



Comparing Four Leading Air-Source Heat Pump Chiller Systems



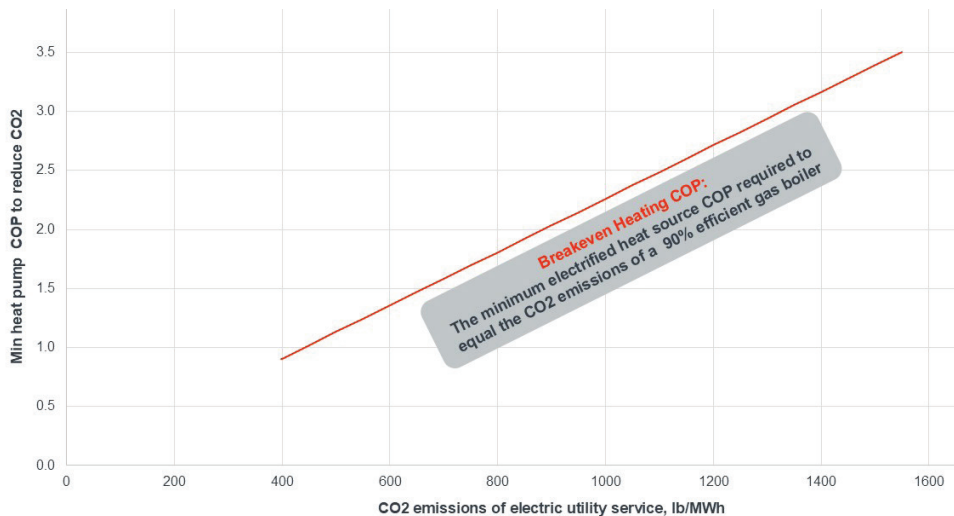
The shift to heat pumps is being driven by a combination of policy, market, and owner priorities.

Globally, over 135 countries have set long-term net-zero targets¹. Across the United States, more than 20 states and territories have established decarbonization goals², more than 45 states offer utility incentives for electrified building equipment, and over 325 cities have made climate-action commitments^{1,2}. These trends matter because buildings account for roughly 40% of total energy use and 38% of associated greenhouse gas emissions, and comfort space heating alone accounts for about 6% of global emissions.² As a result, the heat pump market adoption is expanding rapidly. The global commercial heat pump market is projected to grow from \$17.1 billion in 2025 to \$61.5 billion by 2035, a 13.2% compound annual growth rate (CAGR), with air-source systems expected to lead. A significant portion of a building's energy use intensity (EUI) can be attributed to its heating and cooling systems. Typical heating equipment includes fossil fuel-based furnaces and boilers, electric resistance heaters and boilers, and electric heat pumps, which can be three times more efficient than the alternatives. The term

electrification of heating in this paper refers to applications that increasingly satisfy the heating load using efficient electric heat pump systems. Hybrid gas-electric systems and grid-tied controls can also be used to optimize systems for decarbonization, energy cost or resilience.

Building owners typically invest in and operate HVAC systems to lower their EUI and energy costs while maintaining tenant comfort. Some are also required by code or driven by their business value system to minimize carbon emissions. Heat pump systems can be used to achieve all these goals. When the application is specifically targeting reduced carbon emissions, it is important to consider the minimum heat pump system efficiency needed to offset the electric utility carbon emissions as compared to fossil fuel-based heating, also known as the breakeven COP. This is best evaluated using annual load and performance data, but a first order approximation can be calculated using US EPA eGRID data along with nominal fuel combustion emission rates and efficiencies.³

Heat Pump Breakeven COP



$$\text{COP}_{\text{breakeven}} = \frac{\text{CO2}_{\text{egrid}}}{\text{CO2}_{\text{gas}} * \text{eff}_{\text{gas}}}$$

The breakeven COPs range from less than 1 up to 3.5 which can be achieved within the leading air-source systems covered here.

Comparing Four Major Heat Pump Chiller Systems

**Air-to-Water
Heat Pump
(AWHP)**

**Cascade
Heat Pump**

**Modular
Heat Pump**

**Storage-Source
Heat Pump
(SSHP)**

These four approaches are all based on air-source heat pump system architectures, but they can also be integrated with other heat sources/sinks depending on project needs. For example, air-source heat pump chiller systems can be combined with building cooling loads for heat recovery, with thermal energy storage for load shifting, or with geothermal systems to help reduce operating costs and improve performance.

No single heat pump chiller system architecture is ideal for every application. The best results come from matching the system to the building's thermal needs, operating priorities, and long-term performance goals.

Heat Pump Chiller System Fundamentals

At a basic level, heat pump chiller systems do not heat in the same way a boiler does. They move heat from one location to another using the vapor-compression refrigeration cycle. That distinction matters because it explains why heat pumps can deliver heating coefficients of performance (COP) in the 2 to 4 range, while electric resistance and fuel-based boilers have COPs ranging from 0.8 to 1.0.

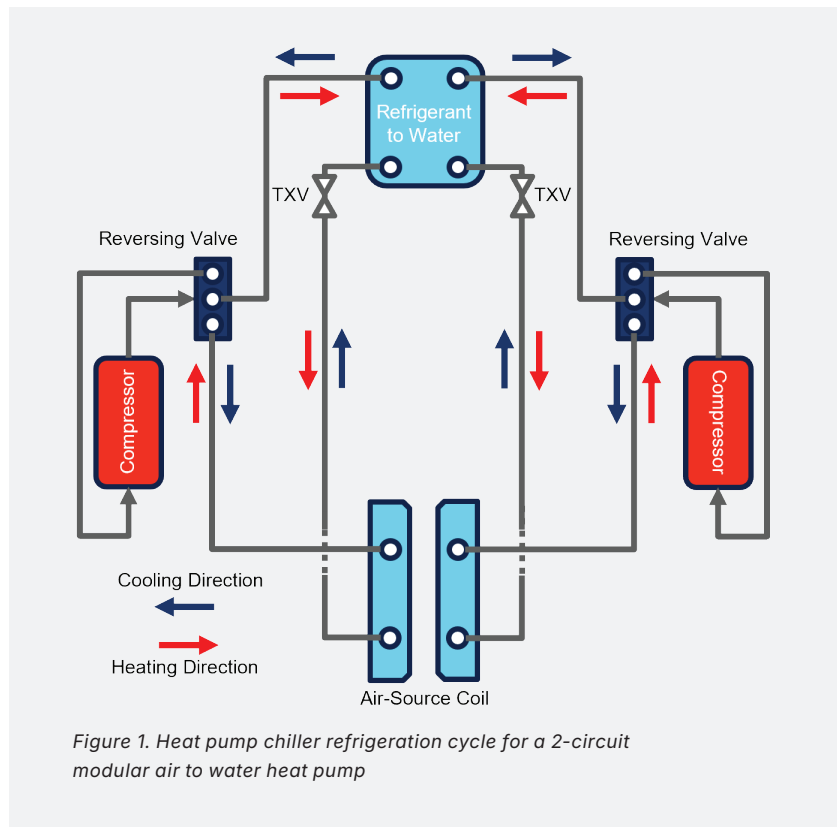
The heat pump chiller refrigeration cycle includes four steps:

- 1 Refrigerant evaporates and absorbs heat from a heat source
- 2 The compressor raises refrigerant pressure and temperature
- 3 Refrigerant condenses and rejects heat to a heat sink
- 4 The expansion device reduces pressure so the cycle can repeat

Heat Pump Chiller System

In heating mode, the condenser side of the cycle becomes the useful side. As the refrigerant condenses, it transfers heat to fluid that can then serve space heating, domestic water heating, process loads, or other building needs. In cooling mode, the evaporator side removes heat from fluid to meet the building cooling load.

Heat pump chiller systems can be especially efficient when buildings have simultaneous heating and cooling loads. When a building has both loads during a given time period, the heat removed to cool the building can be recovered, and applied to heating loads in the building. In those conditions, useful output includes both cooling and heating, which is why simultaneous heating-and-cooling COP can exceed 9.



Heat Pump Chiller System Terms

COP (Coefficient of Performance)

The ratio of useful heating or cooling to the electrical demand required to run the system, with metrics specific to individual modes like cooling COP or heating COP. To capture the entire cooling and heating system, total COP measures the combined ratio of both the useful heating and cooling output to the total electrical power consumed by all system components.

