

CSU DECARBONIZATION FRAMEWORK

TASK 4: TECHNOLOGY REVIEW

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SECTION 4.1:

Introduction

This section will introduce current technologies that will aid CSU campuses in reducing their buildings' carbon footprint and reaching their climate action goals. Reducing and eventually eliminating reliance on natural gas will be critical for campuses to truly decarbonize their space heating and domestic hot water systems. This document will discuss the physical capabilities, limitations, and design considerations for various technology that can be incorporated into a holistic campus decarbonization strategy.

This document will also introduce some emerging technologies that are not yet viable solutions but can become potential options as research and development matures. As the need to decarbonize the built environment becomes more crucial, MEP engineers and building design professionals have urged manufacturers to prioritize research and development of more efficient products. It's expected that efficiency will continue to improve as manufacturers respond to rapidly expanding market demand. The California Energy Commission (CEC), California Public Utilities Commission (CPUS) and the Electric Power Research Institute (EPRI) also support research and development of next-generation heating, cooling and water heating systems through grants and programs that will enable technology advancements.

SECTION 4.2:

Space Heating Technologies

Space heating has the largest natural gas consumption on CSU campuses, and therefore presents a significant opportunity to reduce scope 1 carbon emission. Current commercially available technologies offer many viable options for CSU campuses to consider as alternatives to existing fossil fuel heating system. This section will cover the following categories of space heating technology and review capabilities and limitations of technologies available on the market. These will be reviewed as outlined below:

- 1) Heat Pumps
 - a) Hydronic heat pumps
 - i) Air-to-water heat pump
 - (1) Heating Only
 - (2) Heating / Cooling Only
 - (3) Partial Heat Recovery (Desuperheater)
 - (4) 4-Pipe Heat Recovery
 - ii) Water-to-water heat pump
 - (1) Heating Only
 - (2) Heating / Cooling Only
 - (3) Partial Heat Recovery (Desuperheater)
 - (4) Heat Recovery (4-Pipe)
 - (5) Heat Recovery (6-Pipe)
 - b) Non-hydronic heat pumps (refrigerant/air distribution)
 - i) Water source heat pump
 - ii) Air-to-Air heat pump
 - iii) Variable Refrigerant Flow (air-cooled and water-cooled VRF)
 - c) Emerging technology
 - i) Ammonia- and carbon dioxide-based heat pump
- 2) Electric Heating
 - a) Electric boiler
 - b) Electric resistance heating

The following table provides a summary of the technologies covered, including key performance data, design considerations, best applications, limitations, and operational considerations. The subsequent sections will provide more detailed information.

System	Description	First Cost ³	O&M Cost ⁴	Efficiency [COP] ¹	Max HW Supply	Design Considerations	Best Applications	Limitation and Operational Considerations
Air-to-Water Heat Pump (AWHP)	Heating Only	\$-\$	\$\$\$	Heating COP: 2.8-3.6 @44°F ambient	145°F	Outdoor space requirement Recommend 115-120°F design temp and 10-15°F ΔT Cost Premium for HW >131°F (R-134a or enhanced vapor injection technology)	Distributed HW generation Mild/warm climate Minimal or no CHW load, limited heat recovery potential	Lower efficiency at colder outside conditions, generally when heating loads are highest Requires cascading heating or coil replacement for higher temperature output Outside air does not drop below 32°F
	Heating/Cooling Only	\$-\$	\$\$\$	Heating COP: 2.7-3.4 @44°F ambient Cooling EER: 8.6-11 @95°F ambient	145°F	Assess performance when ambient temperature is low, auxiliary electric heating may be necessary	Distributed HW generation Mild climate Seasonal heating and cooling loads, limited heat recovery potential	
	Heat Recovery (4 Pipe)	\$\$\$	\$\$\$	Heating COP: 3-3.2 @44°F ambient Cooling EER: 9.5-11 @95°F ambient Heat Recovery COP: 6.2-8	131°F	Size for simultaneous heating and cooling base load with 10-15°F ΔT Auxiliary electric heating may be necessary for low ambient condition	Consistent simultaneous heating and cooling load, significant heat recovery potential	Lower efficiency at colder outside conditions, generally when heating loads are highest Requires cascading heating or coil replacement for higher temperature output HW output limited by CHW load Outside air does not drop below 32°F
Water-to-Water Heat Pump (WWHP)	Heating Only	\$-\$\$\$	\$	Heating COP: 4-5 @113°F HW 3-4 @130°F HW	170°F	Cost Premium for HW >130°F (R-134a) Recommend 130-135°F design temp with 20-25°F ΔT Modular heat pump can allow for project phasing and future expansion of system	Distributed HW generation, direct boiler replacement Minimal or no CHW load, limited heat recovery potential	Requires additional heat source for full decarbonization
	Heating/Cooling Only	\$-\$\$\$	\$	Heating COP: 4-5 @113°F HW 3-4 @130°F HW Cooling kW/ton: 0.5-0.8 @41°F CHW	170°F		Central heating/cooling plants Seasonal heating and cooling loads, limited heat recovery potential	
	Heat Recovery (4 pipe)	\$-\$-\$	\$	3.9-4.5 @113°F HW 3.1-3.5 @130°F HW Heat Recovery COP: 6-8	170°F	Cost Premium for HW >130°F (R-134a) Sized for minimum cooling and heating base load	Centralized heating/cooling plants Significant year-round cooling load for heat recovery	HW output dependent on CHW load, limited by the smallest of cooling/heating load
	Heat Recovery (6 pipe)	\$-\$-\$-\$	\$	3.9-4.5 @113°F HW 3.1-3.5 @130°F HW Heat Recovery COP: 6-8	170°F	Cost Premium for HW >130°F (R-134a) Provides additional cooling capacity	Centralized heating/cooling plants Variable simultaneous cooling and heating over course of a year	Requires connection to cooling tower or ground loop as additional heat sink/source
Water Source Heat Pump (WSHP)	N/A	\$-\$	\$\$\$	Heating COP: 4.7-5.7 @68F CW Cooling EER: 13.0-17.4 @86 CW	N/A	Distributed compressors, multiple points of service Maintain condenser water loop temperature between 60 and 90°F	Smaller facilities Simultaneous heating and cooling among the zones Cooling tower water loop available	Requires condenser water loop or ground loop Requires additional heat source to maintain condenser loop temperature
Air-to-Air Heat Pump	N/A	\$	\$	Heating COP: 2.8-4 @ 47°F OSA	N/A	Provides cooling or heating, not simultaneously Does not require connection to CHW or HW	Remote and/or smaller facilities SZAC/RTU unit like-for-like replacement	Lower efficiency, limited capacity Reduced efficiency at colder outside conditions
Variable Refrigerant Flow (VRF)	Air Cooled VRF	\$	\$\$\$	Heating COP: 3.2-4.3 @ 47°F OSA Cooling EER: 9.3-14.4 @ 95°F OSA	N/A	Can be either heat pump or have heat recovery between the zones for maximum efficiency Follow ASHRAE Standard 15 for refrigerant limits	Remote and/or smaller facilities Buildings with extended hours beyond CUP operating period Heat recovery amongst building zones	Significant refrigerant piped through building
	Water Cooled VRF	\$	\$\$\$	Heating COP: 4-6 @ 68°F CW Cooling EER: 10-17 @ 86F CW	N/A	Can be either heat pump or have heat recovery between the zones for maximum efficiency Follow ASHRAE Standard 15 for refrigerant limits	Buildings with extended hours beyond CUP operating period Heat recovery amongst building zones	Significant refrigerant piped through building Requires water-source loop, usually geothermal or boiler/cooling tower system
Ammonia and CO ₂ Based Heat Pump	N/A	Unknown	Unknown	Ammonia: 3 @194°F HW CO ₂ : 2.8-4.1 @ 194°F HW	194°F	Emerging technology, ASHRAE 15 provides guideline regarding refrigerant usage	As HFC becomes phased out, natural refrigerant with 0 GWP will drive up product development	Use of ammonia as refrigerant not yet prevalent in the US
Electric Boiler ²	N/A	\$	\$	0.97	220°F	Efficiency is better than gas boilers but low compared to heat pump	High temperature HW is required (installed where HW is required)	Large electrical load, may require electrical infrastructure upgrade
Electric Resistance ²	N/A	\$	\$	1.0	N/A	Baseboard heating, electric furnace, radiant heater	Buildings with very minimal heating	Large electrical load

¹Efficiency for Air-to-Water heat pump rated at: Cooling 54/44°F @ 95°F ambient, Heating 104/113°F @ 44°F ambient

Efficiency for Water-to-Water heat pump rated at: Cooling 54/44°F, condenser water 85/95°F, Heating 104/113°F

Efficiency for WSHP, water cooled VRF rated at AHRI condition: Cooling with 86F condenser water, Heating with 68F condenser water

Efficiency for Air-to-Air heat pump, Air-cooled VRF rated at AHRI condition: Cooling @ 95°F ambient, heating @ 47°F OSA

² Equipment cost for electric boiler and electric resistance heating are low, but electrical infrastructure needs may significantly add to first cost

³ First cost for equipment only, scale: \$ < \$100/MBH, \$\$ = \$100-200/MBH, \$\$\$ = 200-300/MBH, \$\$\$\$ > \$300/MBH

⁴ O&M cost excludes energy cost, scale: \$ = lower maintenance cost than chiller/boiler system, \$\$ = similar maintenance cost to chiller/boiler system, \$\$\$ = higher maintenance cost than chiller/boiler system

4.2.1 Heat Pump Overview

Electric heat pumps extract heat from a source and transfer it to a sink at a higher temperature. It operates on a conventional refrigeration cycle like a chiller or air conditioner, but a heat pump's primary function is to provide heating. This cycle could be reversed to generate cooling effect if the heat pump is equipped with reversing valve that changes the direction of refrigerant flow, effectively changing the function of the evaporator and condenser. Heat pumps with heat recovery can generate cooling and heating simultaneously, they are commonly referred to as heat recovery chillers or heat recovery heat pumps.

Heat pumps can operate on a variety of heat sources covered in Section 4.5. In cooling mode, heat is extracted from the space and rejected to this source; while in heating mode, heat is extracted from the source and used to heat the space. Because heat pumps move heat instead of burning fuel to generate heat, they are much more efficient than gas equipment. Typical heat pump system can produce three times as much heating or cooling as the amount of electricity it consumes (COP of 3 or above), whereas a gas boiler produces less heating than the natural gas it consumes (efficiency of 80% to 95%). Because heat pumps use electricity instead of natural gas, they are ideal candidates for decarbonization.

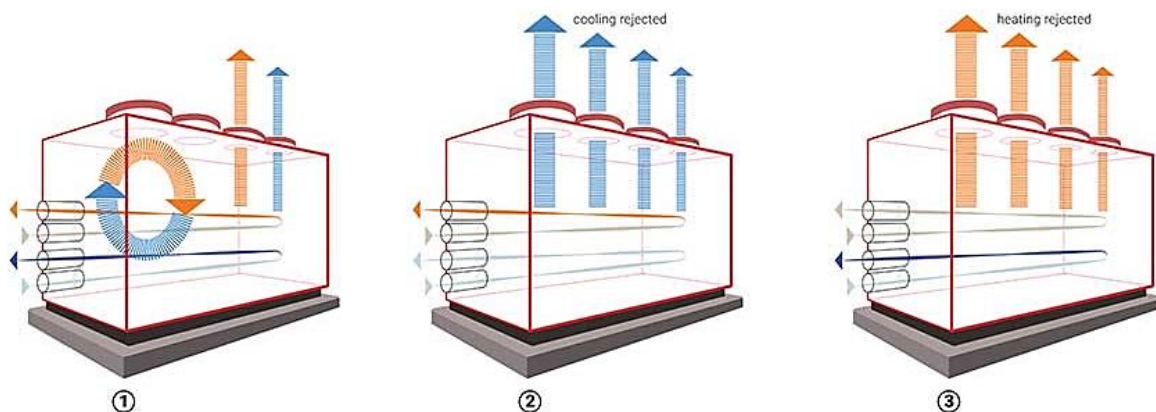
Heat pumps can be categorized into two types: hydronic system and non-hydronic. Hydronic heat pumps use water as cooling/heating medium and thus can easily replace other hydronic heating at CSU campus where heat is distributed as hot water for heating and chilled water for cooling. For applications where air is used to heat/cool buildings, non-hydronic heat pumps offer the opportunity to replace natural gas heating.

4.2.2 Hydronic Heat Pumps

Air-to-Water Heat Pump (AWHP)

Overview

Air source heat pump (ASHP) uses air as heat source, ASHP that use water as heat transfer medium is categorized as Air-to-Water heat pump (AWHP). AWHPs use hydronic system to absorb or dissipate heat from air. They offer significant efficiency improvement over natural gas boilers and can have heat recovery capability. Standard AWHPs can produce hot water around 130°F; however, operation can be limited by low ambient air temperature (see Additional Considerations section below for more detail).



