

An AWHP is able to satisfy the maximum amount of heating load when the balance point is set equal to the low-temperature limit.

Figure 33. AWHP balance point

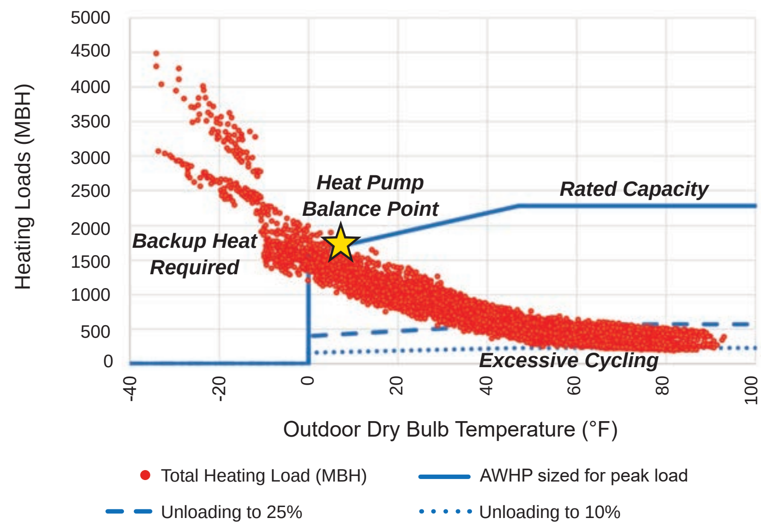


For cost-sensitive projects, design engineers may choose even smaller AWHPs, which moves the balance point to a warmer temperature (Figure 34). In this case, supplemental heat is needed whenever outdoor temperature is colder than this balance point:

When the outdoor temperature is colder than the balance point but warmer than the low-temperature limit, the AWHPs are operating and supplemental heat provides any additional heating capacity needed.

When the outdoor temperature is colder than the low-temperature limit, the AWHPs are turned off, and the backup heating system provides all required heating capacity

Figure 34. AWHP balance point shifted due to installation of smaller AWHPs

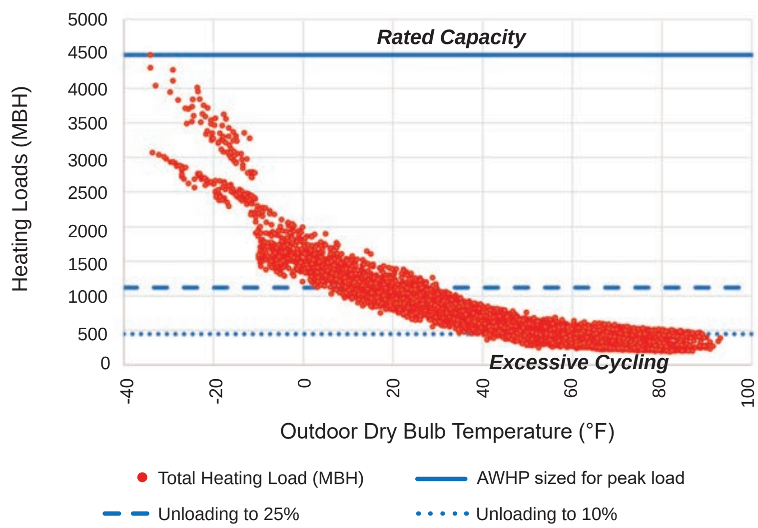


Sizing a water-to-water heat pump (WWHP)

A water-to-water heat pump (WWHP) uses water as the source of thermal energy and transfers that energy to a water loop. Typical sources of heat for a WWHP include geothermal, bodies of water, or heat recovered from a cooling system.

WWHP capacity is not directly affected by outdoor ambient temperature, and therefore does not have the same low-temperature derating or low-ambient cutout as an AWHP (Figure 35). A WWHP is typically installed indoors, so it can continue to operate during very cold outdoor temperatures. However, low-load operation must still be considered to avoid excessive cycling.

Figure 35. WWHP capacity versus building heating load

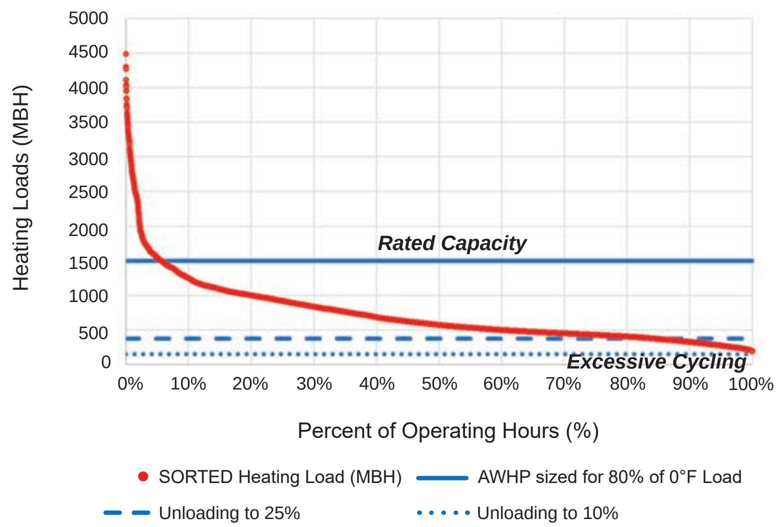


If full electrification of heat is required, then a WWHP is sized based on the peak (design) heating load plus some margin of safety. But if full electrification is not required, a WWHP could be sized to optimally balance cost versus performance.

Figure 36 plots the same annual heating loads as a percentage of operational hours. For this PNNL hospital model, while the peak heating load is 4,500 MBh, 95 percent of heating system operating hours require less than 1,500 MBh of heating capacity. This is one third of the peak heating load!

"Hot Water Heating Design and Retrofit Guide" by Cheng, Wendler and Raftery[9] describes a survey of hydronic heating systems in 259 buildings across the United States. The median buildings spend 94 percent of the time operating at less than 50 percent heating load, which aligns closely with the PNNL model.

Figure 36. Hourly heating loads for one year, plotted from largest to smallest



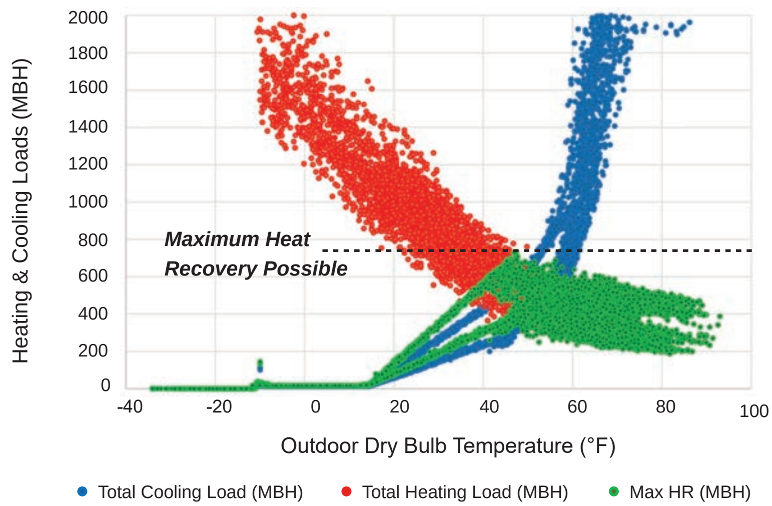
Sizing a dedicated heat-recovery unit

When simultaneous heating and cooling loads exist, heat recovery should be considered. The primary advantage of heat recovery is that one unit can satisfy both the heating and cooling loads at the same time, making it more efficient than operating two separate units.

Since a heat-recovery unit simultaneously cools the chilled-water loop and heats the hot-water loop, cooling and heating loads must exist at the same time. If the cooling and heating loads are not matched, the heat-recovery unit may overcool the chilled-water loop or overheat the hot-water loop, and could trip off due to low or high temperature.

The load profile chart in Figure 37 shows the maximum heat that can be recovered using the PNNL hospital model.

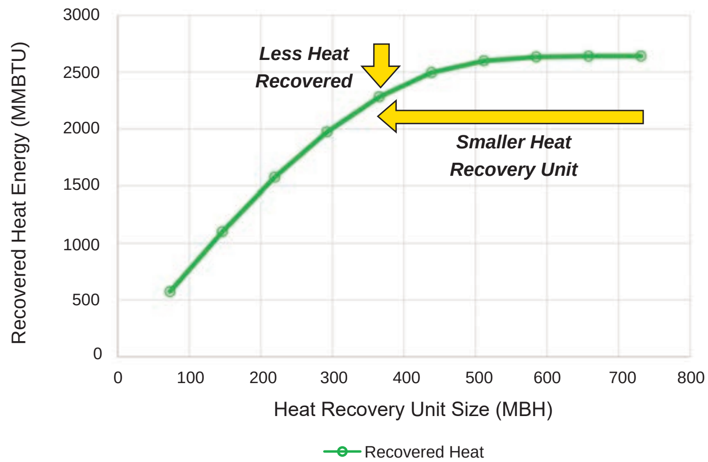
Figure 37. Maximum heat that can be recovered



Note: *Heat-recovery units do not need to be sized for the maximum amount of heat recovery possible. If the unit is sized smaller than this maximum amount, it will operate at rated capacity, and any remaining heating or cooling loads will be satisfied by other equipment.*

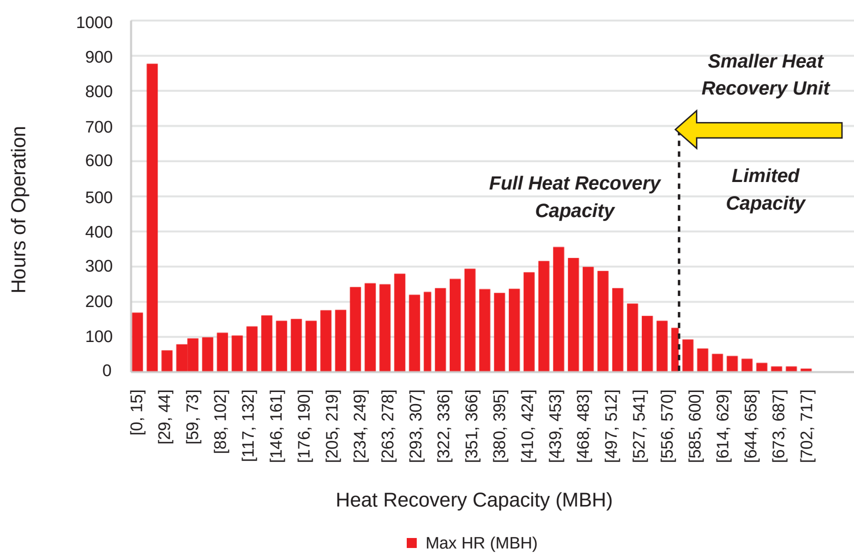
For the PNNL hospital model, downsizing the heat recovery by 30 percent—from 730 MBh to 510 MBh, in this example—has very little impact on the annual amount of heat recovered. Further downsizing results in a more noticeable reduction in annual heat recovered (Figure 38). Therefore, sizing the heat-recovery unit is often a tradeoff between installed cost and system performance.