Heat Recovery

Use of heat that would otherwise be wasted from a system or process (e.g. heat-recovery chiller that rejects condenser heat for heating load).

Heat Pump Chiller

Refrigeration unit that can be controlled to provide either fluid heating or cooling as the primary function, with options for simultaneous cooling and heating.

Heat Pump Chiller System

A hydronic system that has flexibility to accommodate heat pumps, chillers, heat recovery units and booster heat pumps in a common production system.

Thermal Battery System

A system using storage tanks to store heating or cooling capacity used to shift load and improve heat pump chiller system operation.

Cascade Heat Pump System

Arranging heating machines such that the heat output of one machine is the source heat for the second machine to achieve the heating application temperature.

Modular System

A heat pump consisting of multiple modules that function together as a bank. Each module includes an independent refrigerant circuit. In some cases, a single module can be used standalone.

Supporting Research and Evidence

Research and field experience continue to support heat pump systems as a practical path to lower-carbon operation in buildings, but the research also shows that successful application depends on load profile, water temperature, and existing infrastructure.

The International Energy Agency's *The Future of Heat Pumps* identifies heat pumps as a key decarbonization technology, while U.S. Department of Energy research has reinforced their role in commercial electrification, especially where systems can operate at lower hot water temperatures or take advantage of simultaneous heating and cooling⁴.

Just as important, the literature shows that electrification in existing buildings is rarely a simple equipment replacement. In James Del Monaco's ASHRAE Journal article, *Responsible Approach to Decarbonization in an Existing Building* (February 2023), a university campus case study showed that actual building load was far lower than legacy installed capacity suggested⁵. In one building, peak heating demand dropped by more than 60% after control and distribution improvements, including replacing three-way valves, removing bypasses, and improving reset strategy.



That finding is directly relevant to heat pump design. It suggests that engineers should verify actual load before sizing replacement equipment and correct control and distribution problems first. The same study found that most heating hours occurred at only 20% to 30% of peak load, which is important because heat pump systems perform best when properly sized and able to unload efficiently at part load.

The study also compared three approaches: an all-electric air-source heat pump system, an all-electric water-cooled heat pump system, and a hybrid plant using heat pump chillers with condensing boilers for peak load. The hybrid option proved most practical because it balanced emissions reduction, first cost, electrical constraints, and resilience. The broader lesson is that electrification in existing buildings is often best approached as a phased strategy rather than an immediate all-electric conversion.

Key Design and Selection Factors

The most important design question in many heat pump chiller projects is simple: what leaving water temperature is required?

That requirement can quickly narrow the field for equipment and system selection. Lower temperature hot fluid applications are strong candidates for standard air-to-water heat pump systems. Higher-temperature boiler retrofits may push the design toward cascade arrangements or hybrid heat pump/boiler strategies.

Building cooling load profiles matter too. Buildings with significant simultaneous cooling and heating load hours may offer opportunities for heat recovery and better overall system efficiency. In contrast, buildings with non-simultaneous heating and cooling loads will benefit more from storage integration. The load profile should drive the system concept from the beginning of the project.

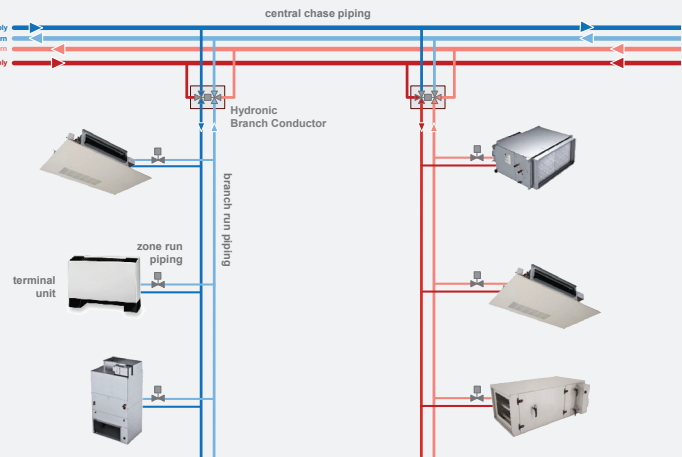
Climate and ambient design conditions remain central to performance, especially in colder climates. Air source-based systems are sensitive to ambient temperatures, and cold-weather operation affects both capacity and efficiency. Cold climate applications can be managed with proper equipment selection, storage, and control strategies.

Retrofit challenges can present significant design constraints to the project. Existing airside coils, piping, mechanical room access, acoustics, structural weight limits, and available electrical service all impact installation feasibility. A heat pump chiller system that looks good on paper may prove difficult to implement if the building piping distribution system requires higher temperatures than the new plant can deliver.

Hydronic Branch Conductors

Hydronic branch conductors can make heat pump chiller systems more practical, particularly in retrofit applications. By using dual-purpose branch piping and coils for both heating and cooling, they can help contribute to reducing distribution complexity, lower installed cost, and preserve the comfort benefits associated with four-pipe systems.

They can also support lower hot-water design temperatures. That matters because lower heating-water temperatures improve heat pump efficiency, expand equipment options, and help reduce the performance penalty associated with higher lift. In that sense, hydronic branch conductors are not a separate plant strategy, but a distribution approach that can make air-source heat pump systems easier to apply and more effective in operation.



Project economics should also be evaluated beyond first cost. Available incentives can improve the business case for certain system configurations, particularly when geothermal systems or thermal energy storage are part of the design. In the U.S., the Federal Investment Tax Credit can materially affect lifecycle economics in qualifying projects. Engineers and owners should consider tax incentives, utility rebates, and jurisdiction-specific programs early in concept development rather than treating them as a late-stage financial add-on.

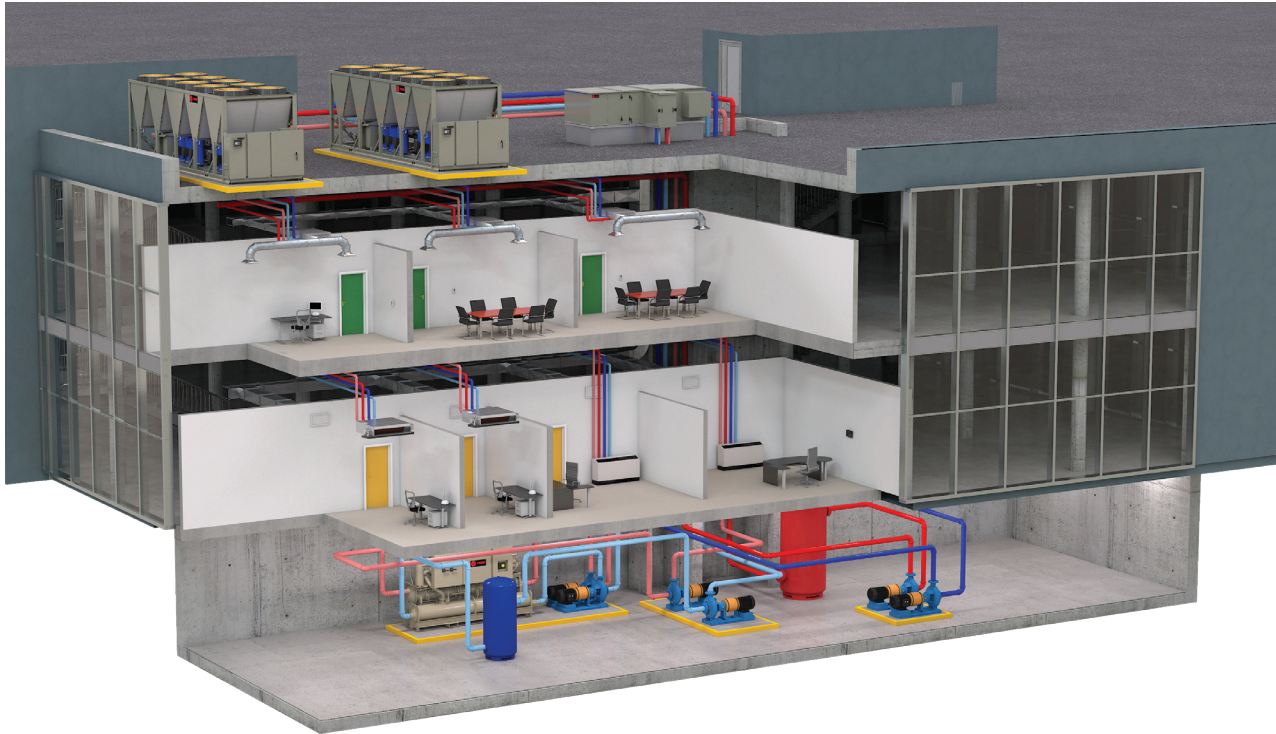
Finally, there are the tradeoffs that show up in almost every project:

- First Cost Versus Lifecycle Value
- Redundancy Versus Central Plant Consolidation
- Simplicity Versus Flexibility
- Control Sophistication Versus Operational Ease

The right system selection depends on the owner's goals, the building's actual load conditions, the available financial incentives, and the project's constraints.