Heat Recovery Air to Water Chiller (HRC) System Diagram

- 1 simultaneous mode / heat recovery
- 2 heating mode
- 3 cooling mode

Figure 4.1: Air-to-Water Heat Pump System ¹

Table 4.2: Air-to-Water Heat Pump (AWHP) Equipment Summary

General Description	Uses air as heat source and hydronic distribution system Ambient air temperature can be a limiting factor on heat pump output capacity and efficiency in cold climate
System Options	Heating Only: can only provide hot water, lowest cost option best suited for direct boiler replacement for decentralized system and where there's limited cooling load available for heat recovery. COP is slightly better than heating/cooling heat pump (3-5% improvement).
	Heating / Cooling Only: 2-pipe with reversing valve, can perform either heating or cooling at a time, requires manual switchover. Best suited when heating load is restricted to winter months and there is limited simultaneous heating/cooling
	Partial Heat Recovery with Desuperheater: reverse cycle heat pump with small heat exchanger between compressor and condenser. When in cooling mode, desuperheater can extract waste heat from cooling process to produce hot water. The amount of heat recovery is not controlled and depends on CHW load and HW

¹ <https://www.esmagazine.com/ext/resources/ES/2019/April/ES-Reigh-fig4-900x550.jpg>

	temperature. Can recover 10-40% of cooling capacity, usually for preheat or reheat.
	Full Heat Recovery: 4-pipe system capable of performing heat recovery during cooling mode. Optimal operation when producing CHW and HW simultaneously, should be sized for simultaneous base load.
Hot Water Temperature	Better suited for low-temperature heating (fan coil units, chilled beam or radiant) Recommended design HW temperature: 115-120°F Standard Options: 130°F High Temp Options: 145°F (requires R134a or enhanced vapor injection, limited availability)
Design Consideration	Capacity: 300-5,000 MBH Important for design to maintain manufacturer recommended minimum water volume to minimize frequent compressor start/stop. Design for low leaving water temperature, recommended temperature of 115-120°F and use cascading system design to reach higher temperature where necessary (see Section 5.3.7 in Conceptual Recommendation) Design for low temperature differential to ensure equipment life expectancy and performance, recommended 10-15°F ΔT Refrigerant: R-410A is typical, using R-134A can allow higher HW temperature. Please reference Section 4.2.4 regarding refrigerant impacts and alternatives. Coil replacement may be necessary to convert existing coils to work with low water temperature, see Section 5.2.2 for heating coil considerations. Recommend design for primary/secondary configuration with constant volume primary flow and buffer tank
Best Application	Best suited in mild climate with low temperature hot water loop Heating only AWHF is best suited for direct boiler replacement for decentralized system with low cooling load AWHP with heat recovery provides superior efficiency when producing CHW and HW simultaneously
Efficiency	Efficiency and capacity depend on OAT and desired HW temperature Heating COP 2.7-3.6 @ 44°F ambient, 104/113°F HW Cooling EER 8.6-11 @ 95 ambient, 54/44°F CHW Heat Recovery COP 6.2 – 8 @ 95°F ambient temperature, 44°F CHW, 113°F HW
Limitation	Limited output capacity at low ambient temperature Design needs to account for defrost in certain CSU climates where temperature drops below 40°F, running defrost will significantly reduce heating output capacity. Recommend avoid using defrost cycle if possible.
First Cost	Heat Pump w/o Heat Recovery ROM: \$90-170/MBH Full Heat Recovery Heat Pump ROM: \$150-200/MBH
O&M Consideration	Expected Useful Life ² : 15-20 year, depending on operation To extend expected useful life (EUL), consider implementing controls for consistent operation, frequent reversing of heat pump cycle can reduce life of equipment. Consider designing primary loop with buffer tank may help reduce short cycling
Technology Readiness	Readiness Level: Tier 9 - Commercialized Available Manufacturers: Aermec, Mitsubishi, Motivair, Multistack, others

² Ian M. Shapiro (2016). *Energy Audits and Improvements for Commercial Buildings, Appendix Q Equipment Expected Useful Life.*

There are a multiple AWHP options and configurations:

- 1) **Heating Only:** heat pump only provides hot water
- 2) **Heating / Cooling Only:** heat pump can provide either hot water or chilled water
- 3) **Partial Heat Recovery (Desuperheater):** heat recovery via small heat exchanger
- 4) **Full Heat Recovery:** heat recovery via large brazed plate heat exchanger

Note that AWHP with heat recovery functionality (either partial or full heat recovery) is sometimes referred to as air-cooled heat recovery chiller. This document refers them to heat pump to emphasize that they are designed for heating.

Heating Only

Heating-only AWHP can only generate hot water and cannot produce cooling. Reversing valve is used only during defrost cycle. They are optimized for heating operation with heating-only counterflow, heating COP is 3-5% better than reverse cycle AWHP. They are best suited for:

- Boiler replacement, distributed heating system
- Limited or no chilled water load
- Limited heat recovery potential

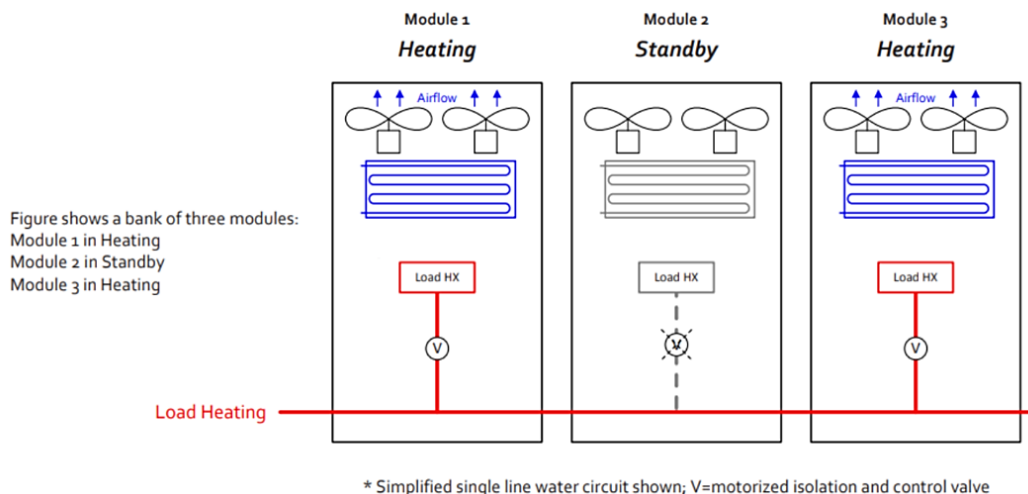


Figure 4.2: AWHP Heating-Only³

Heating / Cooling Only

Reverse cycle AWHP is equipped with reversing valve that changes the direction of refrigerant flow, to provide either heating or cooling at a time. They are configured as 2-pipe system, one supply and one return line with one heat exchanger to provide either chilled water or hot water. They require changeover to connect to hot water or chilled water loop. This type of equipment is best suited for:

³ Climacool Modular Chiller System Application Guide
<https://climacoolcorp.com/download/18.750678b316cc239f42b4c/1567007172970/Application%20Guide%208.28.19.pdf>

- Seasonal cooling and heating load
- Low/no simultaneous heating/cooling potential

Figure 6 UCA SHC, Heat Pump

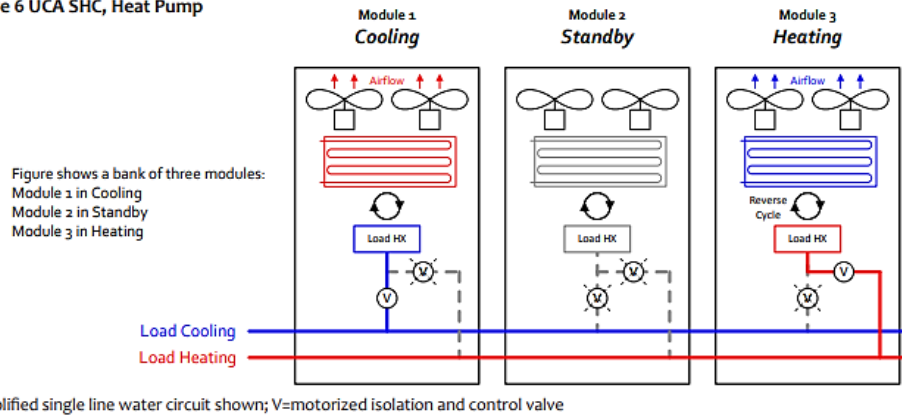


Figure 4.3: AWP Heating / Cooling Only³

Partial Heat Recovery (Desuperheater)

A reverse cycle AWP can achieve partial heat recovery function by adding a desuperheater. A desuperheater is a refrigerant to water heat exchanger placed between the compressor and condenser. When the unit is in cooling mode, hot refrigerant gas from the compressor moves through the heat exchanger, which transfers the energy from refrigerant gas to hot water loop while cooling the refrigerant before it enters the condenser, and hot water is produced as byproduct during cooling. The amount of waste heat recovery is limited and depends on desired hot water temperature. A desuperheater can recover 10-40% of cooling capacity to use for heating. The lower the hot water temperature, the higher heat recovery potential. Desuperheaters are best suited for:

- Domestic hot water production
- Reheat or preheat

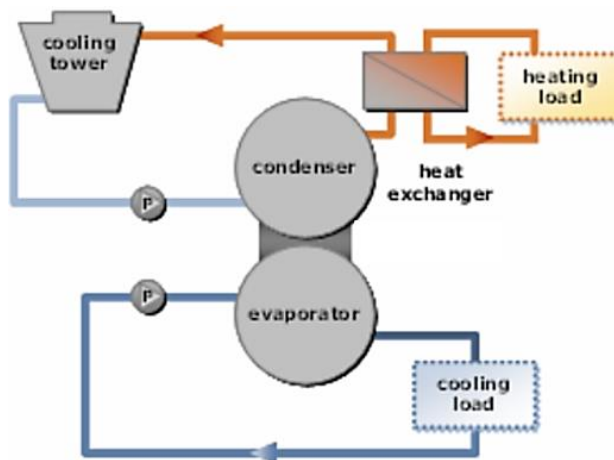


Figure 4.4: AWP with Partial Heat Recovery vis Desuperheater⁴

⁴ Jia, Jing (2006) Introduction of Heat Recovery Chiller Control and Water System Design

Heat Recovery (4-Pipe)

A 4-pipe AHP has full heat recovery functionality, it can produce chilled and hot water simultaneously when there is overlapping demand. This AHP system option offers the highest efficiency because it can satisfy heating and cooling with one power input. A 4-pipe AHP has three heat exchangers: condenser for space heating, evaporator for space cooling and a balancing coil. The third heat exchanger acts as either evaporator in heating mode or condenser in cooling mode. Full heat recovery AHP is best suited for:

- Campus with significant simultaneous heating/cooling load
- Should be sized for simultaneous base load because efficiency decreases in cooling only operation

Given the premium cost of full heat recovery system, a detailed study and analysis is necessary to quantify the simultaneous heating and cooling load and cost/benefit of added efficiency.

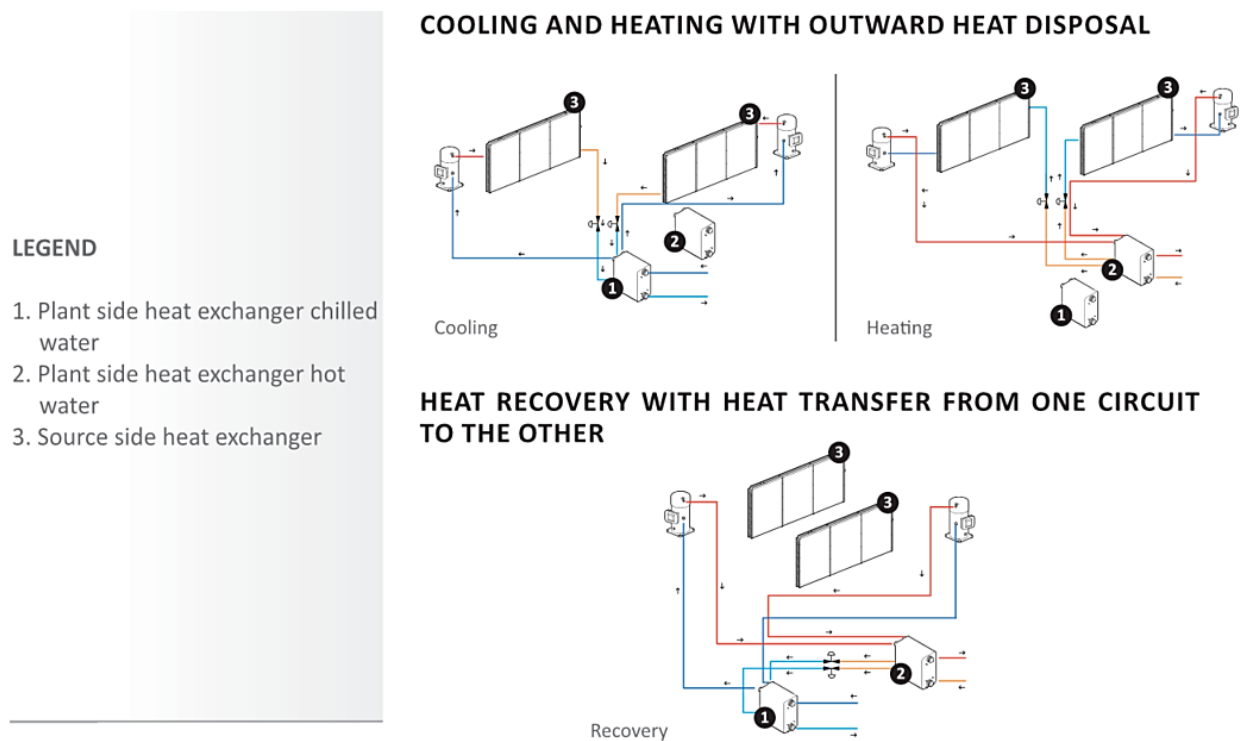


Figure 4.5: AHP with Full Heat Recovery⁵

Additional Considerations

Ambient air temperature can be a limiting factor on heat pump operation especially in cold climate. Standard ASHP can operate down to 32°F outside temperature with reduced efficiency. If low ambient air operation is expected, designer should consider selecting cold-climate heat pumps that use enhanced vapor injection (EVI) to achieve slightly higher COP and leaving water temperature than traditional inverter drive heat pump. Because of technology improvements like EVI, cold-climate AHP on the market today can operate at minimum outside air temperature of 0°F. However, designers must pay special attention to defrost operation when outside

⁵ Aermec Technical Focus https://planetaklimata.com.ua/instr/Aermec/Aermec_Technical_Focus_02-2013.pdf

air temperature drops below 40°F to ensure hot water temperature can still be met during defrost. One solution is to include an auxiliary electric booster heater for low-temperature operation.

For all air source heat pumps, including AWHP, heating capacity and COP are function of outside air temperature and hot water supply temperature. Average heating COP is rated at outside air temperature of 44°F and leaving water temperature of 113°F, but many climates in California can drop lower than that. Therefore, AWHP performance needs to be evaluated over the entire operating range. COP and capacity are also dependent on hot water temperature, the smaller the temperature difference between entering and leaving water temperature (lift), the less work the compressor needs to perform. So, heating COP is highest when leaving water temperature is low and outdoor air temperature is high. Manufacturers recommend designing for 10-15°F delta T and 115/120°F leaving water temperature to ensure optimal performance. See figure below that illustrates this relationship. However, majority of the CSU campus currently operate with HW temperature close to 180°F, in order to operate AWHP at efficient hot water temperature, heating coil retrofit/replacement, HW loop temperature optimization, and cascade heating systems need to be considered. See Section 5 for hot water temperature considerations.