Figure 38. Impact of heat-recovery unit capacity on annual heat recovered



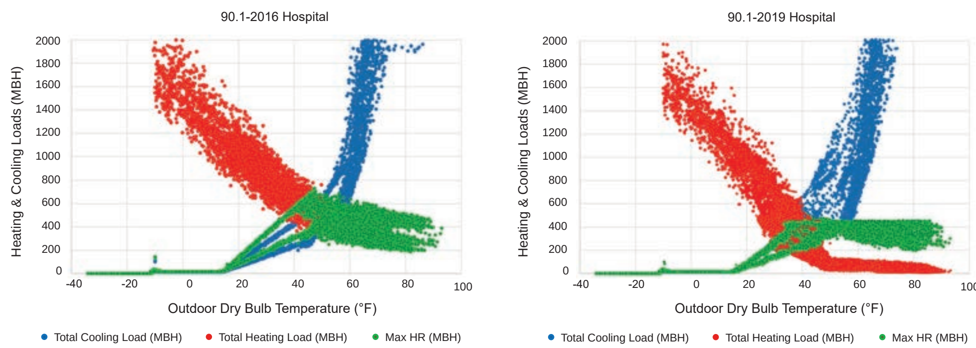
Bin analysis is a good alternative for sizing the heat-recovery unit. In Figure 39, each column (bin) represents the number of hours over the course of a year when a certain amount of heat is available to recover. If a smaller (downsized) heat-recovery unit is installed, it would not be able to satisfy the entire heat-recovery demand during some of the operating hours.

Figure 39. Bin analysis showing annual heat-recovery loads



The PNNL reference models provide a good example of heat recovery sizing. These models are updated to align with the most recent performance requirements of ASHRAE 90.1. In 2019, ASHRAE added a requirement for heat recovery in hospitals. Comparison of the 2016 model to the 2019 model reveals a heat recovery unit sized at 50-60% of the maximum simultaneous heating/cooling load value (Figure 40).

Figure 40. Comparing the 2016 and 2019 PNNL hospital models



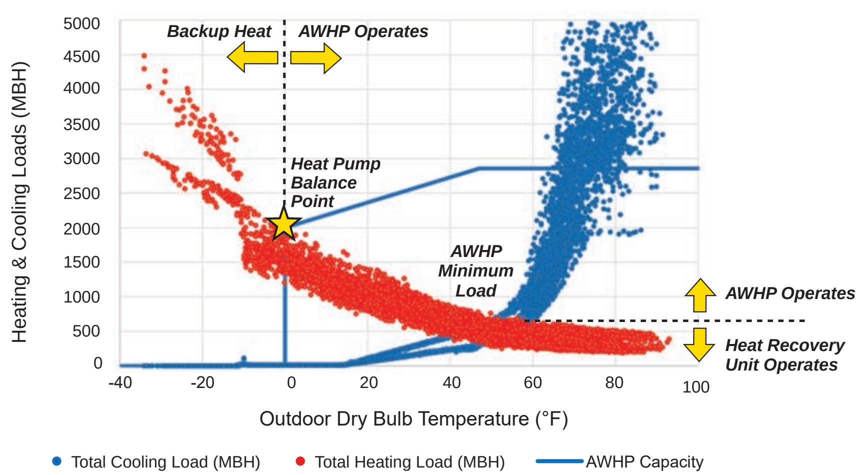
Using both air-to-water heat pumps and a heat-recovery unit

Heat pumps and heat-recovery units each have benefits and drawbacks to consider. Fortunately, the benefits of these two technologies complement each other, so combining heat pumps with heat-recovery units can be a great solution.

Figure 41 shows the 2016 PNNL hospital model, using a combination of an AWHP and a heat-recovery unit:

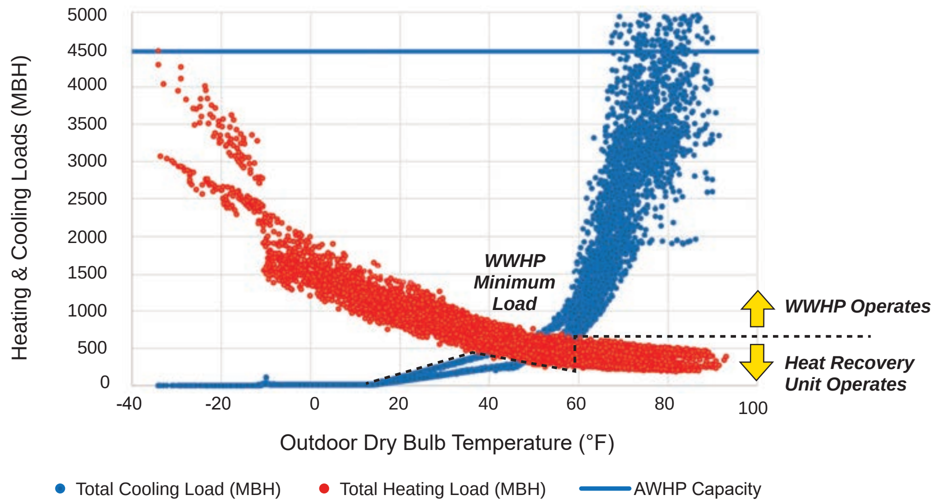
- The AWHP is sized for a balance point of 0°F (-18°C). At ambient temperatures warmer than 0°F (-18°C), the AWHP can satisfy the entire heating load, including any defrost derating factors. At temperatures below 0°F (-18°C), the AWHP cannot operate and backup heat is needed.
- The heat-recovery unit is sized to meet lower heating loads, where the AWHP may cycle resulting in temperature control instability. to unload.
- Operation of the heat-recovery unit is prioritized over the AWHP because its efficiency is higher. When the AWHP is operating, some of the heating load is shifted to the AWHP to maintain a minimum load that prevents excessive cycling.

Figure 41. Combining an AWHP and a heat-recovery unit



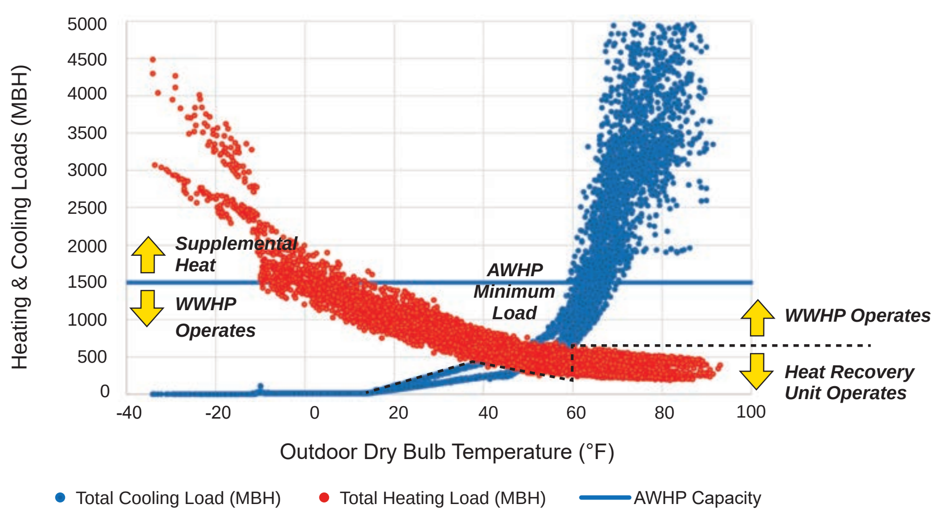
Combining a heat-recovery unit with a WWHP provides similar benefits (Figure 42). The heat-recovery unit improves system efficiency and operates at lower heating loads to avoid the WWHP from cycling excessively. The WWHP can be sized based on the peak heating load instead of the balance point, which affects its minimum turndown.

Figure 42. Combining a WWHP and a heat-recovery unit



If the WWHP is not sized for peak heating load (partial electrification), then a supplemental heat source is required. Reducing the size of the WWHP may allow for operation at lower loads (Figure 43). This also allows more of the heating load to be shifted to the heat-recovery unit, improving overall system efficiency.

Figure 43. Impact of a smaller WWHP when combined with a heat-recovery unit



Comparing heat pump selections for various building types and locations

For more information, refer to the Trane *Air-to-Water Heat Pump System with Cascade Option: Part of the Comprehensive Heat Pump Chiller System* application guide, SYS-APG003*-EN.[21]

While the previous section analyzed the PNNL prototype building model for a hospital in Rochester, Minnesota, several of the other prototype building models also use hydronic systems. Figure 44 compares the hospital to a large hotel, a large office building, and a secondary school in the same location. Some key differences are noted below:

- The peak (design) heating load for all building types corresponds to very cold outdoor dry-bulb temperatures, likely below the limit at which an AWHP can operate. Therefore, if an AWHP is used, a backup heat source will be needed.
- The load profiles for the hospital and hotel indicate a strong correlation between heating load and outdoor temperature, while the profiles for the large office building and secondary school show that heating loads are less dependent on outdoor temperature.
- The hospital profile has the most simultaneous heating and cooling loads, making it the best candidate for dedicated heat-recovery units. The large office and secondary school profiles show very little simultaneous heating and cooling, and therefore minimal opportunity for heat recovery.
- The hospital profile shows more overall (annual) cooling loads than heating loads, while the secondary school shows the opposite: more overall heating loads than cooling loads. The hotel and office profiles show fairly equal annual cooling and heating load. Annual load balance is a key consideration when sizing geothermal (ground-source) heat exchangers.