Four Heat Pump Chiller System Approaches

Air-to-Water Heat Pump Systems (ACX)



Air-to-water heat pump systems using large packaged heat pump units can be a cost-effective system for electrified heating and cooling. With fluid heating capability up to 140° F (60°C) and ambient temperatures down to -15°F (-26°C), the operating range can meet the needs of most comfort heating applications, even in cold climate zones (Fig. 2).

In this system, a given unit can either heat or cool fluid and outdoor air is the source of energy for heating operation and the sink for energy during cooling operation.

Because air is the source and sink, units must be spaced to limit recirculation similar to air-cooled chillers. Unlike chillers, unit sizing must consider both heating and cooling loads along with the impact of defrost on unit capacity. For instance, in a heating-dominant application, a unit sized for the design day heating load will be oversized for cooling and could lead to excessive cycling. Depending on the annual load profile, best practice design strategies include using multiple units of varying sizes or including dedicated chillers.

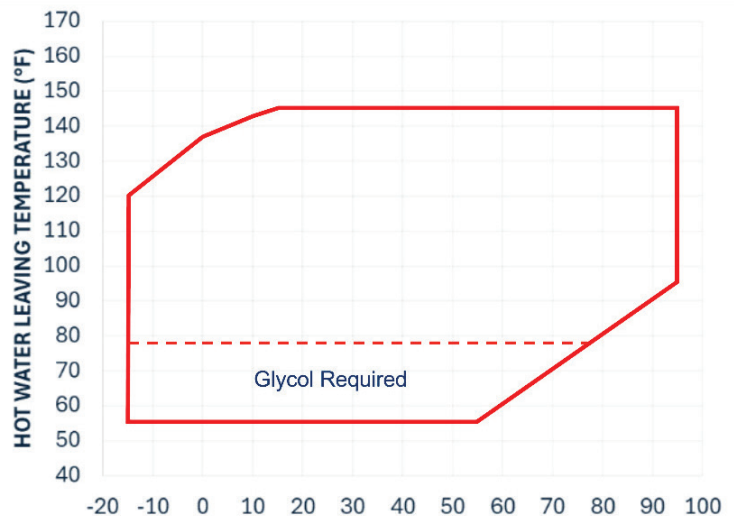


Figure 2: ACX Operating Map, Heating Mode

Four Heat Pump Chiller System Approaches (Cont.)

A typical configuration uses a decoupled plant with multiple heat pumps in parallel serving both heating and cooling distribution loops (Fig. 3). The plant includes an innovative valving design that provides significant flexibility for design optimization and operation. Controls simply stage heat pumps in cooling mode or heating mode to satisfy cooling and heating distribution demand. Lower cost dedicated chillers can be included in the plant for cooling-dominant applications (Fig. 4).

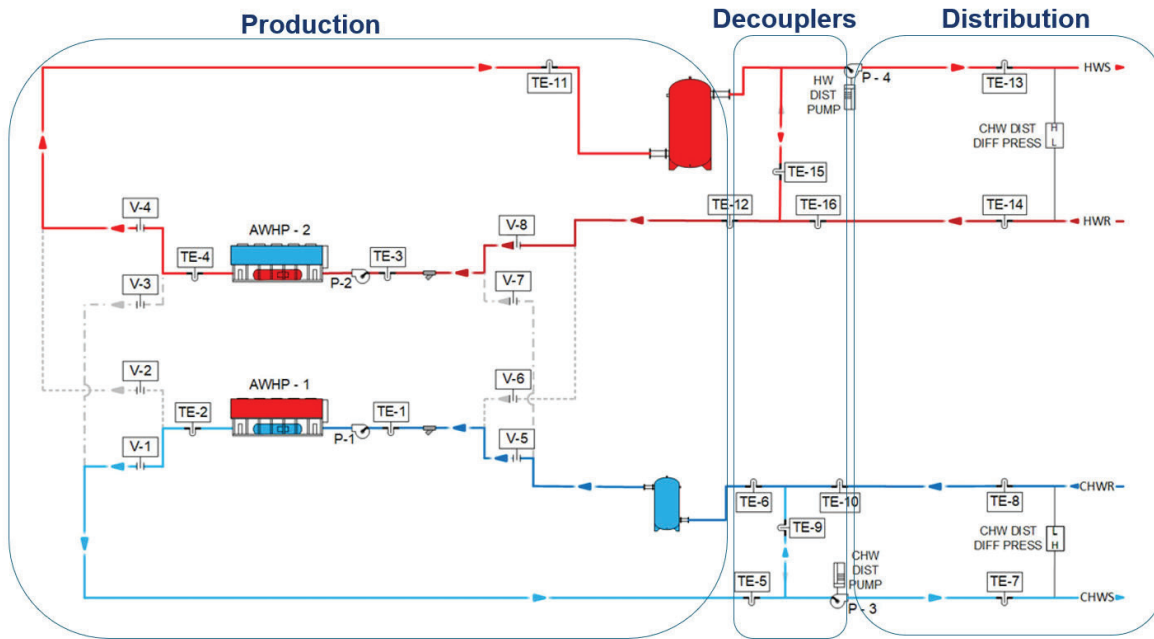


Figure 3: Four-Pipe Distribution, Dual-Feed Heat Pump Chiller System

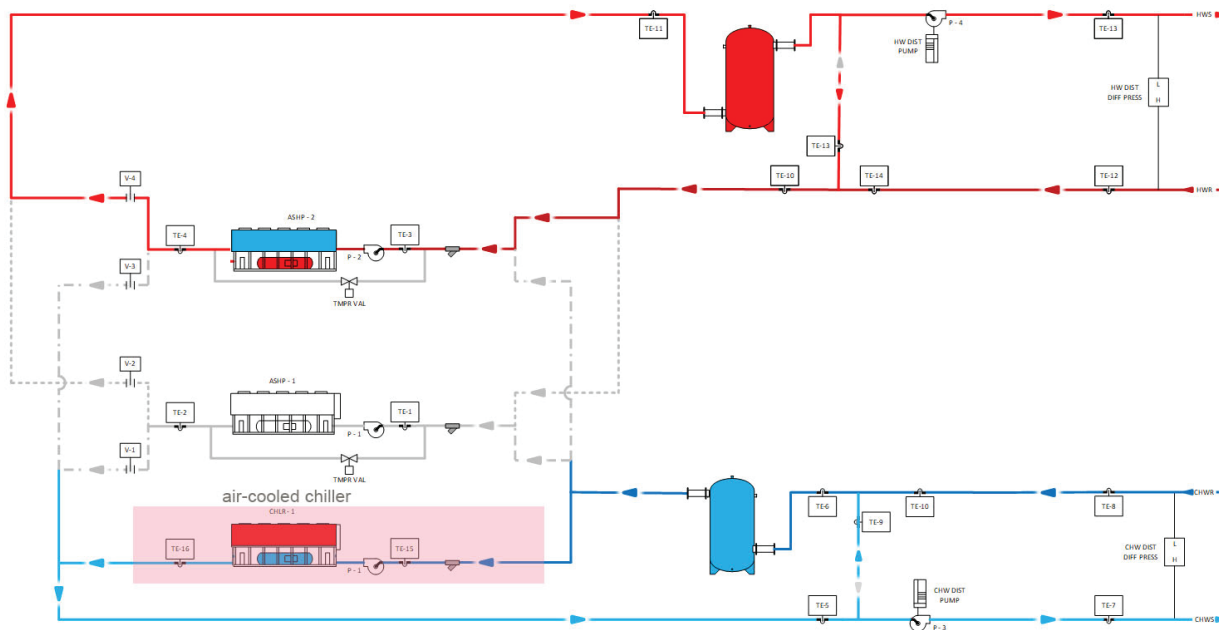


Figure 4: Hybrid Plant with a Dedicated, Cooling-Only Air-Cooled Chiller

Four Heat Pump Chiller System Approaches (Cont.)