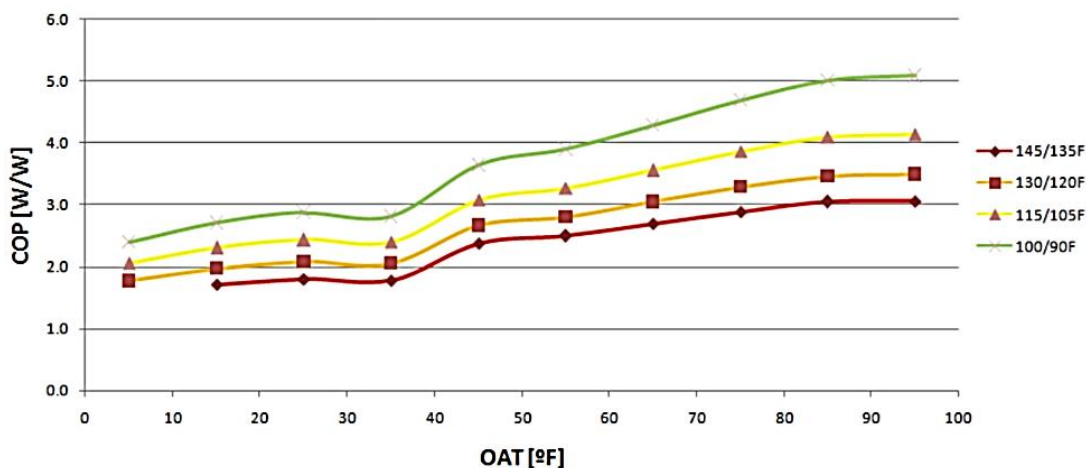


Figure 4.6: AWHP COP vs Outside Air Temperature⁶

To ensure extended equipment life a few things must be considered:

- Frequent compressor start/stop can wear out the equipment, constant loading on compressor is best, consider adding buffer tank on the primary loop to prevent short cycling.
- Frequent reversing the cycle can also cause reduced equipment life.
- AWHP is recommended to be designed with primary/secondary configuration, with constant volume on the primary loop.

⁶ AERMEC presentation Decarbonize with Hydronic Heat Pumps

Water-to-Water Heat Pump (WWHP)

Overview

Water-to-water heat pump (WWHP) uses water as heat source, in the form of groundwater, surface water, cooling tower water or other low temperature process water. Heat is moved into hydronic distribution system to heat the buildings, and the process could be reversed for cooling.

There are a few advantages for using water as heat source as opposed to air:

- Water temperature can be kept relatively stable for most of the year compared to air temperature. Because of lower temperature fluctuation, it is a more reliable source of energy and the performance is not highly dependent on outside air temperature.
- If water source is from the ground, temperature is almost constant throughout the year.
- Water has higher heat transfer rate than air, therefore WWHP have higher heating and cooling efficiency than AHP.

The most commonly used source of heat for water-to-water heat pump is condenser water that would have otherwise been rejected to the cooling tower. Other sources of heat are described in detail in Section 4 with their own design considerations as well as cost and maintenance implications. The following section will focus on heat pump technology independent of heat source, however, common heat sources include:

- Condenser water loop – the system might require additional heat source to maintain tower water temperature. Some manufacturer also advised to design for close loop instead of open tower to ensure water quality and longevity of heat recovery chiller
- Ground water heat pump using nearby well to extract water from aquifers – only applicable if ground water is readily available.
- Surface water can act as heat source with buried pipes between the heat pump and open lakes, ponds or other water streams – depending on the climate, this water temperature may fluctuate slightly.
- Geothermal heat pump circulates water in a heat exchanging ground loop (either vertical, horizontal or spiral coils) buried underground to transfer heat between the ground and the building – When both heating and cooling are needed, heat pump can perform both functions and ground can absorb or supply additional heat that's not available in the building water loops.



Figure 4.7: Water to Water Heat Pump Equipment⁷

Table 4.3: Water-to-Water Heat Pump (WWHP) Equipment Summary

General Description	<p>Uses water as heat source and hydronic distribution system.</p> <p>Water supply can be groundwater, surface water, cooling tower water or other heat sources, see Section 4 for more detail.</p> <p>WWHP connected to ground water source are also known as ground source heat pump.</p> <p>Water has higher heat transfer rate than air, resulting in higher efficiencies.</p>
System Options	<p>Heating Only: 4-pipe system connected to HW supply and return as well as source water supply and return, system does not have cooling capability. It's lowest cost option best suited for direct boiler replacement for decentralized system and where there's limited cooling load</p>
	<p>Heating / Cooling Only: 4-pipe with reversing valve, can perform either heating or cooling at a time, by switching between connection to CHW or HW. Best suited when heating load is restricted to winter months and there is limited heat recovery potential</p>
	<p>Partial Heat Recovery with Desuperheater: 4-pipe reverse cycle heat pump with desuperheater between compressor and condenser can extract waste heat from cooling process to produce hot water. Can recover 10-40% of cooling capacity depending on desired water temperature, the recovered heat can be used for preheat or reheat.</p>
	<p>Full Heat Recovery (4-Pipe): 4-pipe system capable of operating in cooling-only, heating-only, or cooling with heat recovery, heating capacity is dependent on cooling load. Optimal operation when producing CHW and HW simultaneously, should be sized for simultaneous base load.</p>
	<p>Full Heat Recovery (6-Pipe): 6-pipe system is connected to cooling tower or ground source heat exchanger as additional heat source/sink. A 6-pipe configuration can operate in cooling-only, heating-only or heat recovery, it's capable of meeting variable cooling and heating load where there isn't consistent simultaneous heating and cooling over a year.</p>
Hot Water Temperature	<p>Standard: 130°F</p> <p>High Temp: 170°F (may require alternative refrigerant, see Section 4.2.4 regarding refrigerant impact)</p>
Design Considerations	<p>Capacity: 400-40,000 MBH or up to 2500 Tons. Modular heat pump capacity can be expandable with each module 10-85 Ton.</p> <p>Refrigerant: Typically, R-410A, high temp heat recovery may require R-134a, some products also come in R-1233zd. Please reference Section 4.2.4 regarding refrigerant impacts and alternatives.</p>
Best Application	<p>Heat pump options are ideal for direct boiler replacement, or where cooling and heating are seasonal.</p> <p>Heat recovery options are ideal for campus that need additional cooling capacity and have need for simultaneous heating and cooling.</p>
Efficiency	<p>Efficiency depends on source water temperature and HW temperature. Lower leaving water temperature and higher source water temperature result in higher COP.</p> <p>Heating COP 4-5 @113°F HW, 3-4 @130°F HW</p> <p>Cooling kW/ton 0.5-0.8 @41°F CHW</p> <p>Heat Recovery COP 6-8 @113°F HW, 41°F CHW</p>
Limitation	<p>4-Pipe heat recovery: heating capacity is limited by cooling load</p> <p>6-Pipe heat recovery: must connect to cooling tower or additional heat source/sink</p>
First Cost	<p>Heat pump w/o heat recovery: \$60-270/MBH</p> <p>Full heat recovery heat pump: \$100-450/MBH</p>

⁷ ClimaCool and Carrier product catalog

O&M Cost	Service Life: 20 -25 years Maintenance is similar to traditional chiller
Technology Readiness	Readiness Level: Tier 9 - Commercialized Available Manufacturers: Aermec, Carrier, Climacool, ClimateMaster, Multistack, York, etc.

There are a multiple WWHP configurations:

- 1) **Heating Only:** heat pump only provides hot water
- 2) **Heating / Cooling Only:** heat pump can provide either hot water or chilled water
- 3) **Partial Heat Recovery (Desuperheater):** heat recovery via small heat exchanger
- 4) **Full Heat Recovery (4-pipe):** heat recovery to provide simultaneous load
- 5) **Full Heat Recovery (6-pipe):** heat recovery to provide simultaneous load, condenser water to provide additional cooling, secondary heat source required for additional heating

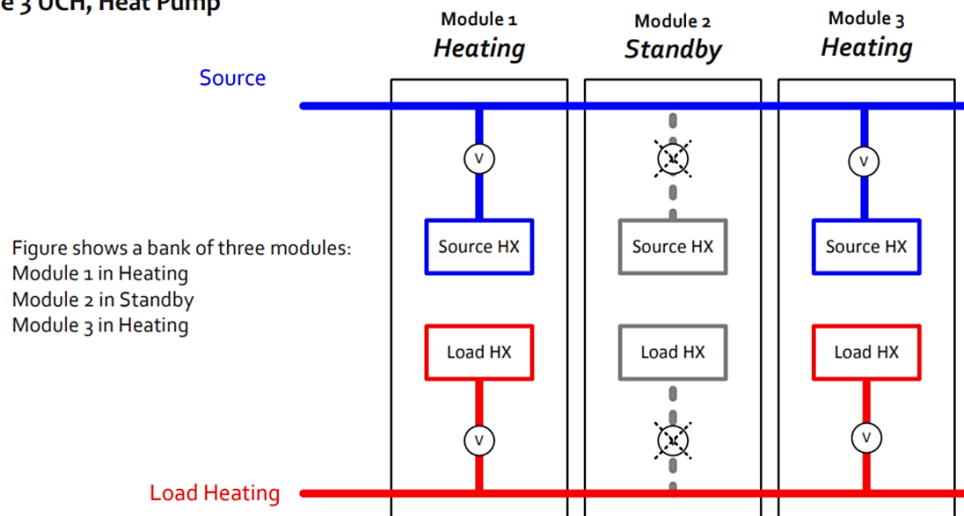
Note that WWHP with heat recovery functionality (either partial or full heat recovery) is sometimes referred to as water-cooled heat recovery chiller. This document refers to them as heat pump to emphasize that they are designed for heating.

Heating Only

Heating-only WWHP does not have reversing valve and are optimized for heating operation. Heating capacity is controlled by leaving condenser water temperature. These are low-cost option best suited for:

- Direct boiler replacement
- Limited cooling load or heat recovery potential
- Utilizing heat from waste streams such as wastewater or process hot water

Figure 3 UCH, Heat Pump



*Simplified single line water circuit shown; V=motorized isolation and control valve

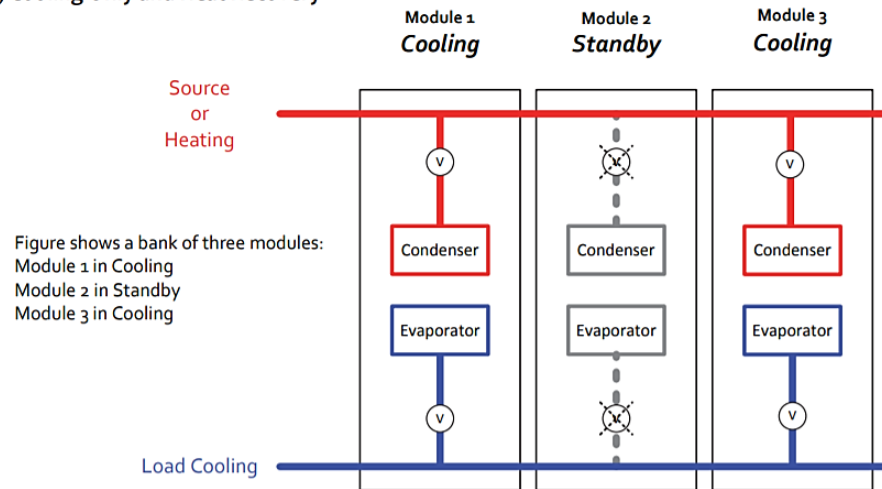
Figure 4.8: WWHP Heating Only³

Heating / Cooling Only

Reverse cycle WWHP is equipped with reversing valve that changes the direction of refrigerant flow, to provide either heating or cooling at a time. They are configured as 4-pipe system with one heat exchanger to provide either chilled water or hot water. They are equipped with reversing valves to allow switching the connect to hot water or to chilled water loop. These are best suited for:

- Seasonal heating load
- Low/no simultaneous heating/cooling need

Figure 1 UCW/H, Cooling Only and Heat Recovery



*Simplified single line water circuit shown; V=motorized isolation and control valve

Figure 4.9: Heating/Cooling WWHP in Cooling Mode³

Partial Heat Recovery (Desuperheater)

Like AWHP, reverse cycle WWHP can have partial heat recovery function by adding a desuperheater. A desuperheater is a refrigerant to water heat exchanger placed between the compressor and condenser. When the unit is in cooling mode, hot refrigerant gas from the compressor moves through the heat exchanger, which transfers the energy from refrigerant gas to hot water loop while cooling the refrigerant before it enters the condenser. Essentially hot water is produced as byproduct during cooling. The amount of waste heat that can be recovered is limited, depending on desired hot water temperature, a desuperheater can recover 10-40% of cooling capacity for heating. Desuperheaters are best suited for:

- Domestic hot water production
- Water preheating / reheating

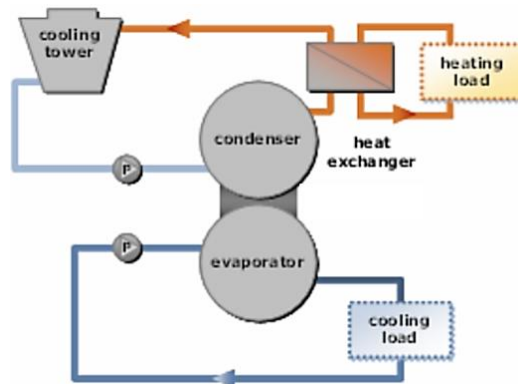


Figure 4.10: WWHP with Partial Heat Recovery via Desuperheater⁴

Heat Recovery (4-Pipe)

Traditional heat recovery WWHP would require a secondary heat recovery condenser that runs parallel to heat pump's main condenser. Other heat recovery WWHP uses a heat changer in series with the main condenser similar to a desuperheater but the heat exchanger is larger and able to recovery more of the cooling capacity. This WWHP connects to chilled water and hot water loop; the heat generated during cooling process is transferred to the hot water loop instead of rejecting to cooling tower. WWHP with heat recovery functionality is sometimes referred to as water-cooled heat recovery chiller. By adding a heat recovery WWHP to a chilled water system, the waste heat that would otherwise be rejected by cooling towers can be captured and use for heating.