Figure 44. Annual load profiles for various building types in Rochester, MN

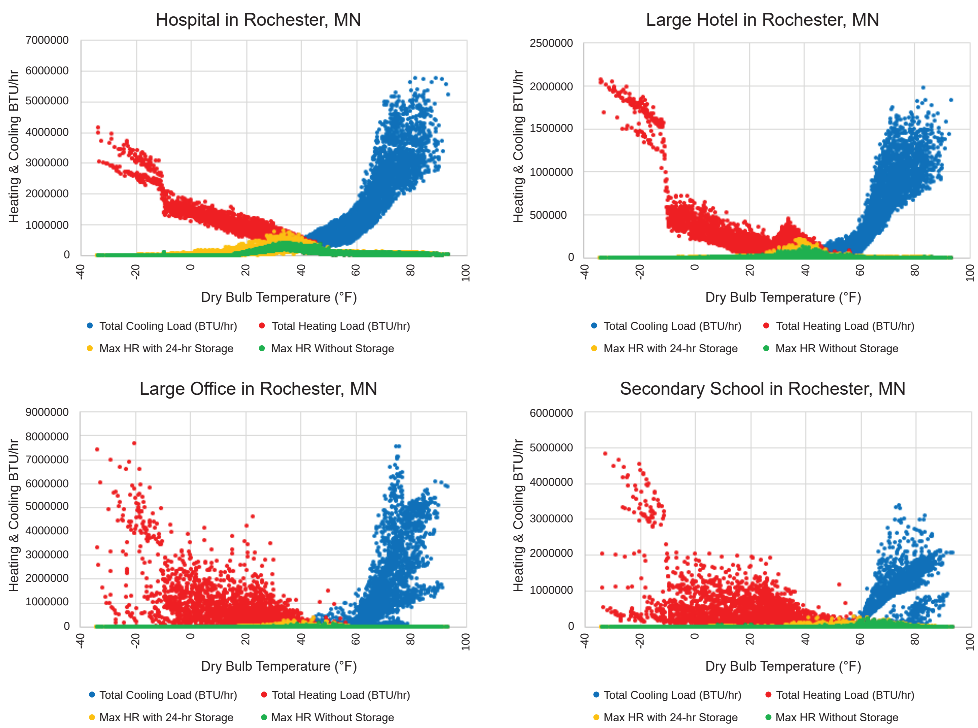
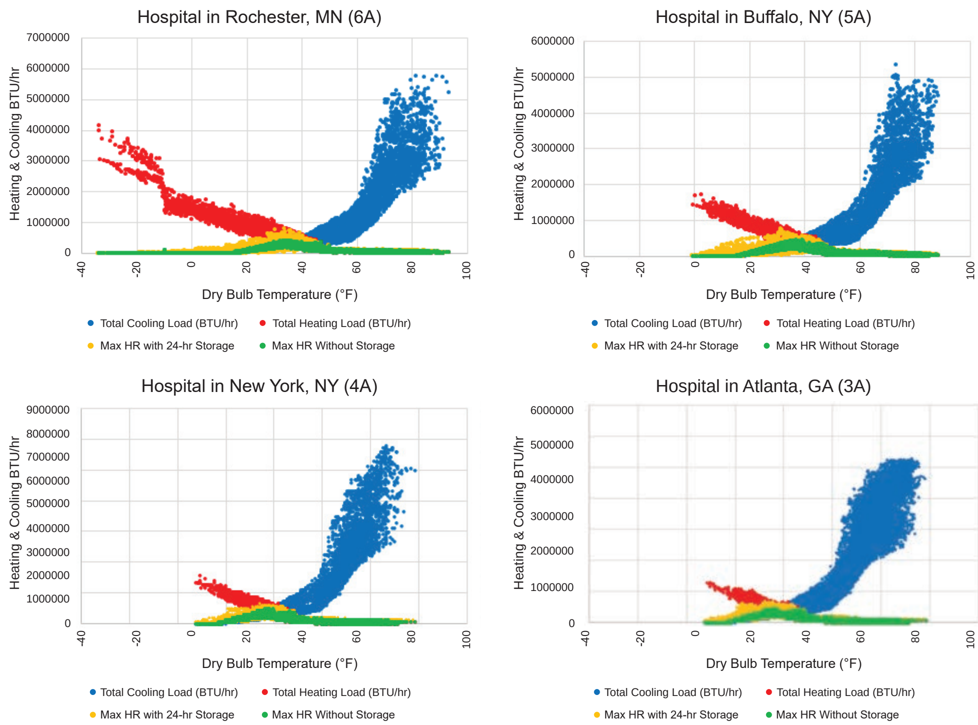


Figure 45 compares the hospital model in Rochester, MN (climate zone 6A), to the same building in three different climates: Buffalo (climate zone 5A), New York (climate zone 4A), and Atlanta (climate zone 3A). The key difference is the range of outdoor (ambient) temperatures:

- In the warmer climate zones, the peak heating loads are lower and occur at warmer outdoor temperatures, making it easier to use fully electrified heating solutions.
- In the warmer climate zones, an optimally-sized heat-recovery unit can be used for a greater percentage of the total heating load.

Figure 45. Annual load profiles for the hospital in various climate zones

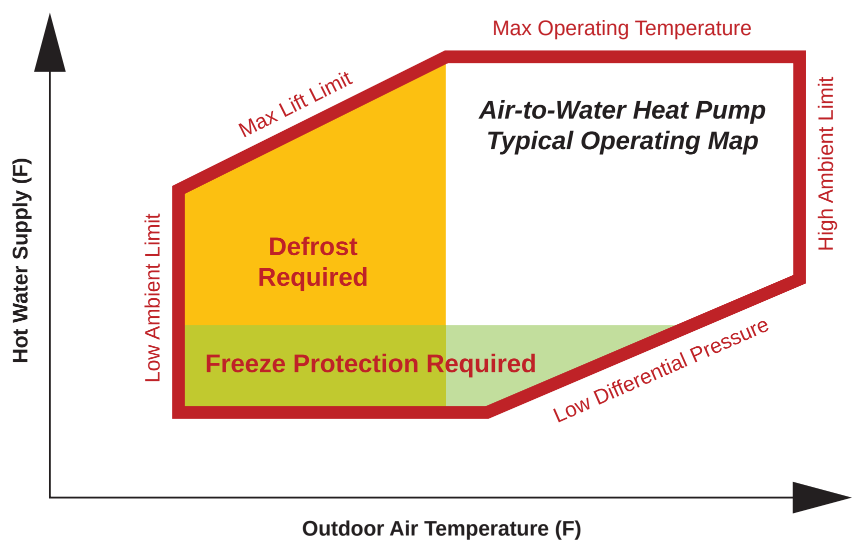


Application considerations when using air-to-water heat pumps

Figure 46 depicts the operating map of an example AWHP, in which HWS temperature is plotted versus outdoor air temperature.

- The Low Ambient Limit is an equipment-specific operational rating. The AWHP will not operate below this temperature, so hot water will not be produced by the heat pump.
- The Max Lift Limit is based on the compressor and refrigerant cycle. When the outdoor air temperature is low, the maximum achievable HWS temperature may be limited.
- The Max Operating Temperature is based on refrigerant pressure and component capabilities.
- The High Ambient Limit is an equipment-specific operational rating. The AWHP will not operate above this temperature.
- The Low Differential Pressure can lead to compressor operational issues, such as oil management problems. Contact the manufacturer to determine the minimum pressure differential for the specific unit being considered.
- Defrost Required indicates that the saturated refrigerant temperature inside the outdoor heat exchanger is below freezing, which results in water vapor from the outdoor air to condense on the heat exchanger and freeze.
- Freeze Protection Required indicates that the fluid temperature is near freezing.
- Freeze protection is often provided by adding either ethylene glycol or propylene glycol to the fluid. Note that this changes the heat transfer properties of the fluid, which impacts the performance of coils in air-handling units or terminal units unless an intermediate heat exchanger is used.

Figure 46. Example operating map for an AWHP

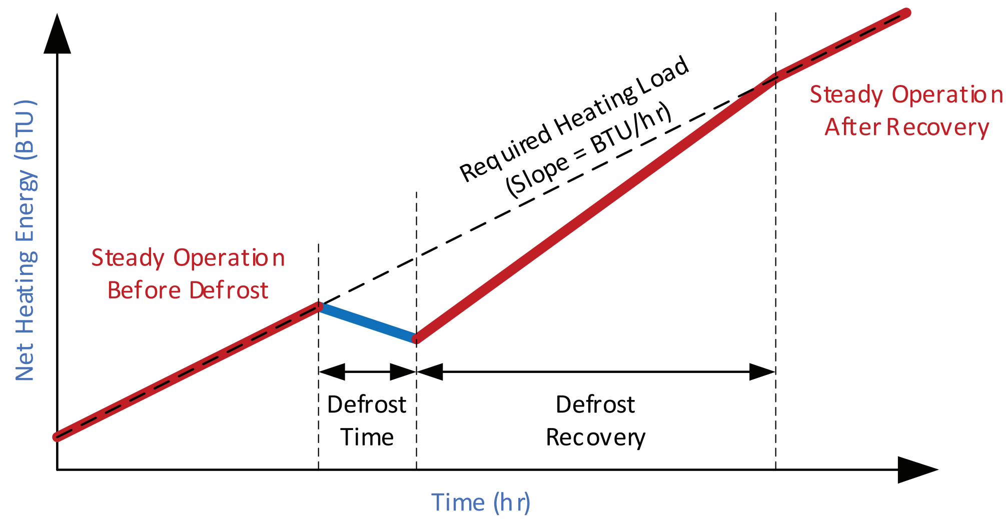


Defrost operation

When operating in heating mode, an AWHP uses a refrigerant-to-air heat exchanger as the evaporator. When the refrigerant temperature inside this heat exchanger drops below 32°F (0°C), frost can form on the outdoor coil surfaces. This frost layer degrades heat transfer and reduces unit performance. Defrost mode temporarily reverses the refrigerant cycle, warming up the refrigerant-to-air heat exchanger and melting the frost.

When an AWHP is operating in defrost mode, the hot-water loop is temporarily cooled instead of heated (Figure 47). When defrost is complete, the heat pump will operate at an elevated capacity until the temperature of the hot-water loop returns to its setpoint. This defrost recovery time depends on how much heat was removed from the hot-water loop for defrost, as well as the amount of excess heat pump capacity available beyond the current heating load.

Figure 47. Depiction of defrost mode and recovery

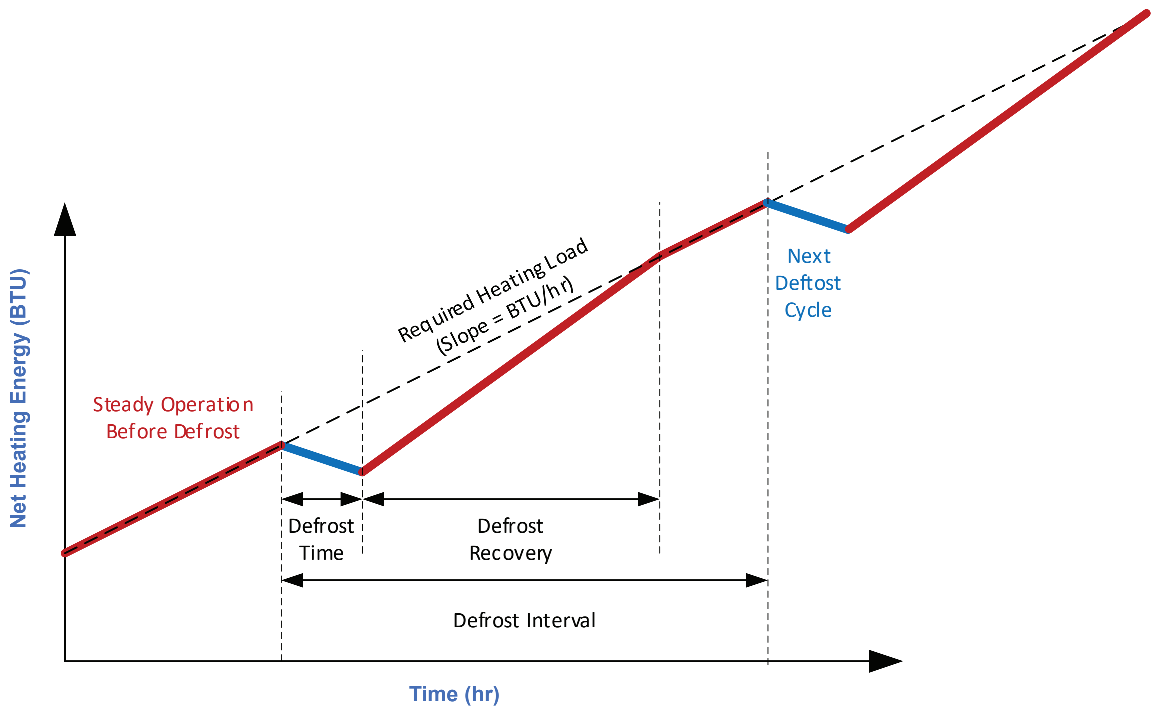


The impact of defrost on system performance can be minimized with the following methods:

- Install a buffer tank at the AWHP outlet to mix cooler water supplied during defrost mode with stored hot water from the tank.
- Enable another AWHP to counteract defrost effects. An AWHP with multiple refrigerant circuits typically includes control programming that operates one circuit in heating mode while another is in defrost mode.
- Enable backup or supplemental heat to counteract defrost effects.