The system also lends itself to including auxiliary heat, dedicated heat recovery (Fig. 5) and cascade arrangements.

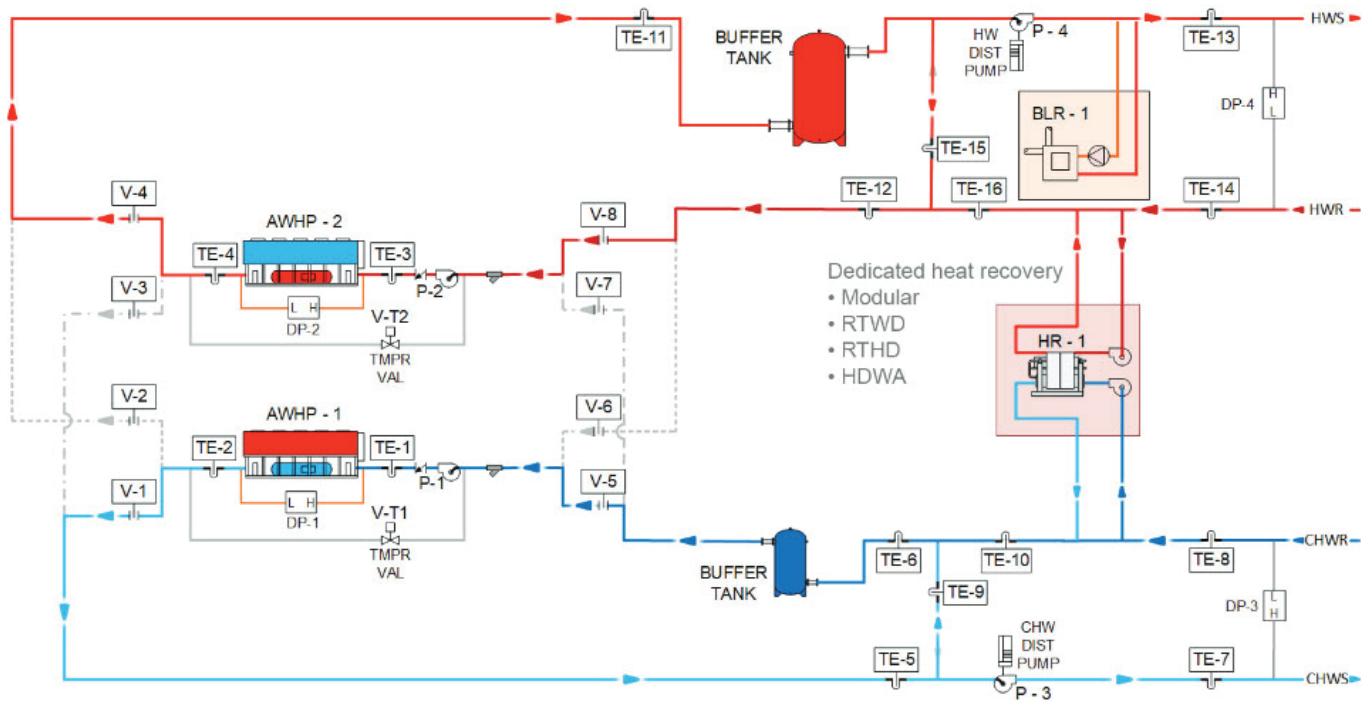
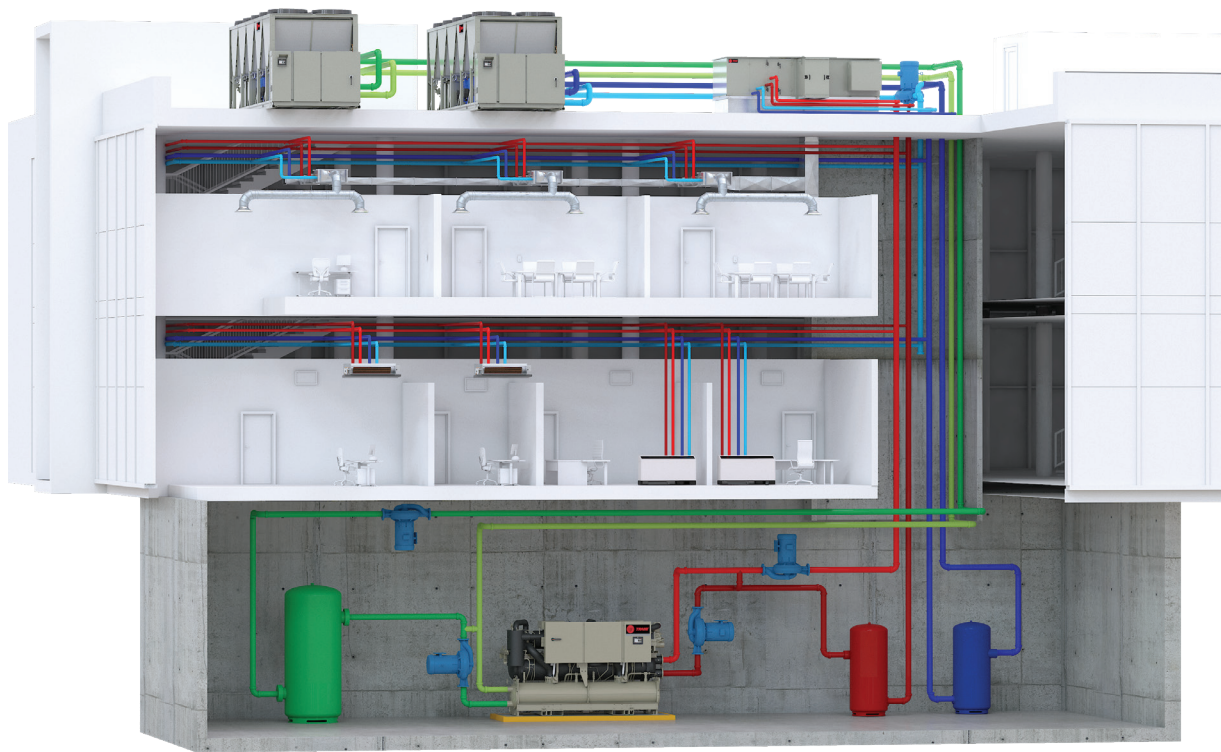


Figure 5: Auxiliary Heat Source Connected to Distribution Loop Supply Pipe, Dedicated Heat Recovery Unit Option

Four Heat Pump Chiller System Approaches (Cont.)

Cascade Systems



Cascade systems combine air-to-water heat pump systems with water-to-water heat pumps to achieve higher hot fluid temperatures. In this system, the air-to-water heat pump leaving hot fluid supplies the evaporator of the water-to-water heat pump, which then raises the temperature further for the heating distribution loop. The heating lift is split between the two heat pumps, enabling higher overall temperatures.

The expanded operating map can reach up to 210°F (99°C) which can be suitable for boiler retrofits as well as meeting some industrial applications (Fig. 6). Sizing the system typically starts with the water-to-water heat pumps heat capacity and considers the desired split of the system lift between the heat pumps and system load turndown. This can lead to a mix of larger and smaller units in parallel to ensure reliable unloading. The air-to-water heat pump unit capacity can then be sized based on design conditions required to deliver the required heating capacity and hot fluid temperature to the evaporator of the water-to-water heat pumps.