This configuration can recover 80-90% of cooling capacity, therefore offers higher efficiency than desuperheater. 4-pipe heat recovery WWHP always needs to reject heat from cooling process to the hot water loop, so hot water loop can only extract as much heat as rejected by the cooling process. This is sometimes referred to as passive heat recovery. Heat recovery WWHP operates most efficiently when there is simultaneous heating and cooling load. In cooling-only mode, a chiller operates less efficiently than a standard chiller because higher condenser water temperature requires higher lift on the compressor.

Because of these limitations, 4-pipe heat recovery WWHP is ideal for:

- Applications where there is substantial amount of simultaneous heating and cooling year round
- Especially works well in campuses with a lot of VAV reheat system

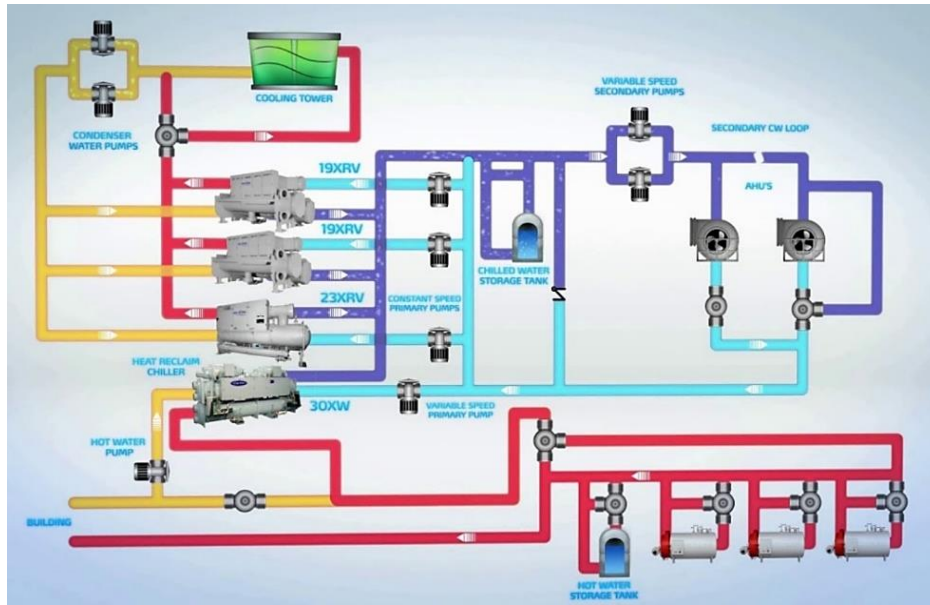


Figure 4.11: WWHP with heat recovery (4-pipe)⁸

Heat Recovery (6-Pipe)

In addition to chilled water and hot water connection as with 4-pipe heat recovery WWHP, 6-pipe system is connected to cooling tower or ground source heat exchanger as additional heat sink/source. This allows the unit to have better flexibility to operate in cooling only or heating only.

When the unit is in heat recovery mode, it operates like 4-pipe system and the additional water loop is not used. When cooling load is higher than heating load, the unit operates in cooling-only and condenser water is rejected through cooling tower, providing additional cooling capacity. When heating load is higher than cooling load, the unit operates in heating-only and the ground can act as additional heat source. This allows for lower condenser water temperature when cooling load is high, but heating load is low or non-existent; allowing for additional cooling capacity without compromising chiller efficiency.

While it has some added benefit, 6-pipe heat recovery chiller requires more piping, connection to condenser water and/or ground loop. It also requires condenser water or ground water to be open to CHW and HW lines, this will require additional consideration to address water quality. The equipment is also more expensive than 4-pipe system, designer should evaluate annual cooling and heating load profile to determine if 6-pipe is the optimal choice.

In general, 6-pipe heat recovery chiller are suitable for:

- Variable cooling and heating load where there isn't consistent simultaneous heating and cooling load throughout the year.
- Available cooling tower or ground-loop to act as additional heat sink or source

⁸ <https://www.carrier.com/commercial/en/us/products/chillers-components/heat-recovery/>

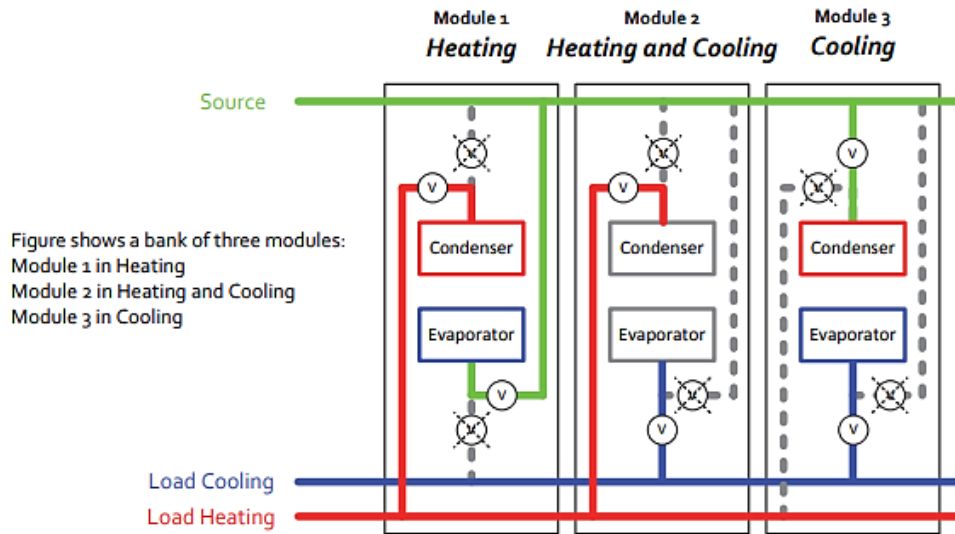


Figure 4.12: WWHP with Heat Recovery (6-Pipe)³

Additional Considerations

WWHP efficiency is dependent on desired hot water temperature and source water temperature as illustrated below. Where possible, hot water supply temperature should be reduced to improve heat pump performance.

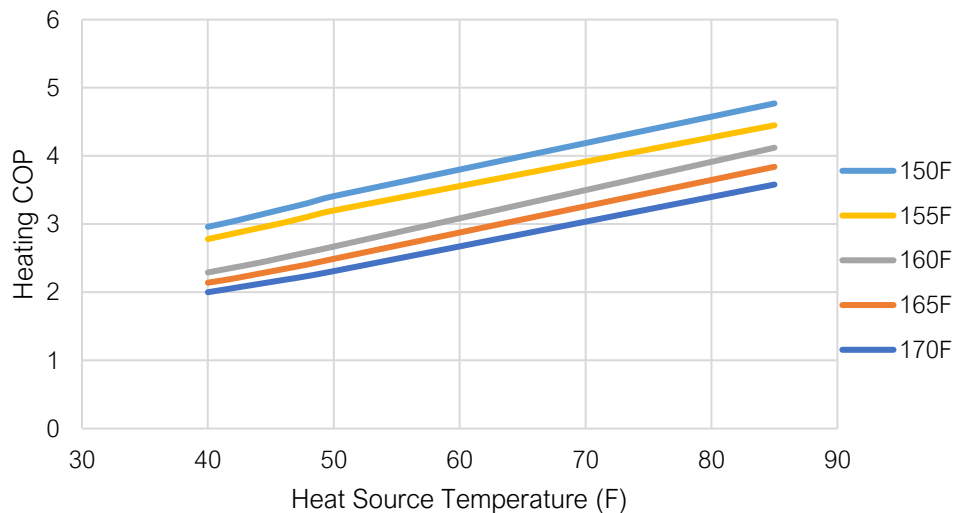


Figure 4.13: WWHP Heating Efficiency vs Source Temperature

When designing for heat recovery WWHP, it is critical to assess annual chilled water and hot water profile because efficiency drastically decreases when unit is not in simultaneous cooling and heating mode. 4-pipe heat recovery should be sized for base heating load that is available year-round to maximize full load hours (first figure below¹). 6-pipe heat recovery can be sized slightly higher for intersection between heating load and heat rejection from cooling load because it can meet variable load (second figure below). It's important to not oversize, oversized heat recovery chiller may short cycle under part load conditions and lead to poor hot water temperature control and reduce equipment life. Because heat recovery WWHPs usually requires backup heating by boiler, they should be sized lower because the backup heating would mitigate the risk of under sizing. Sizing the equipment at the appropriate capacity will also ensure better return on investment.

FIGURE 6 Design point of HRCHLR.

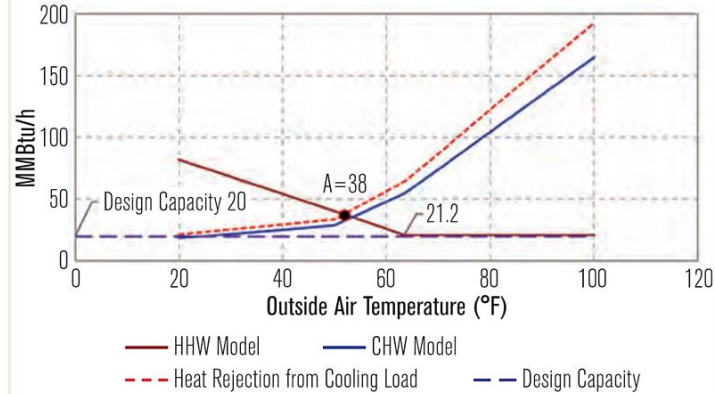


FIGURE 4 Selection point for the simultaneous heating and cooling heat pump (Campbell et al. 2012).

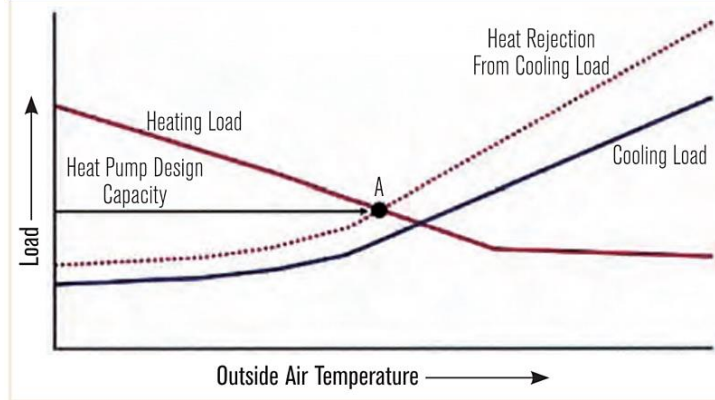


Figure 4.14: Heating Recovery⁹

⁹ ASHRAE Journal (December 2018) "Commissioning an Existing Heat Recovery Chiller System"

4.2.3 Non-Hydronic Heat Pumps

Water source heat pump (WSHP)

Overview

Water source heat pumps (WSHP), also known as water-loop heat pumps or water-to-air heat pump. These heat pumps units are distributed throughout the building and connected to a common water loop. These distributed heat pump units can be horizontal above ceiling, vertical in closets, packaged units in mechanical rooms or rooftop units. A typical WSHP system is supplied by condenser water loop, but a backup heat source may be required to maintain CW temperature.

Whether the heat source is from the ground or condenser water, WSHP operate in a few modes:

- If all zones need **cooling**, the heat pumps transfer the heat from building to the water loop. When water loop temperature rises above 90°F, the excess heat will be rejected through cooling tower.

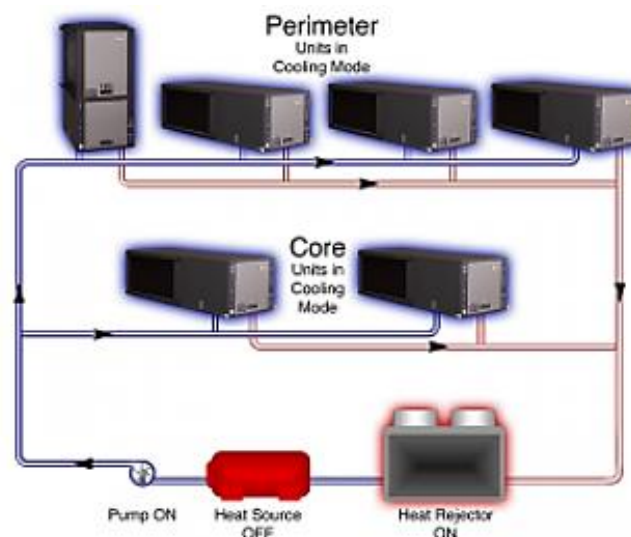


Figure 4.15: WSHP in Cooling¹⁰

- If all zones need **heating**, the heat pumps act as an evaporator and transfers heat from the water loop to the space. When loop temperature drops below 60°F, an additional source of heat will turn on to maintain water temperature. This could be an electric boiler or central heat pumps.

¹⁰ ClimateMaster Water-Source Heat Pump Applications.

<https://www.climatemaster.com/commercial/applications/water-source-heat-pump-applications>

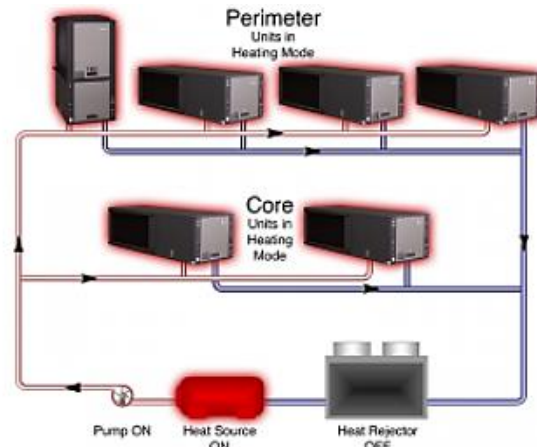


Figure 4.16: WSHP in Heating¹⁰

- In **simultaneous heating and cooling mode**, some zones are in cooling while others are in heating. The cooling zones reject heat into the water loop while heating zones absorb that heat. The system operates most efficiently in this heat recovery mode.