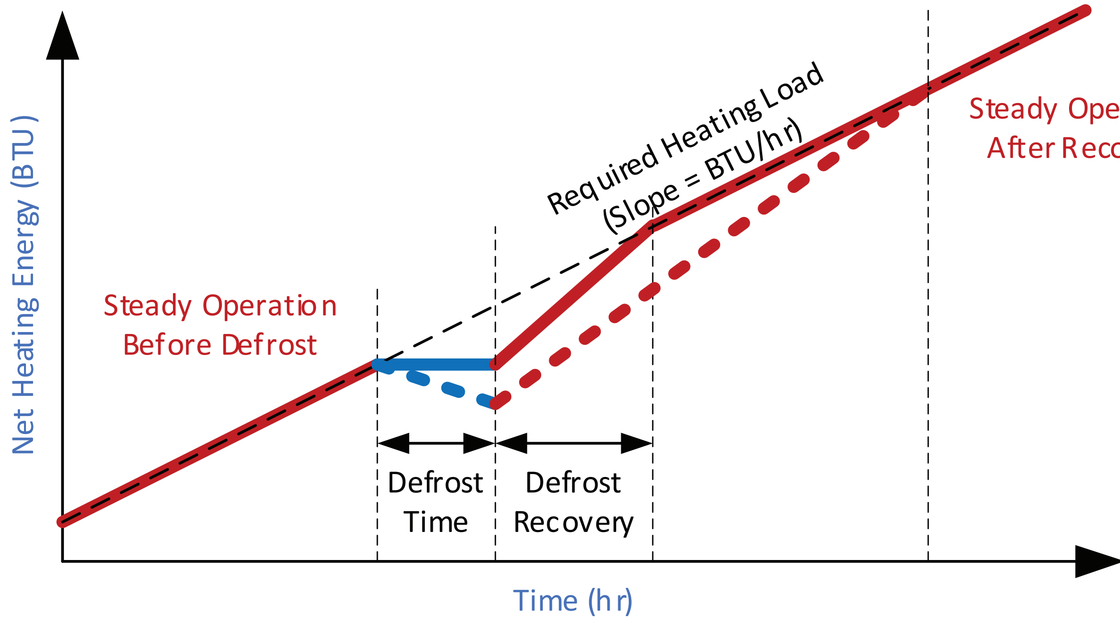
If frequent defrost operation is required, the interval between defrost cycles (“Defrost Interval” in Figure 48) must be longer than the Defrost Time plus Defrost Recovery Time. If the Defrost Interval is too short, the AWHP may not recover quickly enough to keep the hot-water loop temperature at its desired setpoint.

Figure 48. Defrost interval



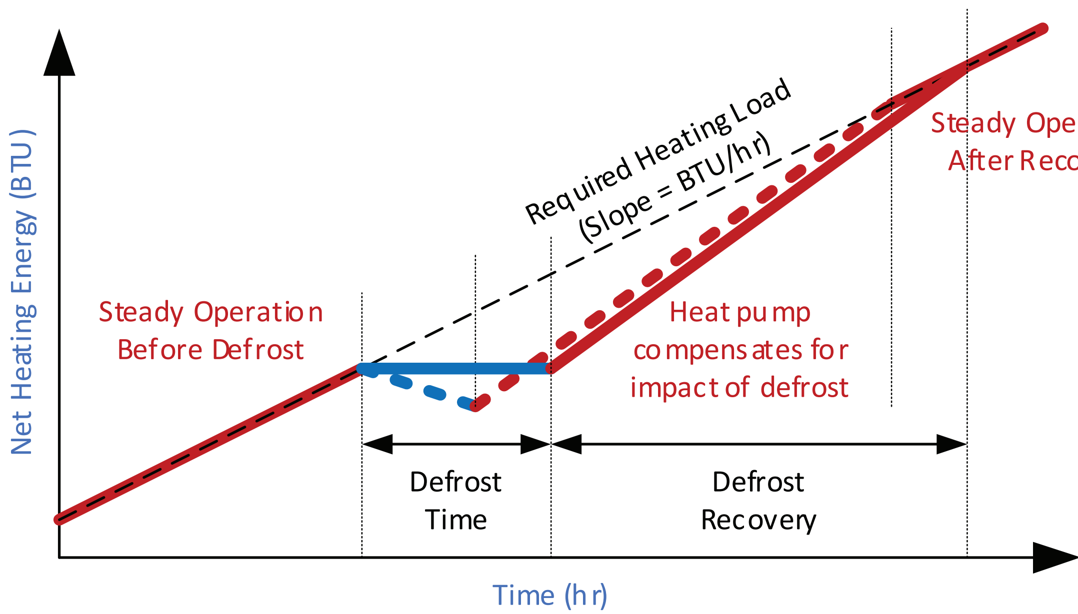
When additional heat pumps are available, the system controller may enable another heat pump to counteract the cooling effect of defrost mode (Figure 49). When defrost is complete, the additional heat pump capacity allows the hot-water loop temperature to recover more quickly (slope of the red line is steeper during Defrost Recovery). This significantly shortens the Defrost Recovery Time.

Figure 49. Operating additional heat pumps to shorten defrost recovery time



It may seem logical that using a slower defrost cycle that avoids cooling the hot-water loop would shorten the defrost recovery time. However, the drawback of this strategy is that while defrost is happening, the heating coils continue pulling heat from the hot-water loop. Figure 50 compares a faster defrost mode (which cools the hot-water loop) to a slower defrost mode (which does not cool the hot-water loop). The faster defrost mode recovers more quickly, returning the loop to setpoint, even though the hot-water loop is temporarily cooled.

Figure 50. Faster versus slower defrost mode



Application considerations when using centrifugal compressor heat pumps

Centrifugal chillers are typically chosen for high efficiency and high capacity. When a centrifugal chiller is used in a heating system, ensure that its unloading characteristics avoid surge conditions.

As the load and the corresponding refrigerant flow rate continue to fall, the radial velocity (force) also drops. At some point, the radial force becomes less than the generated static pressure, allowing pressurized refrigerant vapor to flow backward from the diffuser passages into the impeller. This instantaneously reduces the pressure within the passages below the radial force allowing the compressor to re-establish the proper direction of refrigerant flow.

This condition is known as surge. As long as this unstable condition exists, the refrigerant alternately flows back and forth through the compressor impeller, generating noise and vibration.

Compressor surge happens when the discharge pressure is not high enough to move refrigerant gas from the lower-pressure evaporator to the higher-pressure condenser. When this occurs, the refrigerant cycle becomes unstable, causing high levels of stress and audible noise. Unit controls respond to surge by increasing lift (increasing the rotational speed of the impeller). If the compressor is already operating at a high-lift condition, such as heating mode, it may not be possible for the unit controls to recovery from surge condition.

The following strategies can be used to achieve successful operation of centrifugal compressors in hydronic heating systems:

- Select the chiller to operate at a lower hot-water supply temperature and/or a higher evaporator supply temperature, which will reduce the compressor lift.
- Regulate the hot-water return temperature rather than the hot-water supply temperature, which will naturally reduce lift at lower system loads.
- Add smaller-capacity heat pumps to the system, which can operate when heating loads are below the minimum load value for the centrifugal heat pump.

Reducing the Risk for Contractors

Electrified heating systems are relatively new to many engineers, owners, and contractors. This creates a high-risk environment, especially for contractors tasked with installing these systems. Existing buildings add to this risk due to factors that contractors will already be familiar with, such as unforeseen conditions, tight spaces for installing equipment, lack of project coordination, and the impact these issues have on project cost and timeline.

When preparing a bid on a project, it is important to recognize that heat pumps and other electrified heating systems are being used and how that could impact the project. In many cases, heat pump equipment will be larger, heavier, and potentially more complicated to install and operate. Lower hot-water supply temperatures may increase the size of heating coils, making it even more challenging to fit larger AHUs, VAVs, and terminal units into tight existing mechanical rooms and ceilings. Roof space may be covered with AWHPs and/or solar panels. Ductwork and piping may also be larger and may not easily fit through existing openings and chases. Ultimately, it is the engineer's responsibility to design a building that can be built, but engineers are not experts in how things are installed and constructed. Suggestions related to routing, mechanical room layout, and overall system "buildability" will improve project outcomes and potentially lower project risk and costs.

The most common risk in existing buildings is unforeseen circumstances. Although contractors with experience working in existing buildings may be familiar with this, it becomes even more important when working on electrification jobs. Issues identified during demolition or construction should be brought to the design team's attention as soon as possible to limit impacts on the project timeline and allow the design team to verify that the solution falls within the capabilities of the system design.

Building Information Modeling (BIM) coordination becomes even more critical with electrification since equipment, piping, and ductwork may be larger, and existing buildings were rarely designed with ample space for newly designed systems. Regardless of the software used, clash detection and coordination between the construction manager, contractors, and engineer must be addressed quickly. Frequent coordination calls with all construction team members are an industry best practice. Ideally, issues are identified and resolved in real time during these calls rather than being sent through a Request for Information (RFI) process, which could extend the solution timeline by several weeks or longer. Maintaining good working relationships among the design team improves both the speed and quality of the solutions developed.

Substituting equipment that deviates from the basis of design may be economically advantageous but could be risky with heat pump equipment and should be evaluated carefully. Unlike traditional fossil fuel-based heating systems, heat pump equipment is designed for a specific range of operating conditions, and may differ from manufacturer to manufacturer even when unit capacities are identical. Compressors often have less turndown than modern modulating gas heating systems, and this information may not be clearly identified in the submittal. The engineer reviewing the submittals typically notes that they “take no exception to the information given” when sending submittals to the engineer. It is critical that all important information is provided and that the submittal clearly includes at least the following:

- Capacity at design conditions or rated conditions
- Heating temperatures and source temperatures (often outdoor air or geothermal)
- Unit turndown
- Defrost operation and approximate derate
- Minimum operating conditions
- Maximum heating temperatures and corresponding source temperature requirements

System Maintenance Considerations

As with any mechanical system, proper maintenance is imperative for system performance and longevity. For recommended service tasks and intervals, refer to the equipment manufacturer's installation, operation, and maintenance manual.