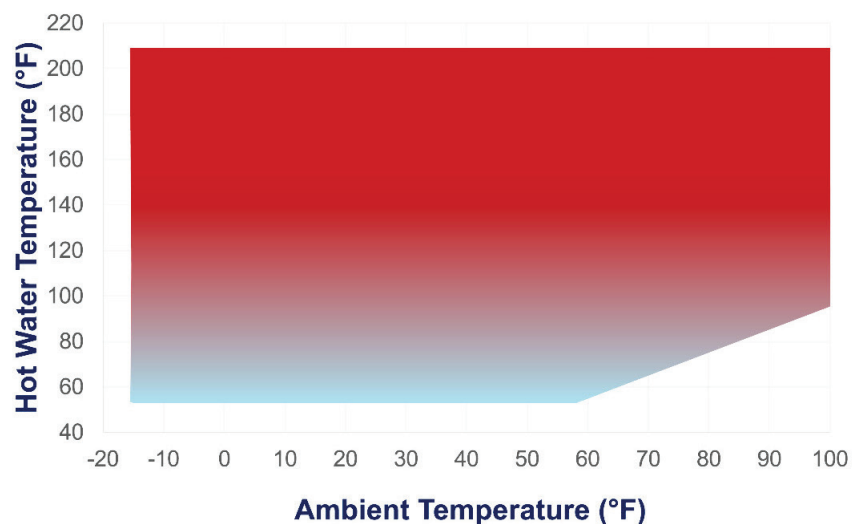


Figure 6: ACX and RTZA Operating Map

Four Heat Pump Chiller System Approaches (Cont.)

In the typical system configuration, the water-to-water heat pumps are located in between and hydraulically decoupled from the air-to-water heat pump plant and the heating distribution loop. Water-to-water heat pumps can be added in parallel to meet capacity requirements and this also enables different sizes for reliable unloading. (Fig. 7)

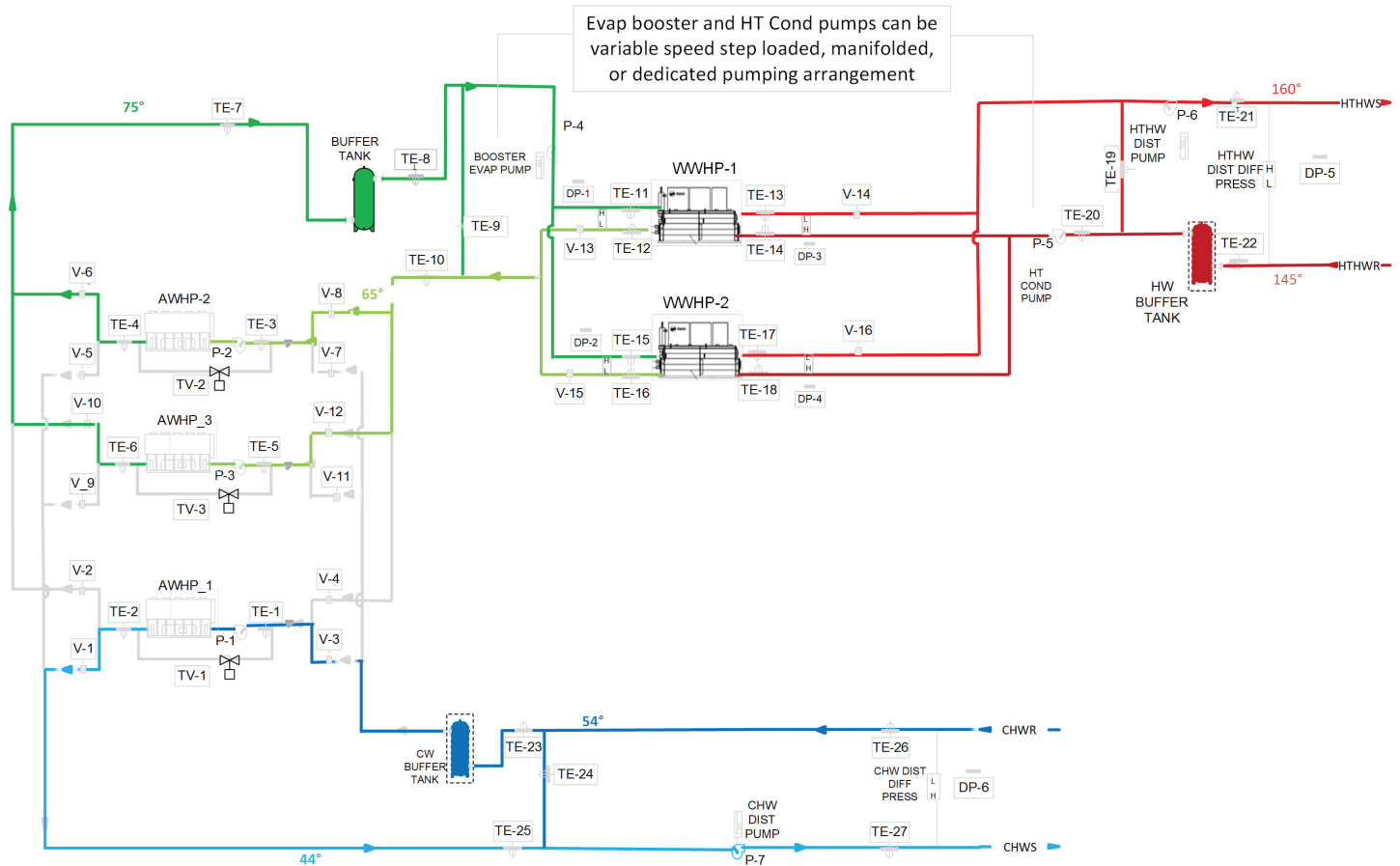
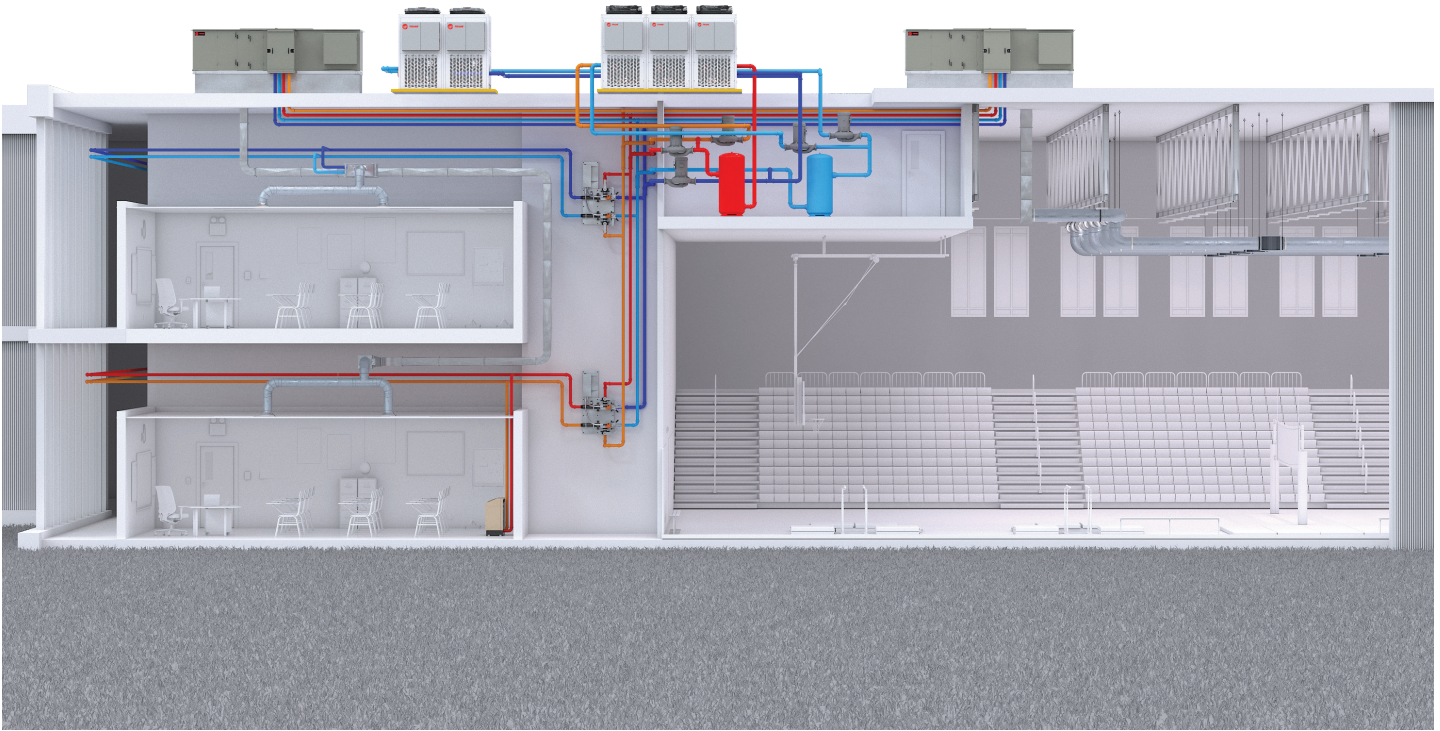


Figure 7: Example of Cascade Arrangement with Simultaneous Heating and Cooling

Four Heat Pump Chiller System Approaches (Cont.)