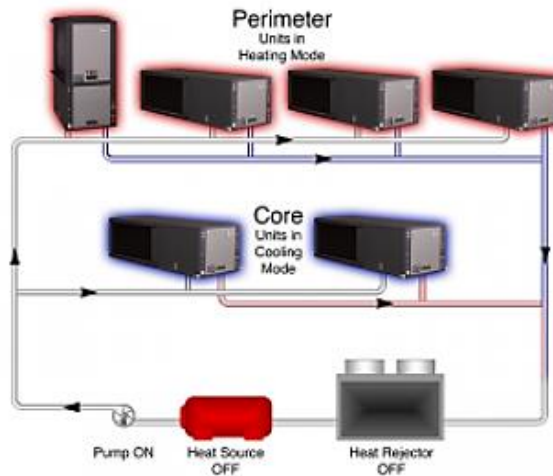


Figure 4.17: WSHP in Simultaneous Heating and Cooling¹⁰

Like water-to-water heat pump, the water loop can be supplied from various sources including cooling tower, groundwater or geothermal loops. A variation of this system is ground-source heat pump. Instead of using boiler and cooling tower as sources of heating and cooling, excess heat from cooling process is transferred to the ground and can be recaptured during heating. Ground-coupled system eliminates the need for boiler and cooling tower because the ground or ground water acts as continuous heat source sink. See section 4 for more details about sources of heat.

Table 4.4: Water Source Heat Pump (WSHP) Equipment Summary

General Description	<p>Also known as water-to-air heat pump, or water loop heat pump uses forced air system to deliver heat.</p> <p>Distributed system: small heat pump units located throughout the building (horizontal, vertical or rooftop units) and connected to a common condenser water loop.</p> <p>A backup heating source is required to maintain loop temperature during heating and heat is rejected through cooling tower.</p> <p>A variation on this design uses geothermal or groundwater as heat source, which can eliminate the need for backup heating and cooling tower because the ground or ground water acts as continuous heat rejecter or heat adder.</p>
System Operating Mode	<p>Cooling: refrigerant-to-water heat exchanger transfers heat from cooling load to the water loop. When water loop temperature rises above 80-90°F, the excess heat will be rejected through cooling tower or to ground source.</p> <p>Heating: refrigerant-to-water heat exchanger acts as evaporator and absorbs heat from the water loop to heat the space. When loop temperature drops below 60-70°F, an additional source of heat will turn on to maintain water temperature. This could be an electric boiler, central heat pumps, or ground source.</p> <p>Simultaneous Heating & Cooling: During shoulder seasons, the cooling zones reject heat into the water loop while heating zones absorbs that heat. System optimal operation when simultaneous heating and cooling.</p>
Design Temperature	<p>Condenser water temperature to be kept between 60 and 90°F</p> <p>Extended-range WSHP are becoming more common, with condenser water 45-110°F</p>
Design Considerations	<p>Unit capacity:</p> <p>Cooling capacity 0.5 – 25 Ton</p> <p>Heating capacity 8,200 – 222,700 Btu/h</p> <p>Refrigerant: R-410A</p> <p>Water flowrate: design with recommended 2-3 gpm per ton of cooling capacity</p>
Best Application	<p>There's a condenser water loop or ground water source close by</p> <p>Simultaneous heating and cooling needs within building</p> <p>Space flexibility: easy to reconfigure the system if space programming changes</p> <p>Where central mechanical space is limited</p>
Efficiency	<p>Efficiency dependent on source water temperature, efficiency with condenser loop:</p> <p>Cooling EER 13-17.4 @ 86F source water</p> <p>Heating COP 4.7-5.7 @ 68F source water</p>
Limitation	<p>Secondary heating source may be necessary unless ground source</p> <p>Increase electrical distribution system</p>
First Cost	<p>\$85-200/MBH for WSHPs, but may require additional cost for cooling tower, condenser loop, and supplemental heating</p>
O&M Considerations	<p>Service life: water loop 19 years, ground coupled 25 years</p> <p>Distributor compressors, numerous points of service in the building, higher maintenance cost</p>
Technology Readiness	<p>Readiness Level: Tier 9 - Commercialized</p> <p>Available Manufacturers: Carrier, ClimateMaster, Trane, etc.</p>

Additional Considerations

WSHP efficiency depends on source water temperature. For condenser water loop heat pumps, heating and cooling efficiency are rated according to AHRI/ISO 13256-1 are rated at source temperature of 86°F for cooling and 68°F for heating. For ground water heat pumps, they are rated for source temperature of 59°F for cooling and 50°F for heating. For ground loop heat pump, they are rated for source temperature of 77°F for cooling and 32°F for heating. See chart below for how this impacts cooling and heating efficiency.

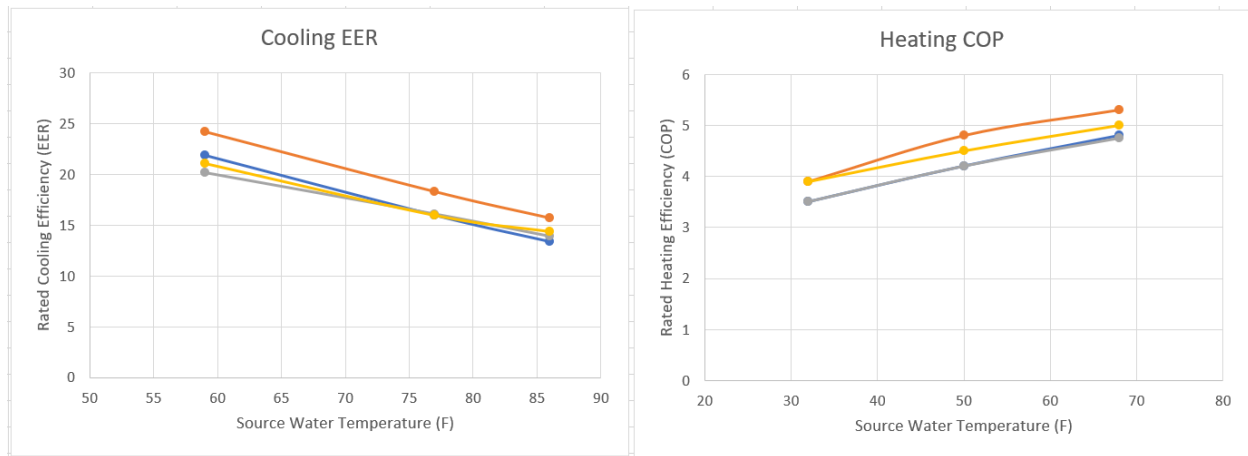


Figure 4.18: WSHP Efficiency vs Source Water Temperature

Operationally, distributed compressors can add to O&M cost. When WSHP is ground-coupled, higher first cost will be expected for installing ground loops but will have lower O&M cost because it eliminates cooling tower and boiler. Filter and coil maintenance are also important to maintain optimal system performance and service life.

Air-to-Air Heat Pump

Overview

Like AWHP, air-to-air heat pump also transfers heat between the outside air and indoor, but instead of transferring the heat to a hydronic system, the heat is distributed by a forced-air system or refrigerant pipes. They can be reversed in the summer to provide cooling and extract heat from the indoor. Air-to-air heat pumps can be ducted split system, ductless mini-split, packaged terminal heat pump, or packaged rooftop units. They are factory-built system installed at the building.

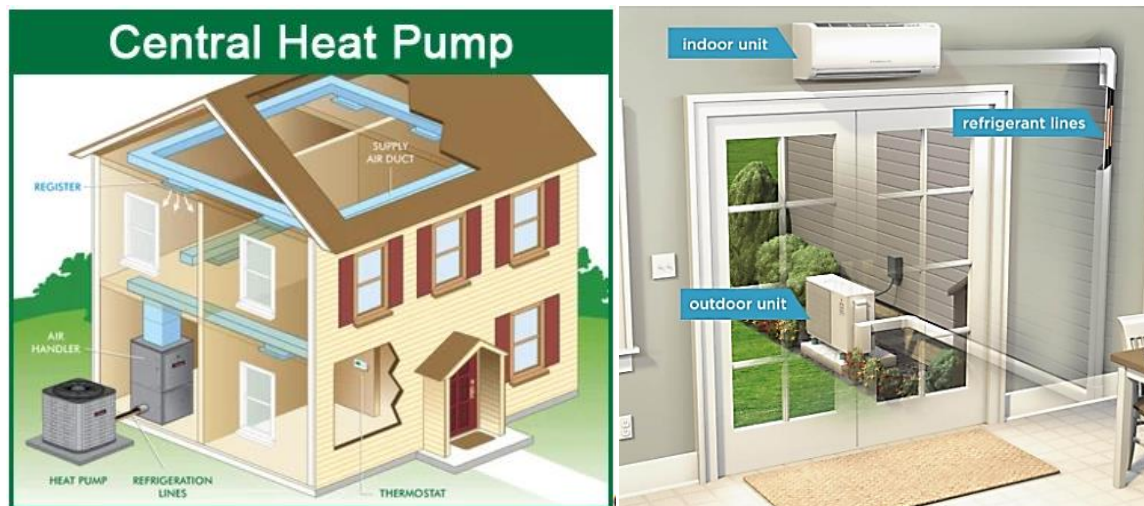


Figure 4.19: Ducted Split Heat Pump¹¹ and Ductless Mini-split¹²

Table 4.5: Air-to-Air Heat Pump Equipment Summary

General Description	Transfers heat between the outdoor and indoor through air distribution system Their capacity is relatively low, and can serve single zone or multiple zones
System Options	Ducted split system: outdoor unit consist of condenser and compressor, connected to single or multiple indoor units containing evaporator.
	Ductless mini-splits: similar to ducted split system but use refrigerant pipes instead of ducts to deliver heating or cooling. They have higher efficiency than ducted system and have no duct loss
	Packaged terminal heat pump (PTHP): stand-alone system where all components (compressor, fans, evaporator coils and condenser) are all in one unit, usually located on an exterior wall serving one zone.
	Packaged rooftop heat pump: Packaged rooftop unit that can serve a single zone or serve multiple zones (with VAV boxes)
Design Considerations	Capacity: 400-500 cfm/ton, available up to 70 MBH heating capacity @47°F OAT Refrigerant: R-410A most common

¹¹ <https://evergreenhomeheatingandenergy.com/blog/bid-219238-types-of-heat-pumps>

¹² https://www.energystar.gov/products/heating_cooling/ductless_heating_cooling

Best Application	Replacement of single-zone air-conditioned (AC), packaged terminal AC or rooftop AC units
Efficiency	Heating COP: 2.8 – 4 @ 47°F OAT, 1.75 – 3.1 @ 5°F OAT
Limitation	Limited capacity
First Cost	Equipment cost ROM: \$80-100/MBH
O&M Considerations	Expected useful life: 15-20 years O&M cost similar to alternative natural gas equipment
Technology Readiness	Readiness Level: Tier 9 - Commercialized Available Manufacturers: Carrier, Mitsubishi, Daikin, LG, Panasonic, York, others

Additional Considerations

Because the heat source is ambient air, air-to-air heat pump efficiency and capacity are also impacted by outside air. When temperature drops, the heating COP drops drastically and heat pump may require supplemental heating, usually electric resistance. In a decentralized system, or when a building is not connected to campus chilled and hot water, air-to-air heat pump can replace air conditioning units with zone reheat.

Variable Refrigerant Flow (VRF/VRV)

Overview

Variable Refrigerant Flow (VRF), sometimes referred to as Variable Refrigerant Volume (VRV), systems are a specialized type of ductless heat pump that consists of an outdoor condensing unit with multiple indoor units, with heat being transferred between them through refrigerant piping within the building. They can control the amount of refrigerant flow to the indoor evaporators, and controls variable-capacity compressor to operate efficiently at part-load conditions. Systems designed with heat recovery also has very high efficiency and takes advantage of simultaneous cooling and heating within a building.

VRF systems can be either air-cooled or water-cooled:

- 1) **Air-cooled VRF** is most common. Multiple compressors are connected to a refrigerant-piping loop. Condenser units are installed outside, often located on the building roof. It can operate when ambient air temperature is between -20°F and 115°F, but heating capacity is impacted in low temperature conditions.
- 2) **Water-cooled VRF** connects the compressors to a water-source loop, usually geothermal or condenser water. Water-cooled VRF have higher annual COP levels and have consistent performance over wider operation range because the water temperature does not fluctuate as much as ambient air. The entering water temperature should be in the 50-113°F range but can operate with loop temperature as low as 14°F in geothermal applications.

Table 4.6: Variable Refrigerant Flow/Volume (VRF/VRV) Equipment Summary

General Description	Special type of heat pump that have one outdoor condensing unit to multiple indoor units. Refrigerant is piped throughout the building to transfer heat from condensers to indoor fan coil units, and between the indoor units for heat recovery. VRFs control the amount of refrigerant flow to the indoor evaporators, and controls variable-capacity compressor to operate efficiently at part-load conditions
System Options	<p>Air-cooled VRF has condensing units are installed outside, usually on rooftop. It can operate when ambient air temperature is between 115°F and -20°F, but heating capacity is impacted in low temperature conditions.</p> <p>Water-cooled VRF connects the condensing units to a water-source loop, usually geothermal or boiler/cooling tower system. Water-cooled systems have higher annual COP levels and have consistent performance over wider operation range because the water temperature does not fluctuate as much as ambient air.</p> <p>Heat Pump Only all indoor units connected to one outdoor unit are in the same mode, cooling or heating.</p> <p>Heat Recovery System can operate in mixed mode when some indoor units are in cooling and others in heating. This improves efficiency by moving waste heat from one zone to be used in another zone.</p>
Design Considerations	Unit Capacity: Outdoor unit capacities range from 1.5 to 64 ton Indoor unit capacities range from 0.5 to 10 ton Should be designed with airflow of 350-450 cfm/ton Refrigerant: R-410A Reference ASHRAE Standard 15 for refrigerant concentration limits

Best Application	Heat pump VRF is suitable for buildings that do not have simultaneous cooling heating Air-cooled VRF does not need to connect to CHW or HW loop, ideal for replacement of decentralized natural gas heating (i.e. RTU with VAV reheat)
Efficiency	Air-cooled VRF Heating COP: 3.2-4.3 @ 47°F OSA Cooling EER: 9.3-14.4 @ 95°F OSA Water-cooled VRF Heating COP: 4-6 @ 68°F CW Cooling EER: 10-17 @ 86°F CW
Limitation	Refrigerant is piped throughout the building, concerns with leaks and safety Not a good option for labs or buildings with special outside air requirements
First Cost	Air-cooled VRF: \$130-180/MBH Water-cooled VRF: \$125-150/MBH, additional cost for cooling tower and source loop
O&M Considerations	Air-cooled VRF lifetime: 15-20 years Water-cooled VRF lifetime: 20-25 years Maintenance is higher than hydronic system due to number of distributed condensers
Technology Readiness	Readiness Level: Tier 9 - Commercialized Available Manufacturers: Daikin, Mitsubishi, LG, Panasonic, Trane, Others

There are a multiple systems options for both air-cooled and water-cooled VRF, including the following:

- 1) Heating / Cooling Only Heat Pump
- 2) Heat Recovery
 - a) 2-pipe
 - b) 3-pipe

Heat Pump VRF

Heat pump VRF can reverse the direction of refrigerant flow to provide heating or cooling, but all indoor units connected to outdoor condensing units are in the same mode. This can be suitable for buildings that have low/no simultaneous cooling and heating load.