A unique aspect of electrified systems is that the equipment may be used year-round, as it provides both heating and/or cooling. Therefore, this equipment may operate for more hours than conventional equipment that provides only cooling or only heating. For example, an AWHP designed to cool in the summer and heat in the winter will accumulate significantly more run hours than a water chiller that cools only in the summer or a boiler that heats only in the winter.

Make use of any planned downtimes, such as summer or winter vacations, for routine maintenance. If shoulder seasons require less capacity, that may also be a good time for routine maintenance. Also, consider the quantity of units when designing a central plant. For instance, three smaller units may allow for easier servicing than one or two larger units.

Maintenance must not be overlooked, and with careful planning during the design process, it can be made simpler for operators to execute.

Total Cost of Ownership

Retrofitting an existing system with electrified heating can present many unique challenges that impact the system choice or configuration. One of the key considerations is total cost of ownership (TCO) or life cycle cost (LCC). It is important to understand the cost of owning a system over its lifetime and use that information to help the owner find the best balance between low first (initial) cost and low operational costs, while also eliminating or reducing site carbon emissions (CO_2e).

The total cost of ownership extends past the initial “first costs” and continues throughout the lifetime or life cycle of the equipment. At the beginning of the project, clear objectives should be established for the designers to follow in order to meet design parameters and owner expectations. These objectives could be existing standards set by the owner or decided upon at the beginning of the project by the owner, architect, and engineer. One method engineers can use to justify their design selections is a Life Cycle Cost Analysis (LCCA). An LCCA is useful when multiple equivalent equipment selections satisfy the design and takes into consideration not only the first cost, but also operational costs, maintenance costs, repair costs, replacement costs, system upgrade costs, and utility rebates.

The LCCA should be based on the owner’s financial requirements and decarbonization goals, providing a framework for system and equipment selections. Organizations such as hospitals, universities, and corporations typically have these guidelines in place along with sustainability requirements, hurdle rates, and long-term performance goals. As the business evolves and the facility ages, these guidelines will assist in developing annual budgets beyond year one and throughout the life of the facility.

Alternatives to the primary design should not only meet the design parameters but also fall into the owner’s financial guidelines for minimum rate of return, user preferences, and effect on the overall HVAC system. Decisions made on individual factors in determining the life cycle cost (LCC) gives only a partial glimpse into the cost analysis, while the sum of the components gives a more holistic view.

For each system, the total LCC can be calculated using the following equation from the 1996 NIST Handbook *Life-Cycle Costing Manual for the Federal Energy Management Program* by Fuller and Peterson[11]:

LCC= I + Repl - Res + E + W + OM&R

where:

LCC = total life cycle cost in Present-Value dollars of a given alternative

I = Present-Value investment costs

Repl = Present-Value capital replacement costs

Res = Present-Value residual value (resale value, scrap value, etc.) less disposal costs

E = Present-Value energy costs

W = Present-Value water costs

OM&R = Present-Value non-fuel operating, maintenance, and repair costs

This equation sums the present value of each component and considers escalating utility costs, labor costs, repair costs, and similar factors into the calculation.

The sum of all LCC component costs represents the true total cost of ownership for the end user. Load and energy modeling platforms and commercially available tools can aid the engineer not only in calculating the load and system performance from a comfort perspective, but also in energy and life cycle costs.

Example: Packaged (unitary) rooftop units

This example models a real-world classroom—occupied in the fall, and spring, unoccupied in the summer—across many climate zones to compare various rooftop system configurations. The space is a single 30-person multipurpose classroom served by one high-efficiency packaged rooftop unit. Design outdoor airflow is 470 cfm, based on ASHRAE Standard 62.1, and the desired space temperatures are 73°F for cooling and 70°F for heating.

This analysis compared the energy use, emissions (CO_2e), and life cycle cost of four different rooftop system configurations:

- First, a gas/electric rooftop unit in which heating is provided by a natural gas burner and cooling by electricity (compressor).
- Second, an electric/electric rooftop unit in which heating is provided by an electric resistance heater and cooling by electricity (compressor).
- Third, a heat pump rooftop unit with an auxiliary electric resistance heater
- Fourth, a heat pump rooftop unit with an auxiliary natural gas burner (often referred to as a dual-fuel heat pump)

Table 4 lists the various locations modeled, along with their corresponding ASHRAE climate zones. In addition to different utility rates, these locations also have differing CO_2 emission factors that affect the CO_2e analysis. The following discussion focuses on four cities that provide a broad sample representation of climates: Orlando, Los Angeles, St. Louis, and Toronto.

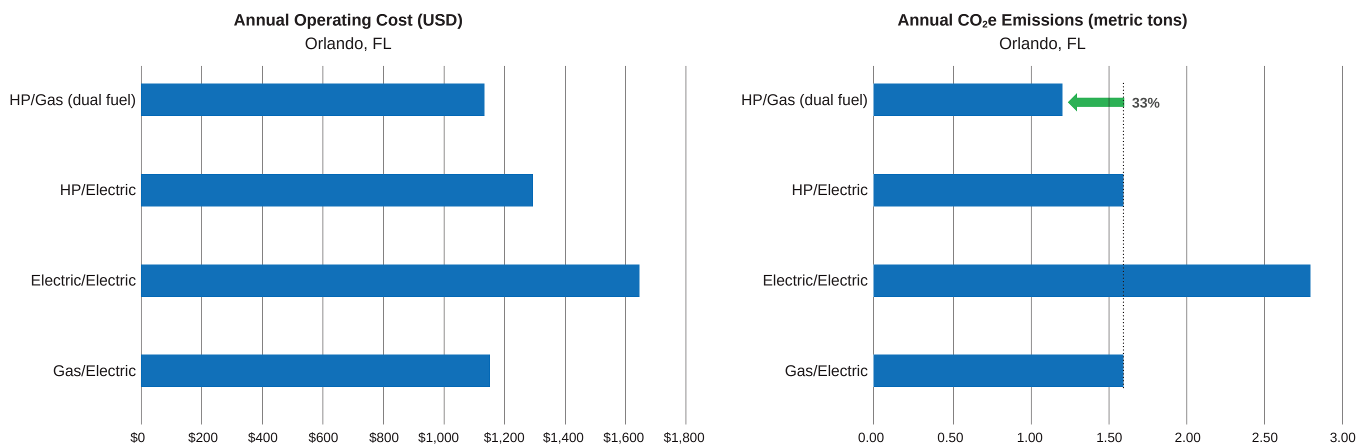
Table 4. Example classroom served by a packaged rooftop unit in various climate zones

Location	ASHRAE Climate Zone	ASHRAE Design (0.4% / 99.6%)		Blended Utility Rates		RTU cooling capacity (tons)	Cooling Load (Btu/hr)	Heating Load (Btu/hr)
		Cooling DBT/ WBT, ºF	Heating DBT, ºF	Electricity ($/kWh)	Gas ($/Therm)			
Orlando, FL	2A	93.8/76.5	37.8	0.12	1.25	5	62,000	25,000
Los Angeles, CA	3B	83.7/63.3	44.5	0.23	1.20	3	34,000	22,000
St. Louis, MO	4A	95.5/76.8	6.6	0.11	1.10	5	60,000	78,000
Toronto, ON	5A	88.5/72.3	-0.5	0.16	1.05	4	46,000	86,000

The following figures depict the simulated energy use and CO_2 equivalent (CO_2e) emissions for this example classroom in four different cities, using the gas/electric rooftop unit as the baseline for comparison.

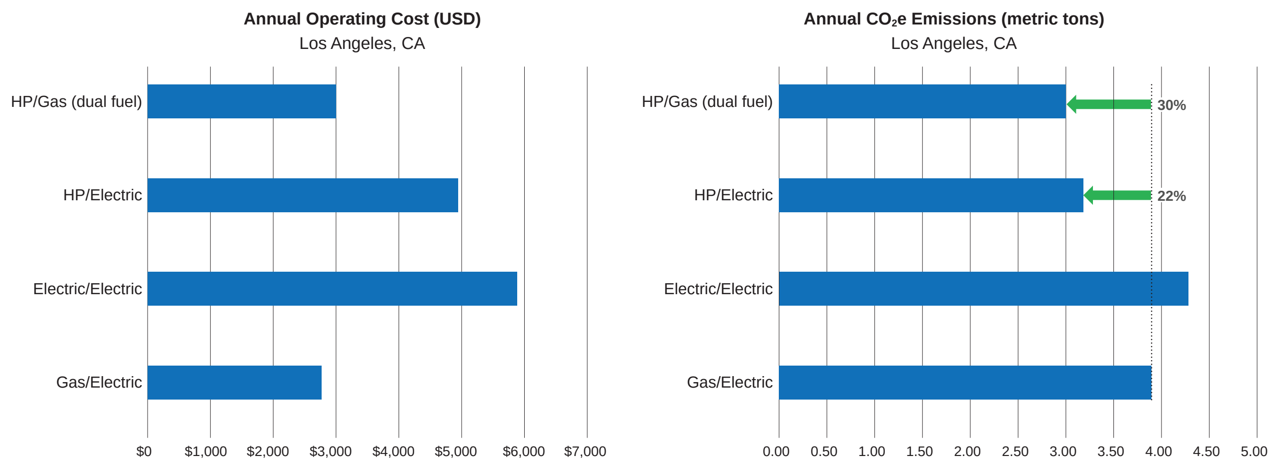
The classroom in Orlando is a cooling-dominant application, with only a small amount of heating required. There is little difference in annual operating energy costs between the two heat pump configurations, but the operating costs increase when using the electric/electric rooftop configuration (Figure 51). As for emissions, a heat pump—whether using auxiliary electric or natural gas heat—shows a 33 percent reduction in CO_2e emissions compared to a traditional gas/electric rooftop unit.

Figure 51. Orlando annual operating costs and CO_2e emissions



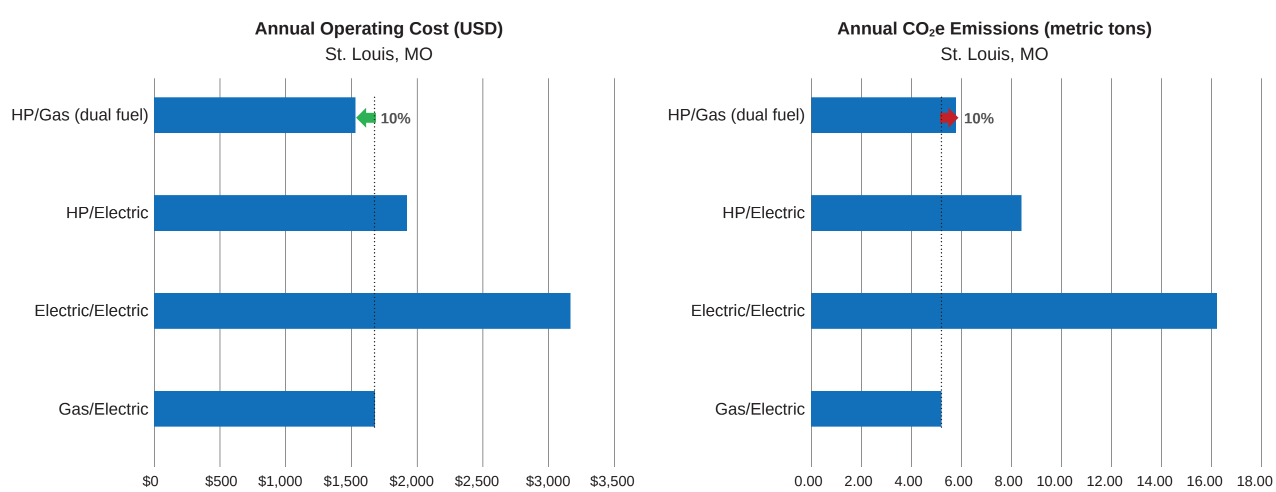
Los Angeles is a mixed climate, where the heating and cooling design loads are similar in magnitude, but requires more heating than Orlando. As a result, there is a somewhat larger difference in operating costs between the four system configurations due to higher electric utility rates (Figure 52). The CO_2e reductions for both heat pump alternatives are similar: 22 percent with auxiliary electric heat and 30 percent for auxiliary gas heat.