Modular Heat Pump Systems



Modular heat pump systems use multiple units staged together to serve common hydronic heating and cooling loops. Their main advantage is flexibility: capacity can be added in smaller increments, matched more closely to actual building demand, and expanded over time. They also improve resilience because capacity is distributed across multiple modules rather than concentrated in one large machine.

Technology advances have improved cold weather performance for these systems. For example, Trane's 2-pipe AXM and multi-pipe MAS modular heat pump chillers can start and operate in heating mode down to -18°F (-28°C) outdoor ambient, and units already operating can continue heating down to -22°F (-30°C). They can also deliver up to 140°F (60°C) hot water when outdoor temperatures are above 10°F (-12°C), although lower hot-water temperatures remain the better design target for higher efficiency. Supplemental boilers are not always required, but they may still be useful for

peak loads or applications with higher leaving-water-temperature requirements. In colder weather, the bank controller can limit how many modules enter defrost at once, helping maintain steadier heating operation.

In buildings with simultaneous cooling and heating loads, like hospitals and schools, MAS doubles the efficiency of standard heat pumps. For instance, in a building where 20% of the annual loads occur simultaneously, MAS based systems cut annual energy use and CO₂ emissions by 5–15% versus standard heat pump systems.

Four Heat Pump Chiller System Approaches (Cont.)

Controls integration is another key consideration. In Trane's modular platform, AXM modules, MAS modules, and larger packaged heat pumps or chillers can be combined in a primary-secondary arrangement. AXM can control either a chilled-water or hot-water setpoint, while MAS can control both at the same time. Factory-installed electronic isolation valves allow modules to stage automatically, while the bank controller manages staging and the system controller coordinates plant operation and pump speed.

Modular systems are often a strong fit for hotels, campuses, office buildings, healthcare facilities, and other projects that need uptime or future expansion flexibility.

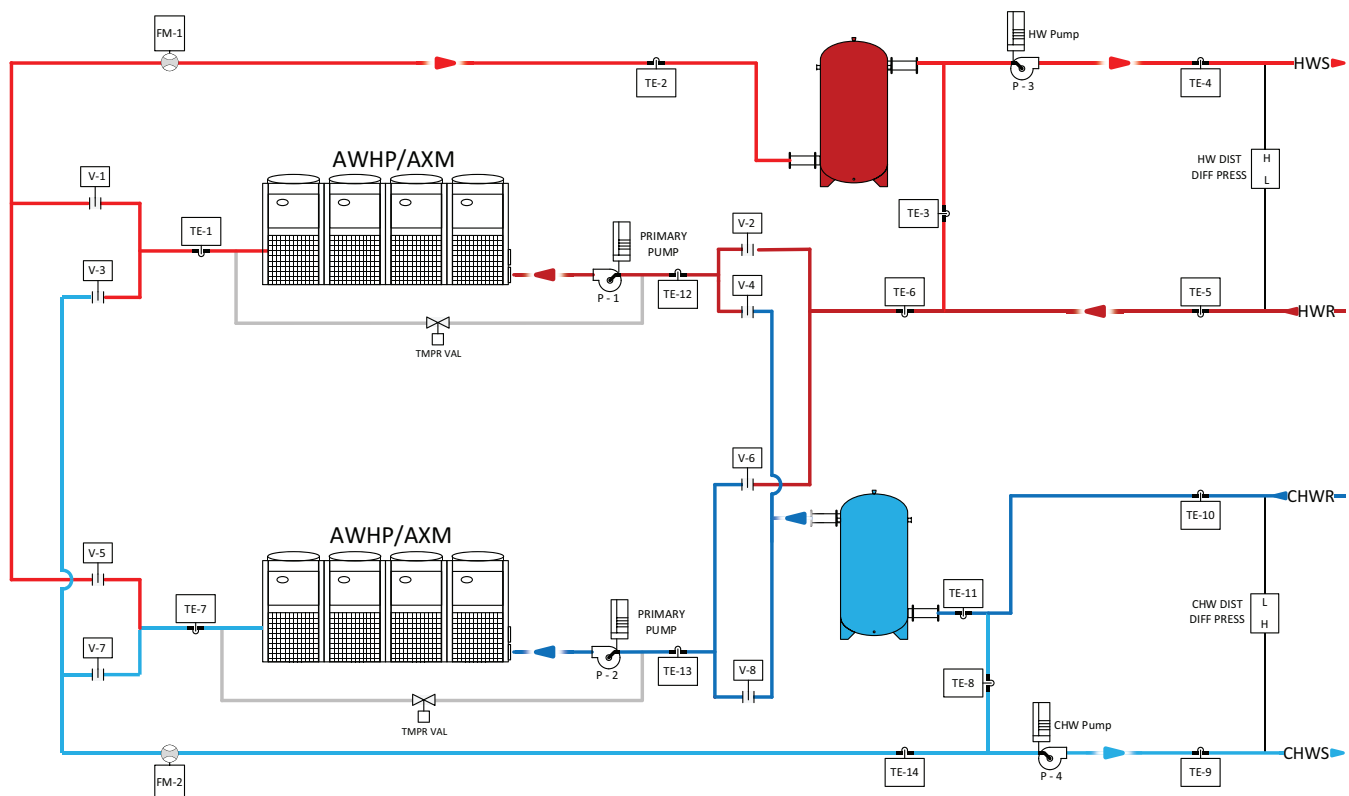
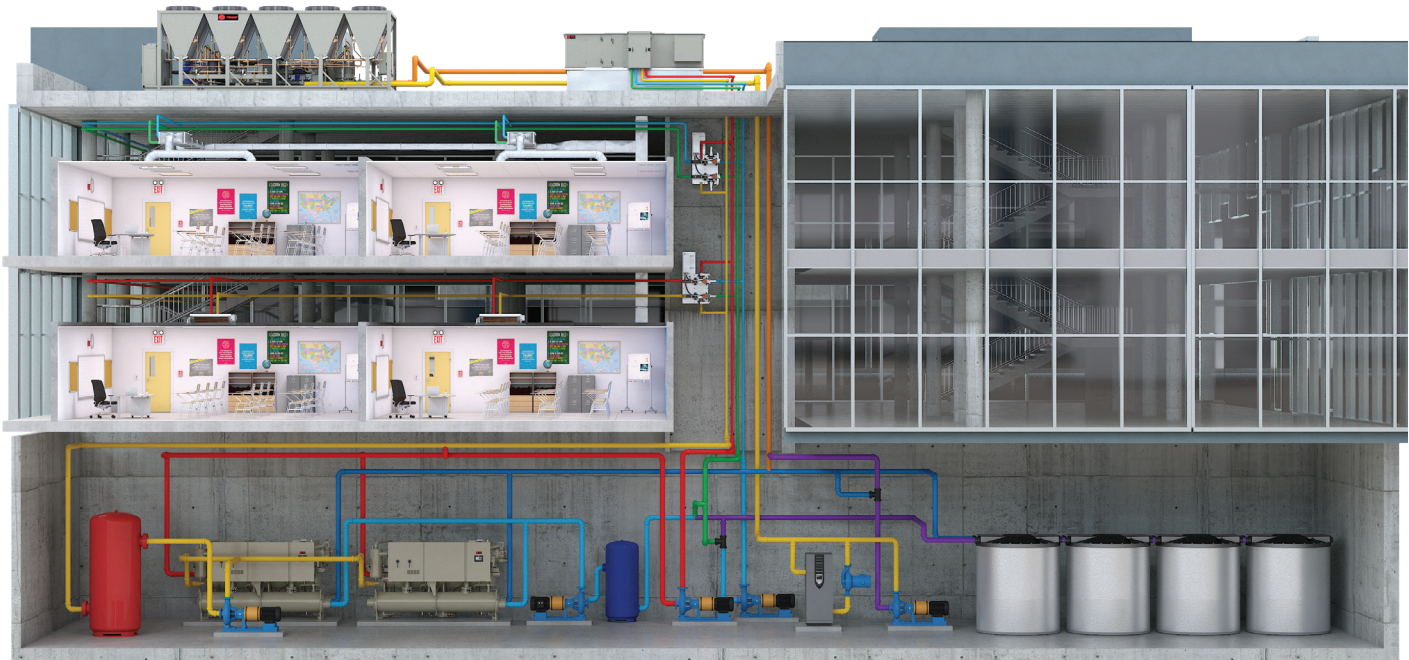


Figure 8: Base AXM Heat Pump System configuration

Four Heat Pump Chiller System Approaches (Cont.)