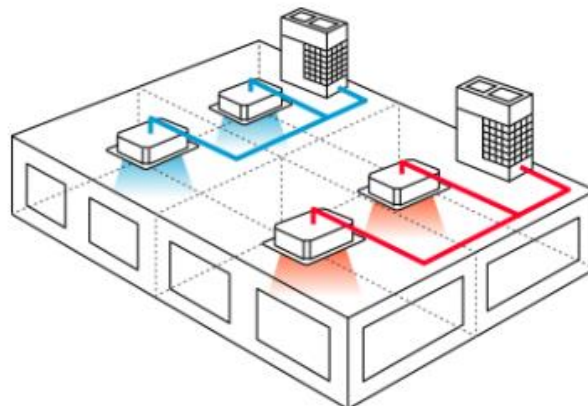


Figure 4.20: Heat Pump VRF System (Heating/Cooling Only)¹³

¹³ https://www.daikin.com/corporate/why_daikin/vrv/modals/1990_02/index.html

Heat Recovery VRF

For buildings that have simultaneous heating and cooling load among the zones, VRF with heat recovery can provide both heating and cooling from the same outdoor condensing unit. This takes advantage of overlapping load and make use of waste heat among the indoor units, resulting in higher efficiency. This can be accomplished in either 2-pipe or 3-pipe configuration, each with its advantages:

2-Pipe systems have a central heat recovery control unit (also referred to as branch controller or heat recovery unit). One high-pressure vapor pipe and one low-pressure vapor pipe are directed from the outdoor unit to heat recovery control unit. In mixed-mode operation, the heat recovery control unit directs high pressure vapor to heating zones, which returns subcooled liquid refrigerant back to controller. The controller then directs this liquid to cooling zones, which returns low-pressure vapor back to the branch controller. This low-pressure vapor is directed to outdoor condenser to be compressed into high pressure vapor, and the cycle repeats. If the system is not in balance, the outdoor unit's heat exchanger will absorb or reject the heat energy to balance heating and cooling loads.

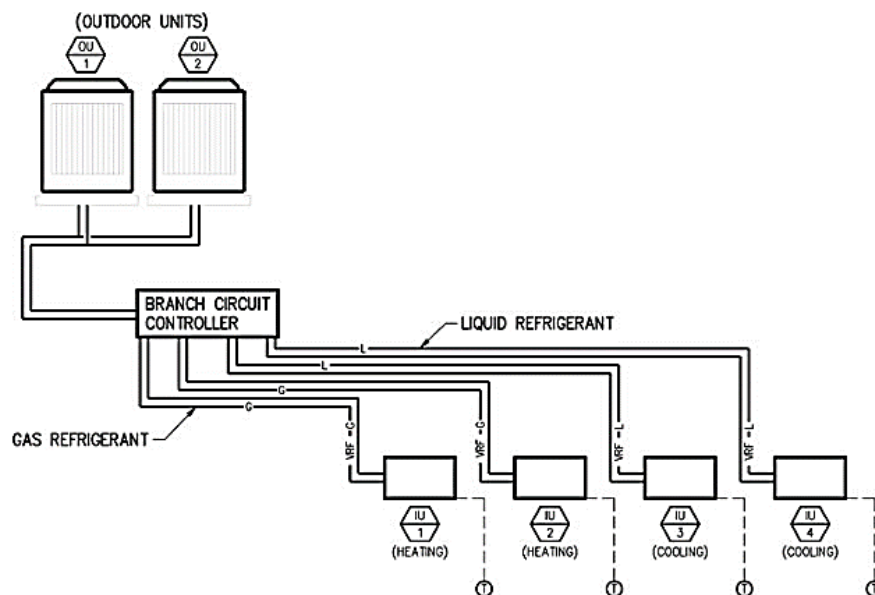


Figure 4.21: VRF Heat Recovery with 2-Pipe Design¹⁴

3-Pipe systems have one high-pressure vapor pipe, one low-pressure vapor pipe, and one liquid pipe from outdoor condensing unit to branch selectors for each zone. The branch selectors direct high-pressure vapor to heating zones and low-pressure vapor to cooling zones. The branch selectors control the direction of refrigerant through indoor units. In heating mode, the high-pressure vapor opens and low-pressure vapor closes, indoor unit acts as condenser. In cooling mode, the low-pressure vapor opens and high-pressure vapor closes, indoor unit acts as evaporator.

¹⁴ Back to Basics: VRF Systems <https://www.csemag.com/articles/back-to-basics-vrf-systems/>

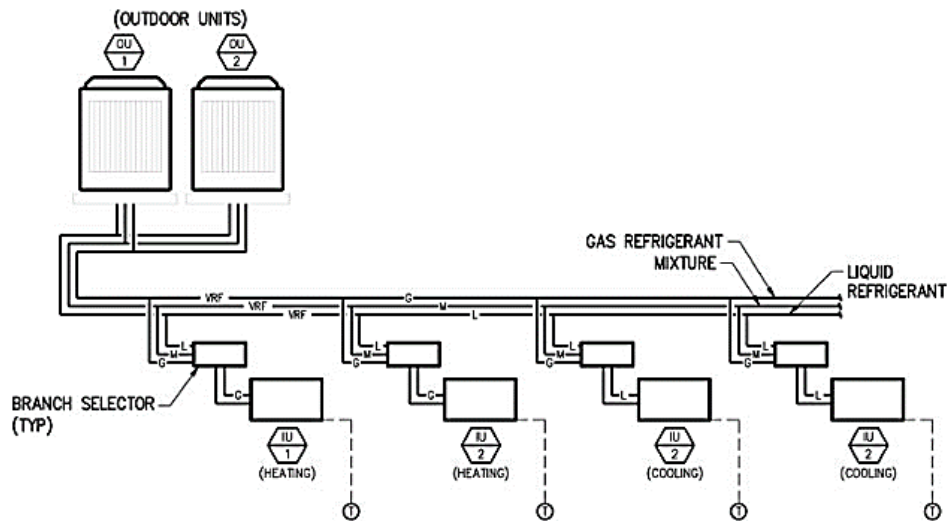


Figure 4.22: VRF Heat Recovery with 3-pipe Design¹⁴

Additional Considerations

R-410A is used by most manufacturers, refrigerant safety classification is group A1: nontoxic and nonflammable with zero ozone-depletion potential. But because the refrigerant is piped to indoor, potential for leak needs to be addressed. ASHRAE Standard 15 addresses refrigerant concentration limit to address safety concerns and must be followed for all VRF installations. If design and installed properly, refrigerant leakage from VRF systems is rare.

4.2.4 Emerging Technology: Heat Pump with natural refrigerant

Overview

Currently, most commercial heat pumps use R-410a or R-134a as refrigerant, both of which are hydrofluorocarbons (HFC's) that have significant global warming potential (GWP), although they are better alternatives to CFC and HCFC that have been phased out. As California Air Resource Board (CARB) is expected to phase out the use of HFC for new centrifugal chillers in 2024¹⁵, many chiller and heat pump manufacturers are now offering HFOs as alternative refrigerants. Natural refrigerants such as ammonia and CO₂ are also expected to rise in adoption. CO₂ based heat pumps are becoming commercially available for domestic water heating and with limited capacity for space heating, while the adoption of ammonia is still facing challenges due to its safety group rating. See below for comparison of GWP among the refrigerants.

Table 4.6: Comparison of Commonly used Refrigerant

Refrigerant	Common Name	Safety Group ¹⁶	Type	GWP ₁₀₀ ¹⁷	Additional Note
R-410a	Puron	A1	HFC	1,924	
R-134a	HFC-134a	A1	HFC	1,300	
R-513a	Opteon XP10	A1	HFO	631	Efficiency penalty over R134a
R-1233zd	Solstice zd	A1	HFO	1	Alternative to R123
R-1234ze	Solstice ze	A2L	HFO	1	More efficient than R-134a
R-717	Ammonia	B2L	Natural	0	
R-744	CO ₂	A1	Natural	1	

Table 4.8: Ammonia and CO₂ Heat Pump Equipment Summary

General Description	Hydronic heat pump using natural refrigerant such as ammonia or carbon dioxide. The same technology can be used for domestic water heating
Hot Water Temperature	Can produce hot water up to 194°F
Design Considerations	Design needs to address proper handling of ammonia that is highly hazardous and poisonous. Adoption requires changes in code to allow for 2L safety group.
Best Application	Large scale ammonia heat pumps have been installed in Europe, but installation in the US is limited to industrial applications CO ₂ heat pumps are commercially available in limited capacity, currently scalable for domestic hot water
Efficiency	Higher than traditional heat pump Ammonia COP 3 when producing 194°F water CO ₂ COP 2.8-4.1 when producing 194°F water
Limitation	Corrosive, toxic and flammable properties of ammonia as refrigerant Availability in US market is limited

¹⁵ Adapted from California Air Resources Board website <https://ww2.arb.ca.gov/>

¹⁶ Refrigerant safety references ASHRAE Standard 34. A means low toxicity, and B means high toxicity. 1 means no flame propagation and 1L means low toxicity and low flammability (burn velocity of <3.9 in./s)

¹⁷ GWP₁₀₀ listed are IPCC Fifth Assessment Report, 2014 (AR5) for 100-year time horizon

First Cost	Likely high upfront cost due to lack of industry familiarity
Technology Readiness	Readiness Level: Ammonia heat pump Tier 8 – System Development Readiness Level: CO ₂ Heat Pump Tier 9 –Commercialized Available manufacture Ammonia Heat Pump outside of the US: Sabroe, GEA, Emerson, etc. CO ₂ Heat Pump: Mayekawa, Permacold, Sanden USA, etc.

Ammonia (R-717), is a natural refrigerant that has 0 global warming potential (GWP). Ammonia has high latent heat of vaporization (602 Btu/lb @-28°F boiling point) that is 6 times higher than R-134a (101 Btu/lb @ -15°F boiling point), resulting in better efficiency and higher temperature output. Due to these factors, there has been increased interest in using Ammonia as a refrigerant in heat pump systems recently. The barrier for wider implementation of ammonia as refrigerant is its hazardous nature. Ammonia is classified as refrigerant safety group B2L (low flammability with high toxicity), whereas R-134A and R-410a are both safety group A1 (no flame propagation and low toxicity). Potential leaks can be highly hazardous and poses health risks for workers. However, Ammonia has a strong odor that helps identify leaks and minimize the risk of exposure to dangerous concentrations. ASHRAE has published a position document that encourages the use of ammonia for heat pump applications, and provides guidance for proper design, safe use and management of these risks.¹⁸ ASHRAE Standard 15 and ANSI / IIAR 2-2-14 have started to address design procedures for applying ammonia while ensure safety. On-going code changes are required to support use of Ammonia in commercial heat pumps. Currently, Ammonia heat pump in the US has been limited to industrial applications but demonstrates potential for commercial applications.

Installation of Ammonia heat pumps are more common in Europe, but still represents only 10% of installed heat pump capacity. Large scale Ammonia heat pumps in Drammen plant in Norway can produce hot water temperature up to 194°F with COP of 3¹⁹. Campuses are expected to achieve higher COP with lower hot water temperature and lift; see below for one European manufacturer's published performance.

¹⁸ *ASHRAE Position Document on Ammonia as a Refrigerant*
<https://www.ashrae.org/File%20Library/About/Position%20Documents/Ammonia-as-a-Refrigerant-PD-2017.pdf>

¹⁹ *Heat Roadmap Europe: Large-Scale Electric Heat Pumps in District Heating Systems. Energies, April 2017.*
https://gallery.mailchimp.com/1a58d05877f2cbb41a7c250a1/files/e8bb1049-a302-438d-8285-2e96817a5147/energies_10_00578_v2.pdf

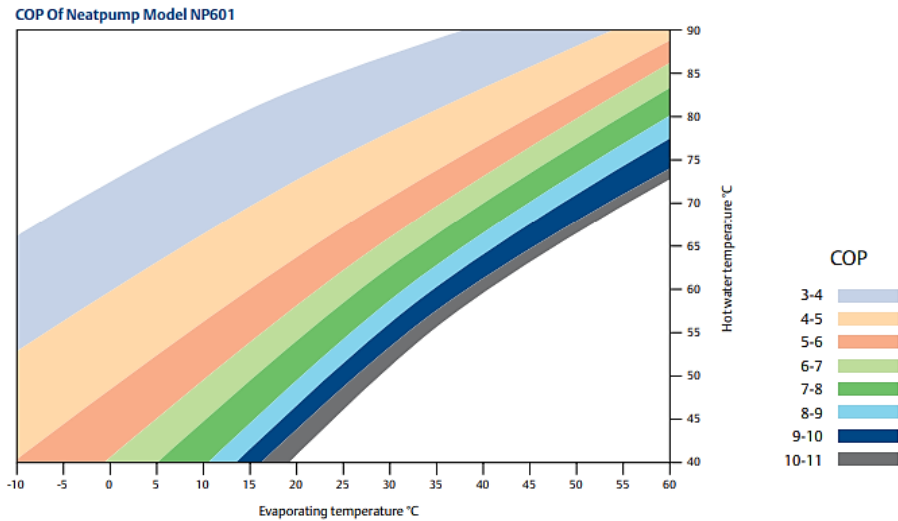


Figure 4.23: COP of Ammonia Heat Pump by European Manufacturer Emerson²⁰

CO₂ is another alternative natural refrigerant used in heat pumps. Electric Power Research Institute (EPRI) has conducted a research to test the performance of CO₂ heat pump for space heating²¹. Water-to-water CO₂ heat pumps are available in capacity up to 340 MBH, and capable of delivering hot water between 149 and 194°F. Lab test results show heating COP between 2.8 and 4.1 while producing 194°F water, and combined COP between 4.5-7.1 during heat recovery. They are available from several manufacturers but are currently more commonly used for domestic hot water applications. Because installation is limited, cost and industry familiarity are prohibiting wider adoption of the technology; while it is not yet scalable for campus space heating, it can be used to produce domestic hot water and has the potential to be implemented for space heating as technology improves.