Figure 52. Los Angeles annual operating costs and CO_2e emissions



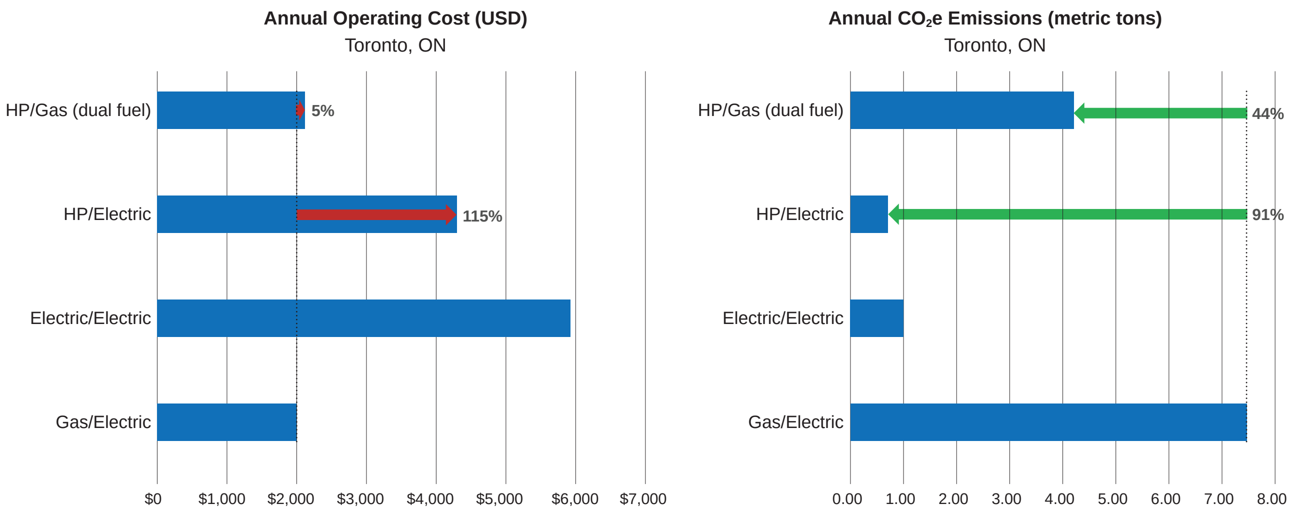
St. Louis is also a mixed climate, where the cooling and heating design loads are similar in magnitude. Due to local utility rates, a heat pump with auxiliary gas heat saves approximately 10 percent in annual operating costs, but CO_2e emissions are 10 percent higher than those of the baseline gas/electric rooftop unit because of the local grid emissions factors (Figure 53). This demonstrates how utility rates and the cleanliness of the utility grid can play a factor in equipment selection. If the owner's goal is to decarbonize, then a traditional gas/electric unit actually results in the lowest CO_2e for this example. However, if the goal is to reduce operating costs, a heat pump with auxiliary gas heat provides the lowest annual cost.

Figure 53. St. Louis annual operating costs and CO_2e emissions



Toronto is the coldest of the four cities analyzed and therefore has the most hours of heating operation. For this example, the baseline gas/electric rooftop unit offers the lowest annual operating cost (Figure 54). A heat pump with auxiliary electric heat costs 115 percent more to operate, but offers an 91 percent reduction in CO_2e due to very low grid emissions.

Figure 54. Toronto annual operating costs and CO_2e emissions



By comparing the annual operating costs (Figure 55) and CO_2e emissions (Figure 56) for these four rooftop system configurations, in these four cities, it becomes apparent that the “best” system depends on the owner’s goals. Is the owner looking to reduce operating (energy) costs as much as possible? Or does the desire to electrify and reduce carbon emissions overrule the desire for the lowest operating cost? Utility costs and the cleanliness of the grid are key factors in selecting the right system for the project.

Figure 55. Annual operating cost comparison (example classroom)

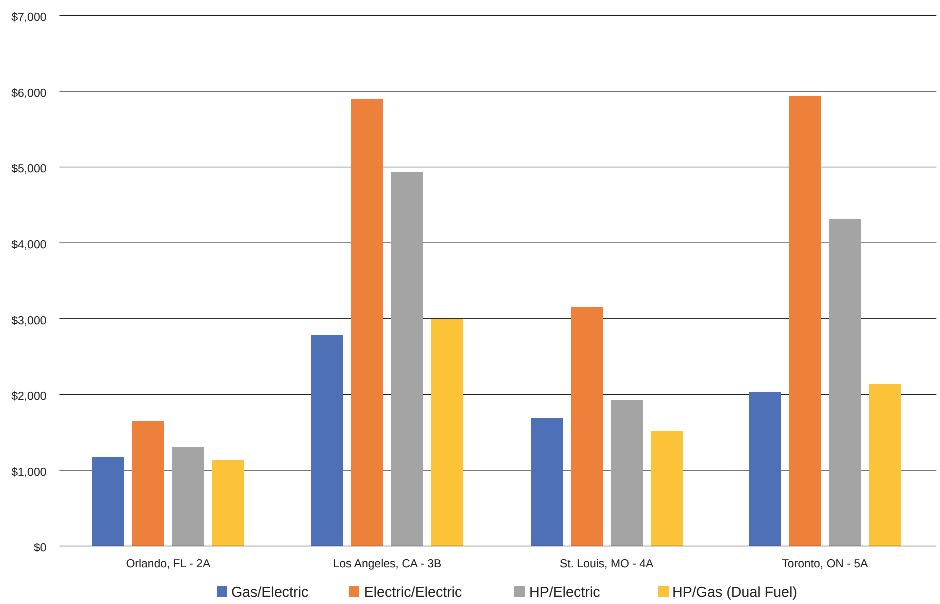
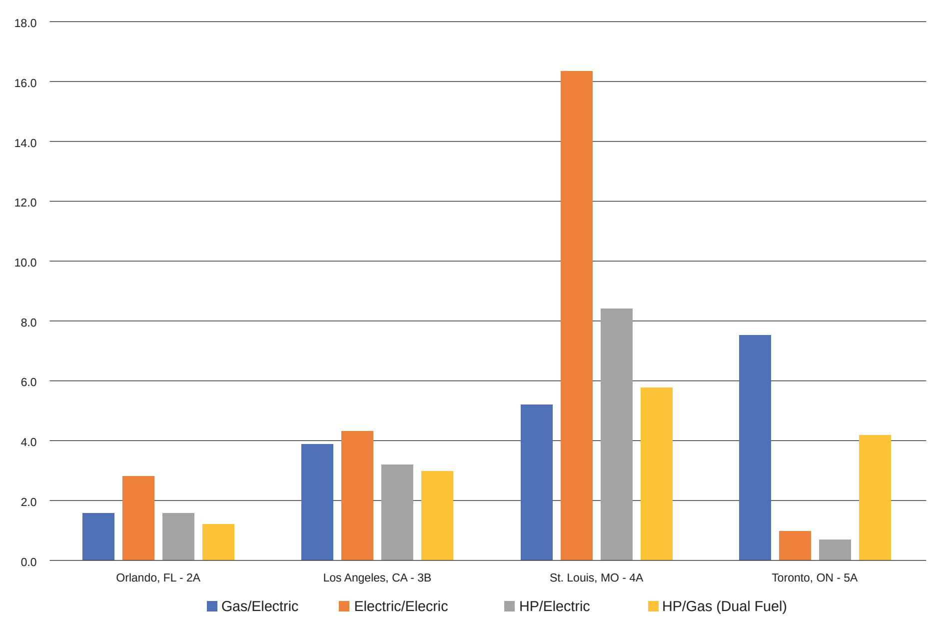


Figure 56. Annual CO_2e emissions comparison (example classroom)



LCC Equation:
LCC= I + Repl - Res + E + W + OM&R

A description of the LCC equation can be found on page 69.

With the annual operating costs estimated, the next step is to conduct a life cycle cost analysis (LCCA). For this example, equipment life is assumed to be 15 years before it will need to be replaced. Other values used in the LCC equation include (Table 5):

- **I**: The cost to install the replacement rooftop unit in each case.
- **Repl**: Replacement costs are assumed to be $0 during the 15-year life cycle since new equipment is being installed and not expected to be replaced during this time period.
- **Res**: Residual value is assumed to be $0 because the equipment has no value after its lifetime of operation.
- **E**: Energy costs for the new equipment are based on the simulated results described previously, assuming 3 percent annual escalation in utility rates.
- **W**: Water costs are assumed to be $0 because packaged, air-cooled equipment is being used.
- **OM&R**: Non-fuel operating, maintenance, and repair costs for the new equipment are assumed to be $75 per ton for Year 1, with a 5 percent annual escalation in subsequent years. This assumes that the cost to maintain a gas/electric rooftop unit is the same as for an electric/electric rooftop or a heat pump with auxiliary electric or gas heat.