Storage-Source Heat Pump Systems



Storage-source heat pump systems provide highly efficient heating and cooling and significantly expand the heat recovery potential of a building, while also providing demand management benefits of typical air-cooled ice systems. The system includes water-to-water heat pumps, air-to-water heat pumps and thermal energy storage tanks arranged into four thermal loops; a heating distribution loop, a cooling distribution loop, an energy transfer loop and an air-source/sink loop (Fig. 9).

The heating load is satisfied by the water-to-water heat pumps which in turn extract energy out of the energy transfer loop, making cold water when there is a simultaneous cooling load and making ice when there isn't.

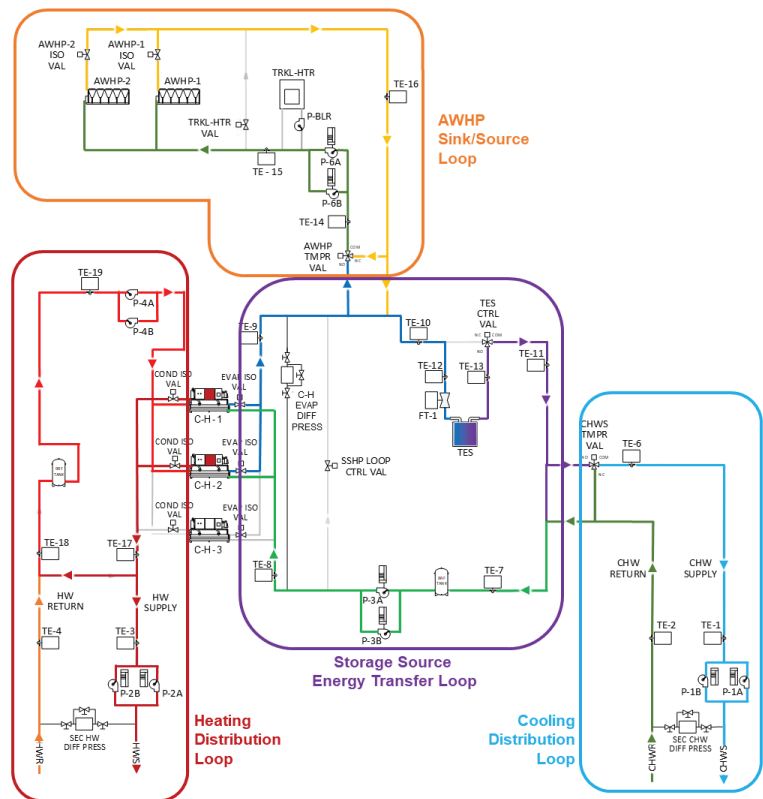


Figure 9: Storage Source Heat Pump with Four-Pipe Cooling/Heating Distribution

Four Heat Pump Chiller System Approaches (Cont.)

The cooling load is satisfied using ice in the thermal energy storage tanks or by the water-to-water heat pumps if there is a simultaneous heating load. The energy transfer loop with the thermal energy storage tanks seamlessly transfers waste heat from the cooling loop to the heating loop even when the loads are not simultaneous, significantly extending the heat recovery potential (Fig. 10). The system expands the operating range for cold-climates well beyond that of air-to-water heat pump systems. It's almost like having a geothermal system in your basement. (Fig. 11)

The system controls the water-to-water heat pumps to the heating fluid temperature, and the chilled water is met by either the water-to-water heat pump simultaneous heating or ice stored in the tanks. The system also maintains a seasonal ice level target using weather predictive control along with demand management schedules. The air-source/sink loop is controlled to collect heat (melt ice) or dispatch heat (make ice) from the energy transfer loop to meet the ice level target. These modes can be thought of as balancing the heating and cooling loads.

For example, during a shoulder season where the loads are similar but light, the target 8 a.m. ice level would be 50% and the air-to-water heat pump would rarely operate because the daily loads are nearly balanced. In the middle of winter when the cooling loads are much smaller than the heating loads, the ice level target would be 10% and the air-to-water heat pump would need to run more often in order to melt enough ice. In the middle of summer, the ice level target would be 90% and the air-to-water heat pump would make ice, to handle the daily cooling load given the light heating loads.

Summer schedules are set to reduce operating the air-to-water heat pump during the middle of the day to avoid demand charges whereas in winter the air-to-water heat pump is scheduled during the middle of the day to take advantage of higher outdoor temperatures.

In this system, water-to-water heat pumps are sized to meet the design day heating load. Designing multiple, unequally sized units ensures robust turndown operation. Thermal energy storage tanks are sized to meet the larger of the cooling design day peak load, heating design day peak load, or the cumulative 24-hr design day heating energy. For very cold-climates, additional tanks can be added to provide stored energy for periods where air-to-water heat pumps can't operate which for today's units would be below -18°F (-28°C). Auxiliary boilers can also be included in lieu of more tanks. In this system, air-to-water heat pumps are sized much like in an air-cooled ice system where the "chiller" is sized for 60% of the cooling design day peak load. Using multiple, unequally sized units ensures robust turndown operation.

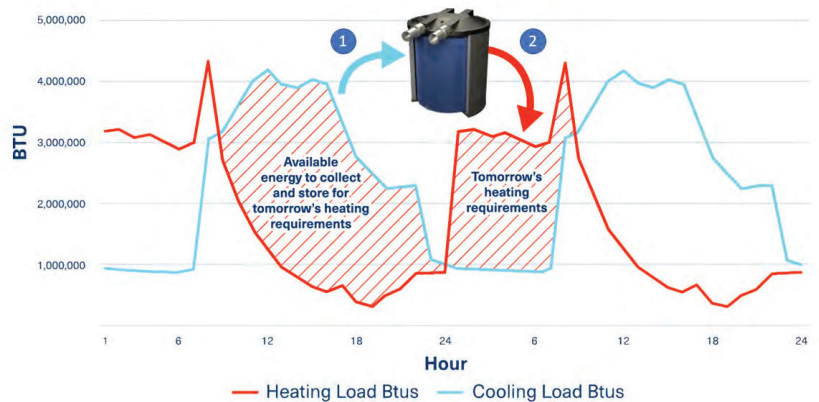


Figure 10: Building Cooling and Heating with Ice Based Thermal Energy Storage

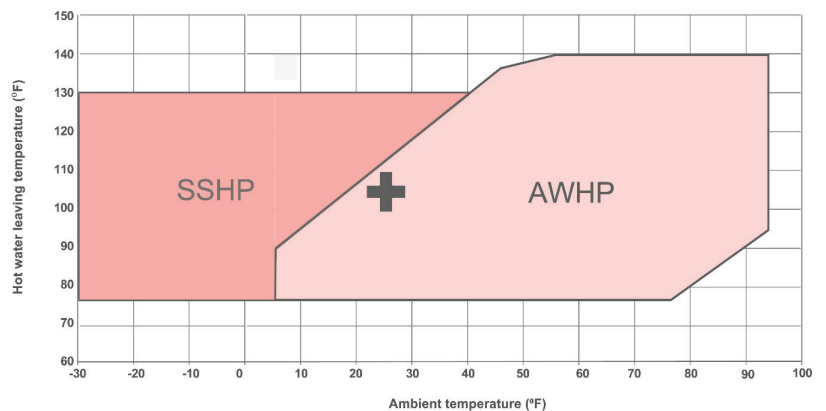


Figure 11: System Operating Map

Comparative System View

Heat pump chiller systems can be applied across a wide range of applications, and each approach offers distinct advantages (Fig. 12).