Ammonia can also be used in a cascade refrigeration system in combination with CO₂. In such system, CO₂ is used in low temperature stage and rejects the heat to high temperature stage that utilizes Ammonia. This allows for reduced amount of Ammonia while using less hazardous CO₂ for most of the operating range.

²⁰ https://ammonia21.com/files/448_dvi143_neatpump_en_1209.pdf

²¹ EPRI CO₂ Heat Pump Water Heaters for Commercial and Industrial Applications presentation https://www.aceee.org/sites/default/files/files/pdf/conferences/hwf/2016/Davis_Session1B_HWF16_2.22.16.pdf

4.2.5 Electric Heating

Electric Boilers

Overview

Electric boiler is essentially same technology as traditional gas boilers but uses electricity to produce hot water. The heating element can either use electric resistance or electrode system and both types of electric boiler have near 100% efficiency. Electric resistance is typically used for smaller applications than central plant and require lower electric connection, whereas electrode boilers need to be connected to up to 10 kV. Electrode boilers have electrodes immersed in water, current flows in water between the electrodes and the electrical resistance of the water generates heat. Electric boilers may seem like the easiest solution to replace existing boilers, however, simply replacing gas boiler with electric boiler will increase energy cost significantly because of demand chargers and electrical infrastructure may not support the added load. Therefore, electric boilers are best used for backup heating to meet peak demand or where high water temperature is required such as laboratories.

Table 4.7: Electric Boiler Equipment Summary

General Description	Same as gas boiler but uses electric resistance or electrode heating element Usually have electric resistance element to convert electric energy to heat energy which is transferred to water
Hot Water Temperature	Up to 180°F for hot water Higher temperature can be achieved for steam
Design Considerations	Capacity: 9 kW to 3,000 kW output (up to 10,000 MBH)
Best Application	Where high water temperature is required, or steam is needed Backup heating for other system types to meet peak demand
Efficiency	100% efficiency
Limitation	Demand charge can make this a costly option Electrical infrastructure capable of supporting added electrical load
First Cost	Equipment costs 20% higher than natural gas boilers Potential added cost for upgrading electrical infrastructure to accommodate additional load
O&M Considerations	Service Life: 15-20 years Does not require annual service as gas boilers Requires little maintenance, but high energy cost due to demand charge
Technology Readiness	Readiness Level: Tier 9 - Commercialized Available Manufacturers: Burham Commercial, Cleaver Brooks, Fulton, Unilux, others

Electric Resistance Heating

Overview

Electric resistance heating converts 100% of the energy in electricity to heat, they are widely used in small scale residential applications, but is not scalable as a standalone solution for CSU campus heating. However, they can be a simple affordable option to supplement other heating technology or provide heating for buildings that have minimal heating. They require little to no maintenance, usually limited to replacing electric heating elements.

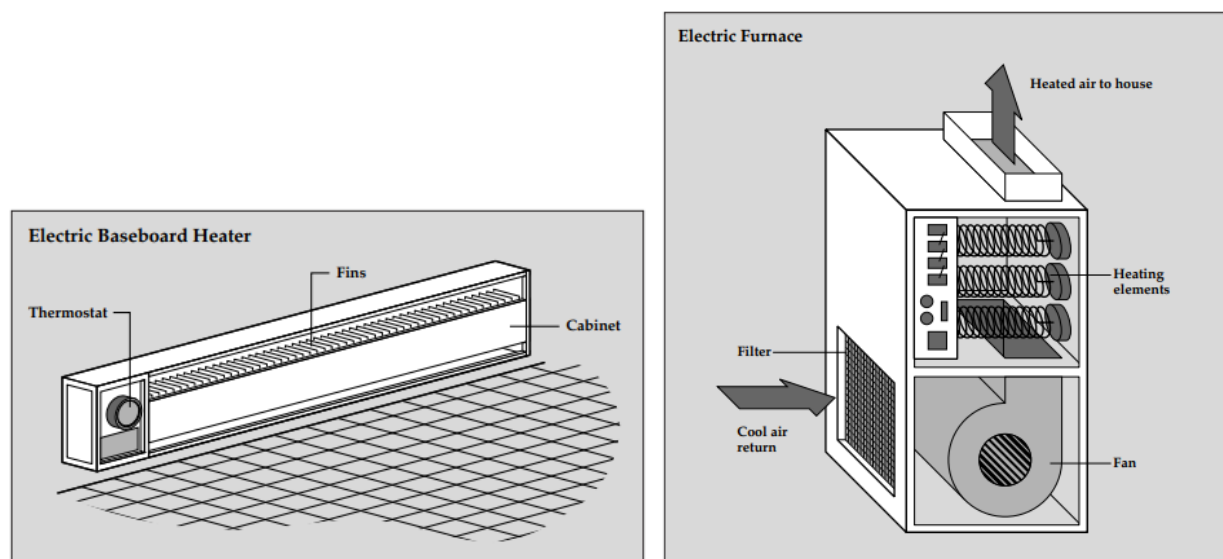


Figure 4.24: Electric Baseboard Heater and Electric Furnace²²

Table 4.10: Electric Resistance Heating Summary

General Description	Simple way to heat selective rooms in a building that has no heating. Can be supplied by centralized forced-air furnace or zone heaters.
System Options	<p>Baseboard heaters: at base of wall underneath windows, warm air naturally rises into the space and cooler air is pulled behind it across heating elements</p> <p>Electric space heaters: can be either wall-mounted or portable. They can have fans to circulate heated air or transfer heat by radiation. Portable heaters are more suited for residential application and can have safety issues in a campus setting. Wall-mounted space heaters can be added to rooms that require heating and respond to room thermostats.</p> <p>Electric furnace: blowers in furnace draws air over electric resistance coils and heated air is delivered through room via ducts. It's subject to duct losses.</p> <p>Radiant heater: electric resistance wiring embedded in floor, ceiling or walls. Infrared radiation heats the surrounding without forced-air distribution.</p> <p>Heating Element: electric heating element to provide heat to an air system (AHU, VAV box, FCU, etc.)</p>

²² Saving Energy with Electric Resistance Heating. <https://www.nrel.gov/docs/legosti/fy97/6987.pdf>

Design Considerations	Capacity: Typically design for 8-10 W/sf, available capacity up to 4000W or 13.6 MBH. Infrared radiant heater can provide heating for larger space.
Efficiency	~100% efficiency
Best Application	Backup heating to air source heat pump at low ambient temperature. Where heating demand is limited to a few rooms within a building.
Limitation	Not a scalable option. Requires electrical infrastructure capable of supporting additional load.
First Cost	Very affordable, but additional cost of electrical infrastructure upgrades
O&M Considerations	Low/no maintenance, but potentially high energy cost of electrical demand. Baseboard heaters: 25 years Wall mounted electric heaters: 20 years Portable electric heaters: 13 years Electric radiant heaters: 10 years
Technology Readiness	Readiness Level: Tier 9 – Commercialized Available Manufacturers: Cadet, Dimplex, King, Runtal, Reznor, QMark, etc.

SECTION 4.3:

Domestic Hot Water Technologies

Another area of high natural gas usage on CSU campuses is domestic water heating. This includes use of hot water for handwashing, residence hall sinks and showers, commercial kitchen, and laboratory. There are many cost-competitive solutions on the market today that can serve as alternative to gas boiler water heating. This section will provide an overview of the technologies, their best applications and limitations, as well as design considerations. Domestic hot water (DHW) technologies covered include:

- 1) Electric Water Heater (Storage Type)
- 2) Heat Pump Water Heaters
 - a) Air-Source Heat Pump Water Heater (Tank Type)
 - b) Air-Source Heat Pump Water Heater (Built-Up System)
 - c) Water-Source Heat Pump Water Heater
- 3) Heating Hot Water Heat Exchanger
- 4) Point of Use Instantaneous Water Heaters
- 5) Solar Water Heater
- 6) Photovoltaic-Thermal

Table 4.8: Domestic Hot Water Technology Summary

System	Description	First Cost ²	O&M Cost ³	Efficiency [COP] ¹	Max Supply Temp	Design Considerations	Best Applications	Limitations
Electric Storage Type	Electric Resistance	\$	\$	0.9-0.95	180°F	Continuous reserve of hot water, good for high DHW draw Temperature is not limited, can produce water up to 180°F Low maintenance	Buildings with minimal hot water demand Natural gas tank type water heater replacements	Higher energy cost compared to gas Efficiency and electricity charge make it costly to operate
Heat Pump	Air-Source (Tank Type)	\$\$	\$	2-3 @70°F ambient	150°F	Indoor installations require adequate rooms air volume to ventilation	Buildings with minimal or moderate hot water demand Natural gas tank type water heater replacements	Capacity and efficiency limited based on indoor space, loads and ventilation Heat pumps operate with backup electric heating when air drops below 50°F
	Air-Source (Modular System)	\$\$\$	\$\$	2 -3 @43°F ambient 3-4 @70°F ambient	150°F	Standard unit provides 140-150°F hot water Storage tanks can be used for peak electrical load shifting Heat pumps can be ducted outside or transfer air	Buildings with large hot water demand Warm or mild climates High temperature applications (ex. kitchens)	Capacity and efficiency limited based on ambient conditions Heat pumps operate with backup electric heating when air drops below 50°F Usually requires outdoor space
	Water-Source	\$\$\$	\$\$	2.5-3 @55°F source water (CHW) 3.4-3.7 @80°F source water (CW)	185°F	Standard unit provides 140-160°F hot water High temp operation (185°F) requires condenser water (85°F) Storage tanks can be used for peak electrical load shifting	Buildings with large hot water demand Buildings with condenser water loops or consistent base cooling load to utilize the CHW return	Requires a consistent water source during all hours of operation requiring DHW
Heat Exchanger	HVAC Heating Hot Water	\$\$	\$	Campus Specific	Campus Specific	Adds an instantaneous heating demand to the HW loop that must be met	Campuses with 24/7 HW loop operation Limited spare electrical capacity	Heating hot water loop needs to operate in order to produce DHW Water temperature based on HW
Electric Point of Use	Electric Resistance	\$	\$	0.9-0.95	140°F	Significant instantaneous electrical demand Eliminates distribution and storage losses	Minimal domestic hot water demand	Hot water production is dependent on flow and temperature rise, not ideal for high DHW demand Space electrical capacity is required
Solar	Solar Thermal	\$\$\$	\$	60-80%	180°F	Design with storage to mitigate difference between DHW load and when solar is available	Buildings with large hot water demand (year-round and weekends)	Produces more hot water during the summer when there is less demand Utility incentives might only cover natural gas savings (unavailable for electric back up)
	Solar Photovoltaic-Thermal	Unknown, \$\$\$	\$	6-8%	Unknown	Produces electricity and hot water at the same time	Buildings with large hot water demand Rooftop PV already planned, can couple with solar thermal	Requires larger surface area to provide equivalent amount of solar thermal energy

¹Efficient ratings are based on 140°F domestic hot water generation with 50°F cold water. Solar efficiency is based on the percent of solar loads that can be converted to usable energy.

²First cost is scaled as: \$ = low cost, \$\$ = medium cost, \$\$\$ = higher cost

³Operations and Maintenance cost does not include energy cost, scaled as: \$ = lower than natural gas equivalent, \$\$ = similar to natural gas equivalent, \$\$\$ = higher than natural gas equivalent

4.3.1 Electric Storage Type Water Heater

Overview

Electric storage type water heaters are very common option; while they are more efficient than gas storage water heaters, they are one of the least efficient ways to heat water with electricity. They consist of cold-water inlet, hot water outlet, anode rod, dip tube, electric resistance heating elements, and thermostats. Smaller systems storage capacity can range from 5 gallons to 120 gallons; however, commercial high-volume models can go up to 2,500 gallons. The benefit of storage type water heater is that they provide continuous reserve of hot water, which works well for applications with high DHW draw. They are slightly more efficient than gas water heaters with energy factor between 0.9 and 0.95. Efficiency loss is mostly due to tank loss. They can provide water at temperature up to 180°F, which can work well for special applications like commercial kitchen, laboratory, etc.

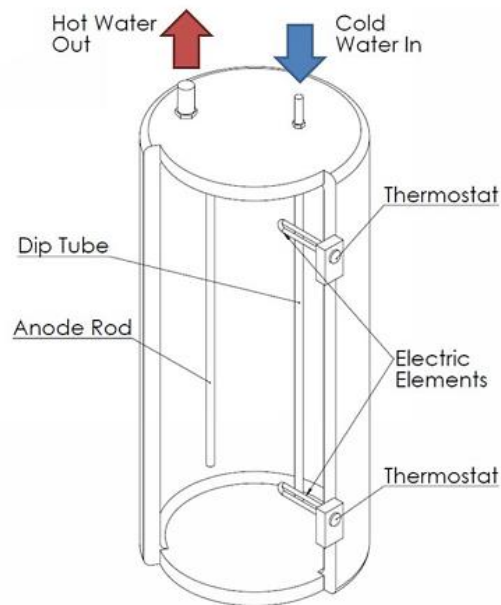


Figure 4.25: Electric Water Heater (Storage Type)²³

Table 4.9: Electric Storage Type Water Heater Summary

General Description	Standard electric resistance tank type packaged water heater
System Options	Typical capacity of 5 gallons to 120 gallons storage High volume models are available up to 2,500 gallons
Hot Water Temperature	Up to 180°F
Design Considerations	Continuous reserve of hot water, good for high DHW draw Water heaters can produce over 180°F water Water temperature does not impact efficiency or capacity is not limited

²³ National Renewable Energy Laboratory, May 2013. Comparison of Advanced Residential Water Heating Technologies in the United States.