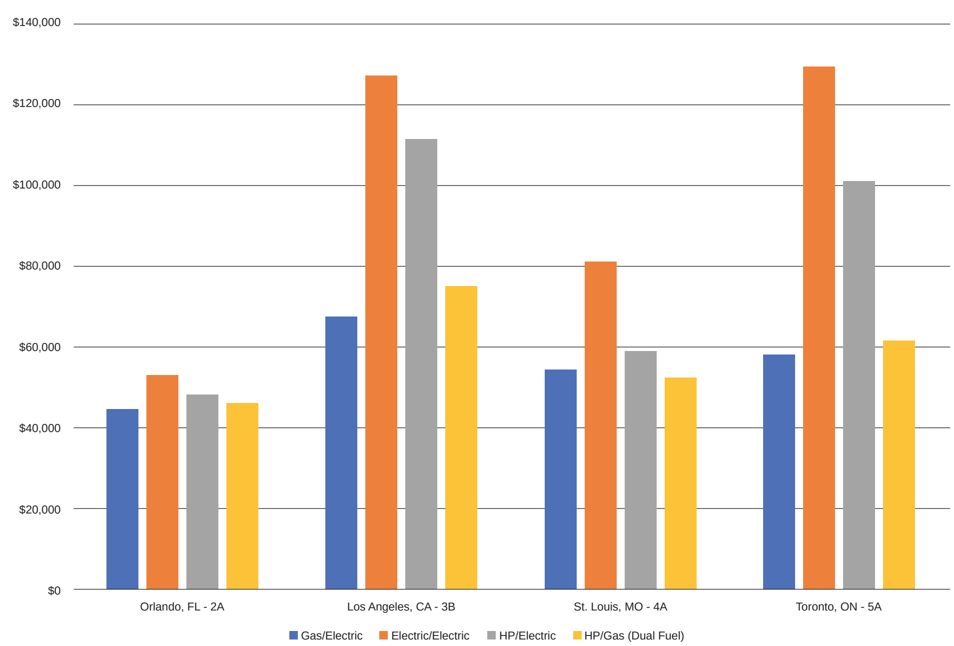
Table 5. Inputs used for LCC calculations

	Alternate	LCC ($)	I ($)	REPL ($)	RES ($)	E ($)	W ($)	OM&R ($)
Orlando, FL	Gas/Elec.	44,778	15,204	0	0	21,482	0	8,092
	Elec./Elec.	53,369	14,682	0	0	30,595	0	8,092
	HP/Elec.	47,897	15,831	0	0	23,974	0	8,092
	HP/Gas (Dual Fuel)	45,609	16,519	0	0	20,998	0	8,092
Los Angeles, CA	Gas/Elec.	68,840	12,671	0	0	51,314	0	4,855
	Elec./Elec.	127,217	12,331	0	0	110,031	0	4,855
	HP/Elec.	109,929	13,065	0	0	92,009	0	4,855
	HP/Gas (Dual Fuel)	74,854	13,886	0	0	56,113	0	4,855
St. Louis, MO	Gas/Elec.	54,356	15,204	0	0	31,060	0	8,092
	Elec./Elec.	81,212	14,682	0	0	58,438	0	8,092
	HP/Elec.	59,428	15,831	0	0	35,505	0	8,092
	HP/Gas (Dual Fuel)	52,807	16,519	0	0	28,196	0	8,092
Toronto, ON	Gas/Elec.	58,093	13,938	0	0	37,681	0	6,474
	Elec./Elec.	130,031	13,507	0	0	110,050	0	6,474
	HP/Elec.	100,786	14,448	0	0	79,864	0	6,474
	HP/Gas (Dual Fuel)	61,301	15,193	0	0	39,634	0	6,474

Figure 57 shows a side-by-side comparison of the total cost of ownership (life cycle cost) for all four cities:

- Heat pumps can often offer a lower LCC; such as, in St. Louis where a heat pump with auxiliary gas (dual fuel offers the lowest TCO).
- If the owner or engineer wishes to electrify to reduce carbon emissions—or if this is mandated by local code—a heat pump is a good choice, since the LCC is lower than that of the electric/electric rooftop.
- Using a dual-fuel heat pump (equipped with auxiliary gas heat) is a viable option in colder climates like Toronto and St. Louis, resulting in a lower LCC than a heat pump equipped with auxiliary electric heat.
- A factor not considered is local utility incentives and rebates as these vary but would directly reduce equipment first cost or investment (I) in the LCCA.

Figure 57. Total cost of ownership (life cycle cost) comparison (example classroom)



Total cost of ownership (life cycle cost) is only one of many factors that influence the selection of equipment that meets project requirements and desired outcomes.

System Operation and Control

Owner's Project Requirements (OPR): a written document that details the functional requirements of a project and the expectations for how it will be used and operated. These include project goals, measurable performance criteria, cost considerations, benchmarks, success criteria, and supporting information (The term "project intent" is used by some owners for their commissioning process Owner's Project Requirements.).

Building operating staff ultimately determine whether a system provides its intended purpose and attains the desired increase in efficiency and/ or reductions in emissions. Involve building operators early in the design process and provide materials so they can help deliver the Owner's Project Requirements (OPR), save energy, and reduce emissions.

Proper building and system operation and control determine project success. The ASHRAE Advanced Energy Design Guide for K-12 School Buildings (Achieving Zero Energy)[4] provides an example OPR that includes energy efficiency, environmental sustainability, personnel training, and operation and maintenance criteria. Systems can be designed and installed as intended, yet operation and maintenance determine whether the OPR are achieved. Including building operators as early as possible in the project process provides continuity from project inception through delivery and daily operation, improving the chances of delivering the desired performance.

Reducing design loads is very important, as is reducing operational loads such as:

- Reducing VAV minimum airflow settings
- Resetting discharge-air temperature setpoints
- Optimizing morning warmup operation
- Implementing demand-controlled ventilation

Other sections in this guide discuss control of electrified heating systems. Additional control details are covered in the *Trane Chilled-Water VAV Systems* Applications Engineering Manual[17], with control sequences available from Trane Design Assist.[24] Additionally the "Hot Water Heating Design and Retrofit Guide," by Cheng, Wendler and Raftery,[9] covers the importance and impact of operations and control in existing systems.

Pumping configurations

In his address,"Greater Efficiency Today, Blue Skies Tomorrow" (2007), ASHRAE Presidential Member Kent Peterson stated,"Energy efficiency should always be the elegant alternative to fuel consumption."[19] Albert Einstein asserted,"Everything should be made as simple as possible, but not simpler." Combining efficiency and simplicity leads to elegant design and understandable, reliable operation. Examples include:

Sidestream heat recovery. Previous sections in this guide discuss the efficiency benefits of recovering heat. However, many building operators may be unfamiliar with the operation of heat-recovery units and systems, resulting in the removal of heat recovery as a system operating mode.

Placing a WWHP in the sidestream position delivers efficiency and operation is very simple:

- When heating is needed, the unit's pump is enabled and flow is proven.
- The heat pump is set to heating mode and supplies the desired hot-water (condenser water) temperature; the resulting leaving chilled water temperature is what it becomes.

- Compressor “lift” and power are reduced since the water leaving the evaporator is only cooled as much as needed to produce the desired hot water temperature.
- The remaining cooling load is satisfied by additional cooling-only chillers.

Primary-secondary pumping configuration. Industry trends often influence standard system design preferences. One example is the shift of variable-flow chilled-water systems from primary-secondary to variable-primary-flow (VPF) configurations. This transition accelerated in the mid-1990s, and has resulted in the majority of current designs using the VPF configuration. However, for today’s electrified hydronic heating systems, there are reasons to revisit the primary-secondary configuration for simplicity and greater reliability.

Many heat pumps today have minimum flow rate limitations that result in the heating minimum flow rate being very close to the heating design flow rate. In a VPF system, this is a poor combination. In this case, the primary-secondary configuration (for both cooling and heating) provides system operators with a simple, understandable, and reliable system:

- Dedicate a production pump to each heat pump, even though it reduces pump redundancy. From a piping standpoint, manifolding pumps is more complex and results in more complex controls.
- Set the production pump to one of two speeds depending on whether the heat pump is operating in cooling or heating mode.
- Change a valve position at each heat pump to send water to either the heating or cooling loop.

This is an elegant system because it reduces number of components (e.g., valves). Each system component provides an additional possible point of failure. For example, a pump check valve prevents fluid from flowing backwards through the pump while it is off. Some designs also provide an isolation valve to allow equipment servicing or replacement. However, adding an isolation valve to ensure fluid cannot flow backwards through the pump is redundant with the check valve. Additionally, confusion about the purpose of an isolation valve can lead to an operator opening the valve during their shift, while an operator on a later shift closes that same valve. Therefore, the control sequence must address situations in which the isolation valve is open or closed. High reliability occurs when only the necessary components are provided and each fulfills its purpose.

Understandable unit sequencing

Many systems include multiple units, so unit sequencing must be provided by the system-level controller. Unit sequencing includes:

- Load, flow, temperature, and pressure measurements to determine when a unit should be enabled (turned on) or disabled (turned off).
- For a primary-secondary configuration, the simplest unit sequencing is to enable another unit when the plant supply-water temperature deviates more than 2°F (-17°C) (adjustable) from setpoint for 15 minutes (adjustable), and to disable a unit when excess flow through the bypass line reaches 110 percent (adjustable) of the unit's design flow rate.
- Enabling ancillary equipment (pumps, cooling towers, auxiliary heating units) as needed.

For units that use water for heat rejection in cooling mode:

- Keep condenser water flow rate and pump speed constant to simplify operation.
- Implement the chiller-tower optimization sequence and maximize the number of cooling tower cells available for heat rejection to increase system efficiency.

Fault detection and diagnostics

Fault Detection and Diagnostics (FDD) is the process of uncovering errors in physical systems and identifying the source of those errors. Automated FDD uses data to detect, isolate, identify, and evaluate (or diagnose) faults. Lawrence Berkeley National Laboratory provides significant guidance regarding the fault detection on airside systems and chiller plants.[15] FDD for combined cooling and heating plants may include:

- Leaving-temperature sensor bias (chilled water, heat rejection water, and heating water)
- Distribution or secondary pump differential pressure sensor bias
- Leakage or sticking of any three-way or bypass valves
- Heat exchanger fouling (evaporator, heat rejection, or heating)

Defrost coordination

As discussed previously in this guide, when heat is extracted from cold outdoor air, frost may form on the outdoor coils. This results in reduced heat transfer and airflow. Air-to-water heat pumps include frost detection and will switch the unit into defrost mode, during which unit heating is limited or cooling of the building may occur. Since unit defrost is important, system controls should monitor unit defrost operation and coordinate units to ensure they do not all defrost at the same time.

Broad operating maps

There is no replacement for raw efficiency. Selecting and installing efficient equipment is a simple way to reduce energy use, particularly when that efficiency is maintained throughout the expected annual load profile. Equipment with a broad operating map remains online and is likely to operate efficiently. Capabilities and technologies that achieve a broad operating map include:

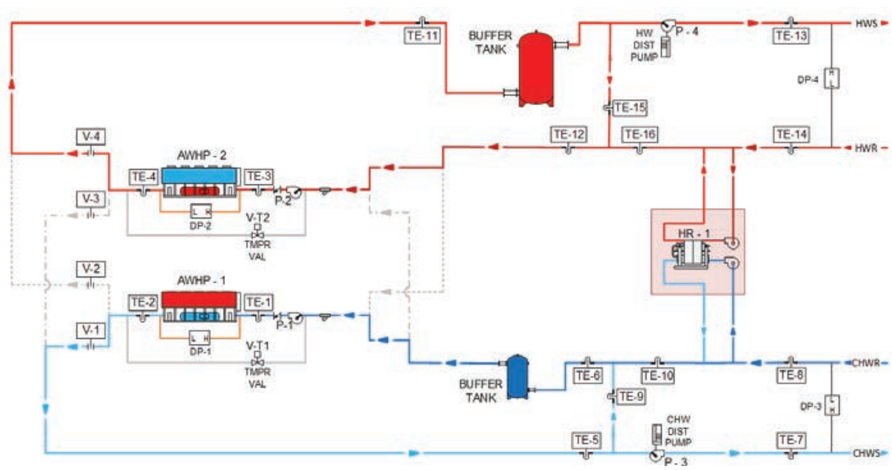
- Unloading potential (often using a variable speed drive)
- Continuous unloading mechanism for more consistent temperature control
- Multiple stages of compression when using centrifugal compressors

Operating knowledge

Improving building and system operator knowledge is perhaps the simplest and most effective way to increase the simplicity, reliability, and efficiency of a system. In addition to specific training, a few methods to achieve this include:

Accurate and understandable system schematics. While complete system design drawings are required for construction, accurate and understandable schematics and sequences of operation provide operators with a high-level knowledge of the design intent. Schematics also provide graphical representations for building automation systems. Such diagrams should include major system components, such as heat pumps, control valves, pumps, temperature sensors, heat rejection equipment, auxiliary heating equipment, and other important components. An example system schematic with two air-to-water heat pumps is shown in Figure 58. One unit is operating in cooling mode, one in heating mode, and a dedicated heat-recovery unit is in the sidestream position.