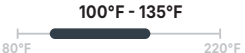
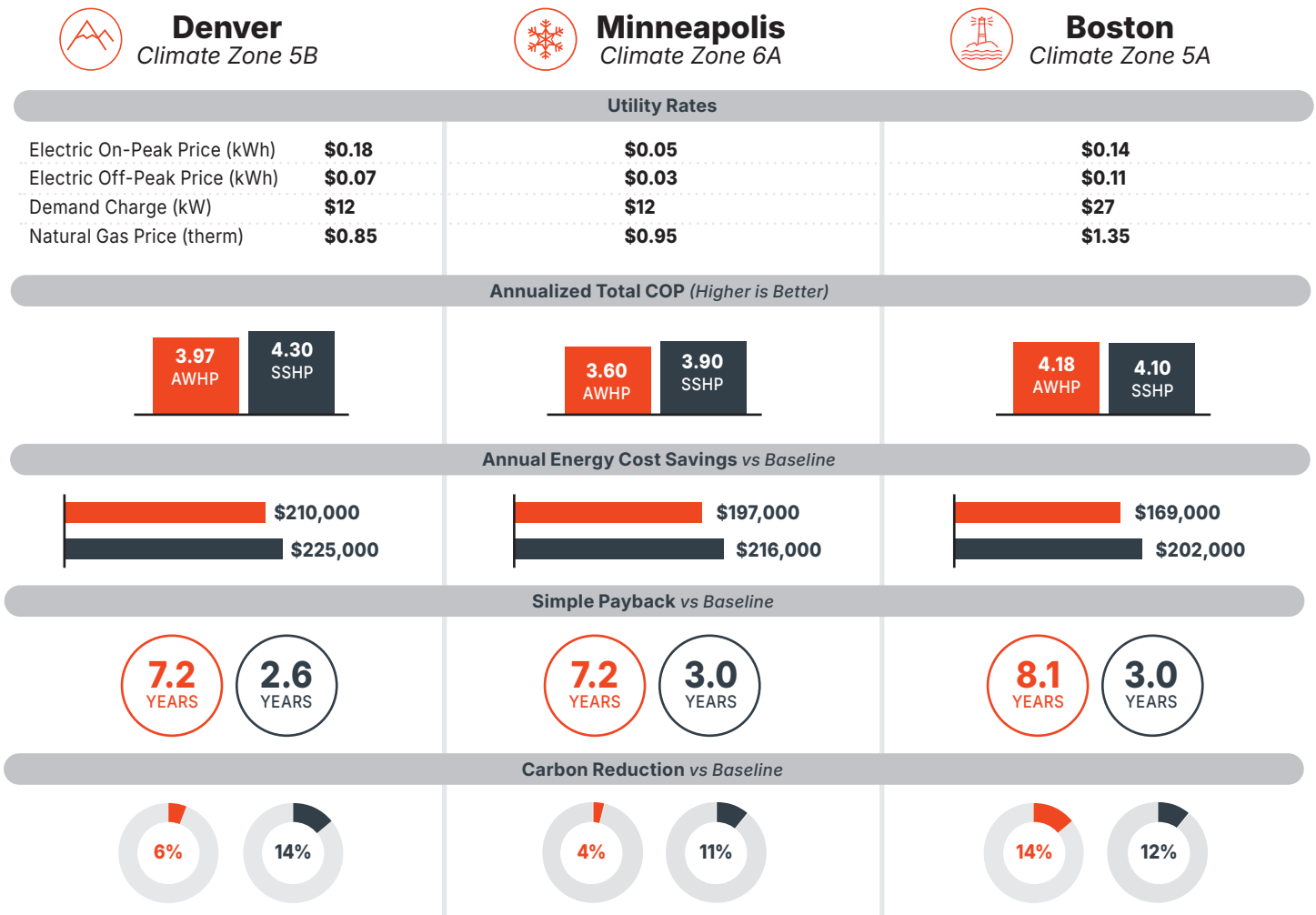
	Air-to-Water Heat Pump (AWHP)	Cascade Heat Pump	Modular Heat Pump	Storage-Source Heat Pump (SSHP)
 Ideal Climate Suitability	 Warm & Mixed Climates	 Warm, Mixed & Cool Climates	 Mixed, Cool & Cold Climates	 Mixed, Cool & Cold Climates
 Typical Hot Water Temps	95°F - 130°F 	120°F - 210°F 	100°F - 140°F 	100°F - 135°F 
 Minimum Ambient Operation	 -15°F	 -15°F	 -18°F	 less than -30°F
 Ease of Retrofit	↓ Low	↑ High	→ Medium	↓ Low
 Efficiency	Better	Good	Better	Best
 Heat Recovery	 Simultaneous Recovery	 Simultaneous Recovery	 Simultaneous Recovery	 Simultaneous & Extended Heat Recovery
 Load Shifting	✗ No	✗ No	✗ No	✓ Yes
 Incentives Available	☆ Some	☆ Some	☆ Some	☆☆ Yes
 First Cost	\$	\$\$\$	\$\$	\$ (First cost assumes Tax Credit Incentives)

Figure 12: Comparison of 4 Leading Heat Pump Chiller Systems

Standard air-to-water systems are often the most practical fit for moderate-temperature applications, while cascade systems extend electrification into projects with higher hot-water temperature requirements. Modular systems broaden the application range by improving cold-climate applicability and adding scalability and redundancy. Storage-source systems add load shifting and the ability to store heat for later use rather than relying solely on simultaneous heating and cooling to achieve high efficiency. Across these approaches, lowering hot water temperature requirements with the use of hydronic branch conductors on the distribution system can improve efficiency and lower the installation and operating costs.

Comparative System View

Energy modeling tools can help compare system performance across climates, utility structures, and plant configurations, and they were used to evaluate air-to-water heat pump and storage-source heat pump systems against a traditional chiller and gas boiler baseline (Fig. 13).



■ AWHP = Air-to-Water Heat Pump

■ SSHP = Storage-Source Heat Pump

* Savings, carbon reduction, and payback shown relative to a traditional chiller/boiler system.

AWHP and SSHP results are compared against a traditional chiller/boiler system (baseline).

Figure 13: Modeled total heating and cooling COP, energy cost savings, carbon reduction, and payback for AWHP/SSHP Systems versus a chiller/boiler system.

Using ASHRAE® 90.1 office load profiles and a 300-ton peak cooling load, the modeling shows that both heat pump approaches improved annual energy cost and carbon performance across Denver, Minneapolis, and Boston. In general, the air-to-water system delivers significant savings and emissions reductions versus the conventional system, while the storage-source system provides the strongest overall value by delivering higher overall efficiency, greater cost savings, and lower carbon emissions across the scenarios evaluated. The financial results for the storage-source system reflect a potential 30% Investment Tax Credit (ITC) for thermal battery systems. The availability of this credit is subject to specific eligibility and effective-date requirements, and ultimately depends on the facts of each project. If a project qualifies, the ITC can significantly reduce its installed costs and shorten the payback period relative to the air-to-water system.

Conclusion

Across all four approaches, there are some common themes around system value: flexibility, efficiency, reliability, and long-term operating value.

Heat pump chiller systems offer multiple paths toward lower-emission building operation, but they do not all solve the same problems in the same way. For consulting engineers, the opportunity is not just to specify new equipment. It is to help owners choose an HVAC solution that fits their loads, their buildings, and their long-term goals.

That makes heat pump system selection a strategic engineering decision. The right choice can support decarbonization, improve performance, and create a more adaptable plant for the future. The wrong choice can add cost and complexity without delivering meaningful benefits. As electrification continues to reshape HVAC design, understanding the differences among these system approaches will become even more important.



References

1. Net Zero Stocktake 2025 Report: "Target-setting rising, despite political headwinds"
2. Clean Energy States Alliance (CESA): "Table of 100% Clean Energy States"
3. US EPA's Emissions & Generation Resource Integrated Database (eGRID), <https://www.epa.gov/egrid>
4. International Energy Agency, The Future of Heat Pumps: [IEA: The Future of Heat Pumps](#)
5. James Del Monaco, "Responsible Approach to Decarbonization in an Existing Building," ASHRAE Journal, Vol. 65, No. 2, February 2023

Disclaimer: This is for informational purposes only. Trane believes the facts and suggestions presented here to be accurate. However, final design and application decisions are your responsibility and will affect actual financial and energy efficiency results. Trane disclaims any responsibility for actions taken on the material presented.



All trademarks referenced in this document are the trademarks of their respective owners.

Trane – by Trane Technologies (NYSE: TT), a global climate innovator – creates comfortable, energy efficient indoor environments through a broad portfolio of heating, ventilating and air conditioning systems and controls, services, parts and supply. For more information, please visit trane.com or tranetechnologies.com.