Figure 58. Example system schematics



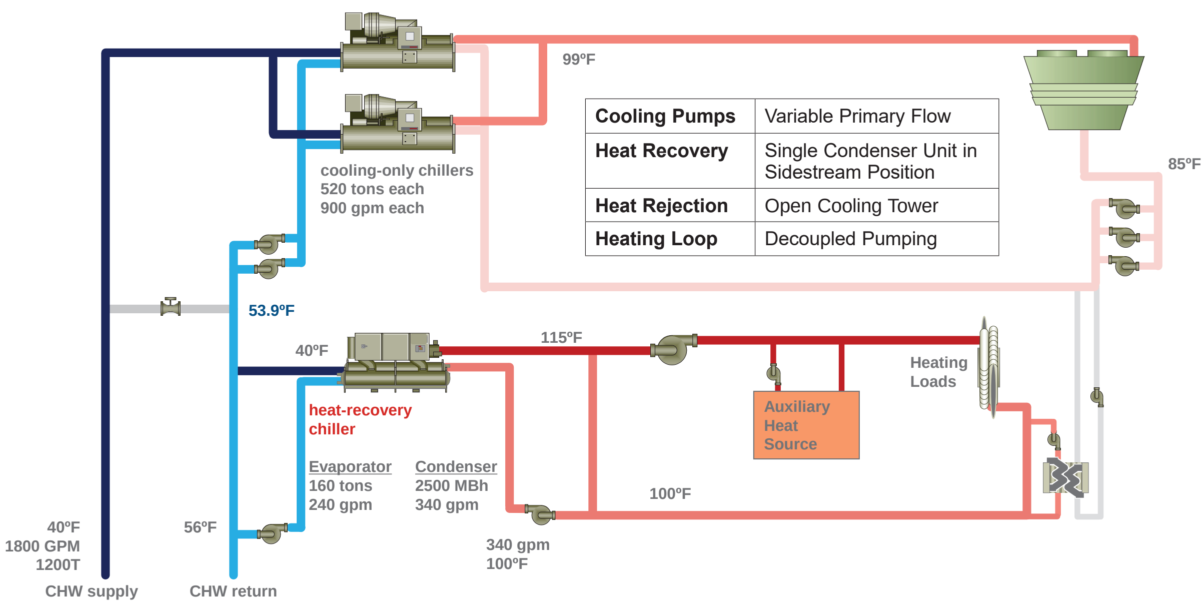
Descriptions of subsystem intent and operation. Describe the intended operation of each subsystem or component in simple and clear terms. The goal is to provide enough information for a building operator—who likely has different training than the design engineer—to understand how the system is expected to operate. Figure 58 depicts the following subsystems:

- Dual-feed air-to-water heat pumps may be connected to either the cooling loop or the heating loop through the use of hydronic isolation valves.
- Primary pumps maintain flow through the heat pump.
- Secondary pumps maintain distribution differential pressure.
- A buffer tank in the cooling loop return improves cooling supply temperature regulation.
- A buffer tank in the heating loop, downstream of the AWHP, buffers the system from temperature changes during defrost.

- A dedicated heat recovery unit is connected in a sidestream to the heating loop return and cooling loop return, maximizing heat recovery potential and simplifying temperature control logic.
- A supplemental boiler is included in the heating loop supply, allowing the boiler to supplement AWHP capacity during peak heating load, or to replace AWHP capacity when the ambient temperature is too cold for the AWHP to operate.

Mode charts. Mode charts are a critical but often missed piece of information to provide for building operators. The example mode chart in Figure 59 depicts system operation in one mode and includes valve positions, control setpoints, and other related setpoints. Each mode allows the operator to understand the intended system operation and allows them to determine if the system is operating as intended.

Figure 59. Example system mode chart, sidestream heat recovery, one heat pump operating in cooling



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Glossary

air-to-water heat pump (AWHP). A unit that heats or cools fluid by transferring energy between the fluid and the air via a refrigeration circuit and often contain a reversing valve. AWHPs may contain more than one refrigeration circuit and can be configured as a two-pipe or four-pipe unit (see Multi-pipe heat pump). Two pipe AWHPs that either cool or heat include a reversing valve and four-pipe units that can cool/heat, cool only, or heat only do not have a reserving valve.

ASHRAE®. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE/IESNA Standard 90.1-2022. A publication titled Energy Standard for Buildings, Except Low-Rise Residential Buildings that provides minimum requirements for the energy-efficient design of buildings (except low-rise residential buildings), including the HVAC system.

building automation system (BAS). A combination of controllers and other software products that communicate and control various mechanical systems to enable building management. These include the heating, ventilation, and air-conditioning (HVAC) systems as well as lighting systems, access control, and miscellaneous other devices within a building; also known as a building management system (BMS).

building information modeling (BIM). The human activity of using BIM software and other related software, hardware, and technologies to create and use in a building information model. Building information model is a data specification for representing building information for the purposes of interoperable data exchange. Also, a data model of a specific building or its systems, components, or other information elements based on that specification.

centrifugal compressor. A type of compressor that uses force generated by a rotating impeller to compress the refrigerant vapor.

chilled water. The cold water produced by the chiller and pumped to the air-handler coils throughout the building; also known as leaving chilled water or leaving evaporator water.

coefficient of performance (COP). A dimensionless ratio used to express the efficiency of a refrigeration machine. A higher COP designates a higher efficiency. For an electric chiller, it is defined as evaporator cooling capacity divided by the electrical energy input. Additional COP definitions are described in this manual.

compressor. A mechanical device used in the vapor-compression refrigeration cycle to increase the pressure and temperature of refrigerant vapor.

condenser. A component of the refrigeration cycle in which refrigerant vapor is converted to liquid as it rejects heat to air, water, or some other fluid.

condenser water. Water obtained from the source (tower, river, pond, and so forth) to which heat is rejected, and which flows through the tubes in a chiller's condenser.

cooling tower. A device used to reject the heat from a water-cooled condenser by spraying the condensing water over the fill while drawing outdoor air through the fill.

dedicated heat-recovery (DHR). A unit that can move energy from one distribution stream to the other in only one direction.

dedicated outdoor air system (DOAS). A system that uses separate equipment to condition all of the outdoor air brought into a building for ventilation and delivers it to each occupied space, either directly or in conjunction with local or central HVAC units serving those same spaces. The local or central HVAC units are used to maintain space temperature.

evaporator. A component of the refrigeration cycle where cool, liquid refrigerant absorbs heat from air, water, or some other fluid, causing the refrigerant to boil.

fouling. Minerals in the water that form scaling on the internal surfaces of the heat exchanger tubes.

global warming potential (GWP). An index developed to provide a simplified means of describing the relative ability of a chemical compound to affect radiative forcing, if emitted to the atmosphere, over its lifetime in the atmosphere, and thereby to affect the global climate. Radiative forcing reflects the factors that affect the balance between the energy absorbed by the earth and the energy emitted by it in the form of longwave infrared radiation. The GWP is defined on a mass basis relative to carbon dioxide. The GWP for a compound must be calculated up to a particular integrated time horizon, for example, 20, 100, or 500 years. The time horizon most widely accepted is 100 years.

heat exchanger. A device used to transfer heat between two physically separated fluids.

heat recovery. The process of capturing the heat that is normally rejected from the chiller condenser and using it for space heating, domestic water heating, or another process.

heat sink. An environment into which unwanted heat is directed.

heat source. An environment from which heat is extracted.

heat transfer. The movement of heat from one body or substance to another. The three methods of heat transfer are conduction, convection, and radiation.

helical-rotary (screw) compressor. A type of compressor that uses two mated rotors to trap the refrigerant vapor and compress it by gradually shrinking the volume of the refrigerant.

HVAC. Heating, Ventilation, and Air-Conditioning.

load-shedding economizer. An airside economizer that works in conjunction with the cooling system to balance the amount of mechanical cooling performed with the amount of heat required.

multi-pipe heat pump. A hydronic refrigeration unit that provides heating and cooling output with independent control of the heating and cooling temperatures. Multi-pipe heat pumps include three heat exchangers; one for cooling, one for heating, and one that can sink or source heat as needed to achieve thermal energy balance. Air-source multi-pipe heat pumps are 4-pipe while water-source multi-pipe heat pumps are 6-pipe.

outdoor air (OA). Air brought into the building, either by a ventilation system or through openings provided for natural ventilation, from outside the building.

potable water. Water that is drinkable.

preheat. The practice of heating air or water ahead of other processes.

scroll compressor. A type of compressor that uses two opposing scrolls to trap the refrigerant vapor and compress it by gradually shrinking the volume of the refrigerant.

setpoint. The desired condition of the controlled variable in a control loop.

storage-source heat pump (SSHP). A heating and cooling system for buildings, combining thermal energy storage with heat pump chillers and other energy collection devices such as air-to-water heat pumps to enable the collection, use, and storage of thermal energy for future use in a grid-interactive way, based on building usage, grid emissions, and customer goals.

surge. A condition that may occur in a centrifugal compressor, causing refrigerant to alternately flow forward, then backward through the compressor.

temperature, ambient. The temperature of the air surrounding the object under consideration.

temperature, dry-bulb (DBT). The temperature of air indicated by an ordinary thermometer shielded from solar and long wave radiation.

thermal energy storage (TES). Technology or systems of accumulating cooling or heating capacity for future use. These systems can be used for balancing energy demand for the building between daytime and nighttime or shift the balance of energy use towards off-peak periods with better renewable energy utilization.

TRACE™. Trane Air Conditioning Economics. A comprehensive building and economic analysis computer program that aids comparison of building architecture, airside systems, air conditioning equipment, and economics.

variable-frequency drive (VFD). An electronic device that varies its output frequency to vary the rotating speed of a motor, given a fixed input frequency. Used with fans or pumps to vary the flow in the system as a function of a maintained pressure.

v**ariable primary flow (VPF) system.** Type of chilled-water system that is designed to vary the flow of water throughout the entire system—through the evaporator of each operating chiller as well as through the cooling coils.

water-to-water heat pump (WWHP). A unit that controls to a heating or cooling temperature by transferring heat between two fluid sources and it may or may not include a reversing valve to change to roles of the heat exchanger. These units can be used as a dedicated heat-recovery or as a booster heat pump in a cascade system.

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