Best Application	Minimal hot water demand Direct replacement of natural gas tank type water heater replacements
Efficiency	0.9-0.95%
Limitation	Efficiency and electricity charge make it costly to operate
First Cost	Medium first cost
O&M Cost	Service Life: 13 years Low O&M Cost
Technology Readiness	Readiness Level: Tier 9 – Commercialized Available Manufacturers: A.O. Smith, Rheem, American Standard, others

4.3.2 Heat Pump Water Heaters (HPWH)

Overview

Like electric heat pumps for space heating, heat pump water heaters move heat from the source and deposit it to heat water. They are significantly more efficient than electric water heaters. They can be stand-alone heat pump water heater, or water can be diverted from space heating air-to-water or water-to-water heat pump to provide for DHW.

Heat pump water heater can be divided into a few types:

- 1) Air-Source Heat Pump (Tank type)
- 2) Air-Source Heat Pump (Modular System)
- 3) Water-Source Heat Pump

Table 4.10: Heat Pump Water Heater Summary

General Description	Move heat from the source and deposit it to heat water
System Options	Air-Source tank type: smaller load, usually installed either indoor Air-source modular: can serve larger DHW load, indoor or outdoor installation Water source: either from chilled water return, condenser water loop, or ground source
Hot Water Temperature	Air-source: up to 150°F Water-source: up to 185°F
Design Considerations	Capacity: Ensure air conditioning load > cooling capacity, tank up to 120 gallons Refrigerant: R-410a or R-134a, CO ₂ are starting to be used (see Section 4.2.4 for more detail) Backup heating is required, usually electric resistance, when source water/air temperature drops below 50°F
Best Application	Air-Source tank type: small to moderate hot water demand Air-source modular: large hot water demand Water source: Large hot water demand, with connection to CHW return or condenser water loop
Efficiency	Air-source COP: 2-3 Water-source COP: 2.5-3 @55°F source water (CHW); 3.4-3.7 @80°F source water (CW)
Limitation	Capacity is limited by cooling load for both air-source and water-source systems
First Cost	Tank-type: medium cost Modular type: medium to high cost
O&M Cost	Service Life: 10 years O&M Cost: Low to no maintenance
Technology Readiness	Readiness Level: Tier 9 – Commercialized Available Manufacturers: A.O. Smith, Colmac, Nyle, others

Air-Source Heat Pump (Tank Type)

Air-Source Heat Pump Water Heater (ASHPWH) are very common, and extracts heat from either outdoor air or indoor air. When outdoor air is used as heat source, the performance varies with air temperature and operation will be inhibited when ambient air temperature falls below 50°F. In these cases, backup electric

resistance heating is required to enable defrost. When an ASHPWH is located indoor, it should be installed in space with excess heat for heat transfer, allowing it to operate efficiently. When installed in compact space, designer needs to ensure enough airflow is provided. Design also needs to ensure that cooling capacity of the ASHPWH does not exceed the air-conditioning load of the space. Otherwise, the space can be overcooled, and backup water heating would be required via electric resistance. Ideal locations would include mechanical penthouses, provide weather protection and are typically well ventilated whilst not impacting thermal comfort of occupied spaces. These tank type heat pump water heaters have capacity range to provide for moderate domestic hot water needs, but not suitable for large scale water heating.

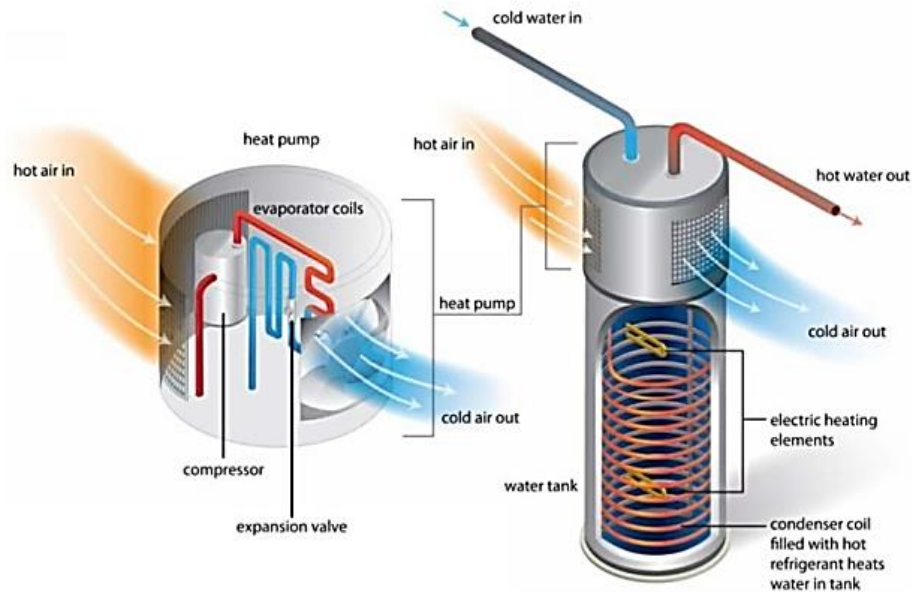


Figure 4.26: Air-Source Heat Pump Water Heater (Tank Type)²³

Air-Source Heat Pump (Modular System)

Modular (built-up) Air-Source Heat Pump Water Heater are more suitable where there is high hot water demand such as student dormitories. Their footprint is bigger than tank type HPWH but can be modular to allow high capacity. The output capacity is dependent on entering air temperature, whether it's outdoor air or indoor air. Heating efficiency and capacity decreases as air temperature drops, and operation will be inhibited when air temperature falls below 50°F. Designing them with storage tank can prolong equipment life and reduce compressor wear.



Figure 4.27: Air-Source Heat Pump Water Heater (Modular)²⁴

Water-Source Heat Pump

Water-source heat pump water heater (WSHPWH) can absorb heat from return chilled water, condenser loop water, ground water, or hot water loop. When designing water-source heat pump water heater, it's important to select a source that can provide continuous heat load that can satisfy domestic hot water needs. When connected to chilled water or condenser water loop, space cooling load must be greater than the heat pump cooling capacity during all hours of operation, otherwise backup heating must be provided.

WSHPWH efficiency decreases as source water temperature drops, see figure below for one manufacture's COP rating with 50°F cold water make-up and 140°F design temperature. Manufacturers recommends source water temperature below 100°F, but higher entering water temperature can be achieved using custom units. Water source heat pump can produce water up to 185°F, and minimum allowable source water temperature is 50°F, temperature below that will require glycol/water mixture.

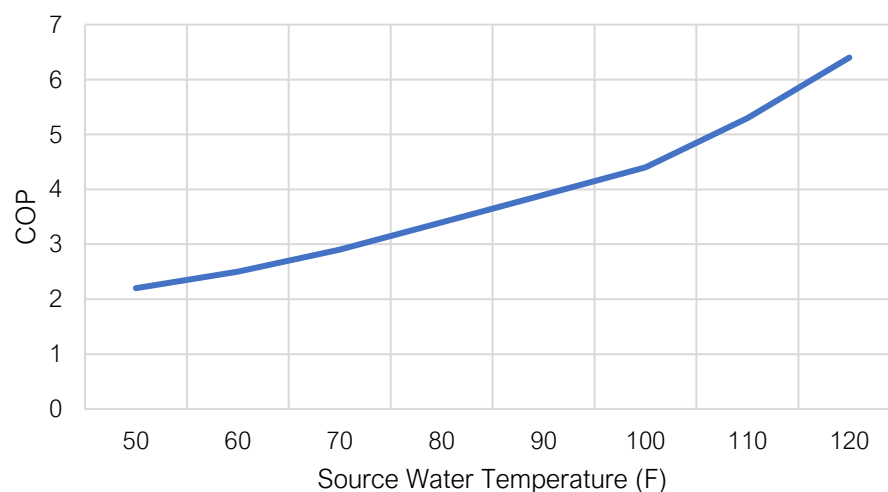


Figure 4.28: Water-Source Heat Pump Water Heater Efficiency vs Source Water Temperature

²⁴ Colmac and Nyle product brochures

Design Considerations

HPWH should not be sized like a boiler; instead of using peak hourly hot water demand to size the equipment HPWH should be sized based on daily usage. Heat pump should be designed to smallest units possible as to not oversize for capacity that is not needed. They are most efficient when running for 16-20 hours a day; in addition, long/constant run times can prevent excessive compressor wear. This can be achieved by adding storage tank sized to cover peak usage conditions, see below for sample schematic for such system.

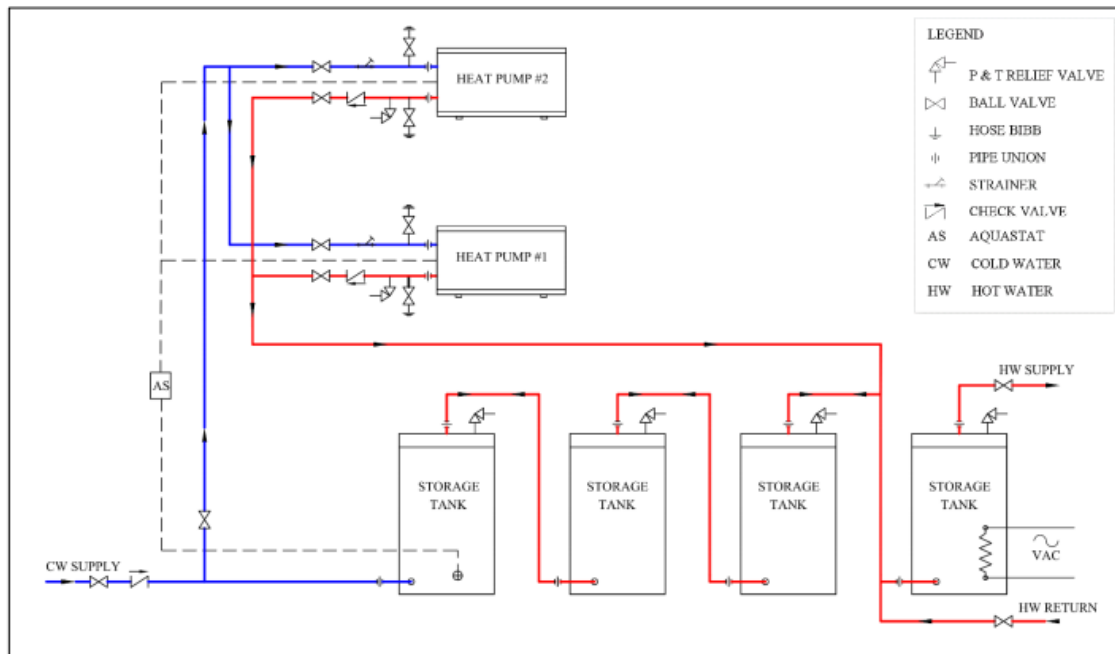


Figure 4.29: Heat Pump Water Heater with Storage Tank²⁵

²⁵ COLMAC WaterHeat Engineering Bulletin: Piping Arrangements for Heat Pump Water Heating.
https://colmacwaterheat.com/wp-content/uploads/2017/09/14_Engineering-Bulletin_HPWH-Piping-Arrangements.pdf

4.3.3 Heating Hot Water Heat Exchangers

Overview

Water-to-water heat exchanger connected a hot water source, extracts heat from the source to heat water for domestic water use. The system can be designed as on-demand water heater or combined with a hot water storage tank to provide reserve of hot water. The heater is usually plate and frame type heat exchanger connected to an existing hot water loop. One limitation of this application is the availability of source hot water: if source water loop is not operating, heat exchanger can't extract heat from the loop.

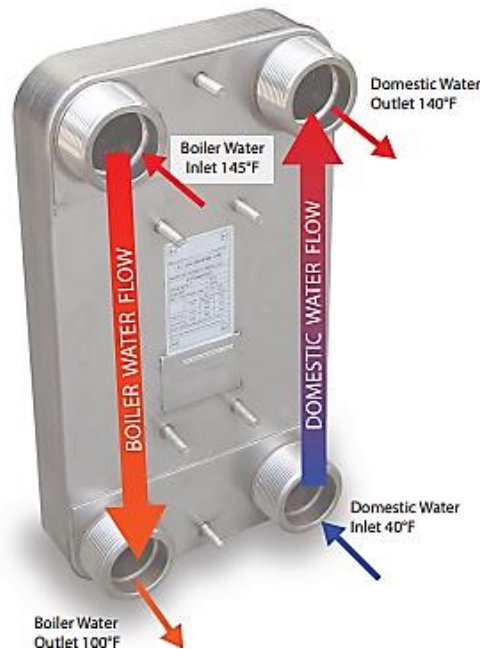


Figure 4.30: Heat Exchanger for Domestic Hot Water²⁶

Table 4.11: Heating Hot Water Heat Exchanger Summary

General Description	Connected a hot water source, extracts heat from the source to heat water for domestic water use Can be connected to hot water generated by boiler or heat pump
Hot Water Temperature	Depends on campus HHW loop temperature
Design Considerations	This strategy adds heating load to the HHW loop, ideal if HHW production is electrified
Best Application	Heat recovery heat pump that needs additional heat sink, DHW can absorb additional heat that can't be absorbed by HHW load
Efficiency	90-99%
Limitation	HHW loop needs to operate to produce DHW, limited by HHW temperature

²⁶ <https://www.pvi.com/dfsmedia/0533dbba17714b1ab581ab07a4cbb521/53697-source/ez-plate-semi-instantaneous-brochure-8659>

First Cost	Low cost
O&M Cost	Service Life: 24 years O&M Cost: Low to no maintenance
Technology Readiness	Readiness Level: Tier 9 – Commercialized Available Manufacturers: Hubbell, Lochinvar, others

4.3.4 Point of Use Instantaneous Water Heaters

Overview

Point of use water heaters are also known as instantaneous water heaters; they provide on-demand hot water without a storage tank. They heat water as it flows through a heat exchanger, within the heat exchanger, electric resistance coil heats the water to desired temperature. Compared to storage type water heaters, tankless water heaters do not need to cycle on and off to maintain tank water temperature and is not subject to storage loss. However, because they do not maintain supply of hot water, it takes a little longer to produce hot water.

Instantaneous water heaters are rated for maximum temperature rise achievable at a given flowrate. It's necessary to determine maximum simultaneous hot water demand and required hot water temperature to right-size the water heater. The higher the temperature rise, the less water the heater can produce.

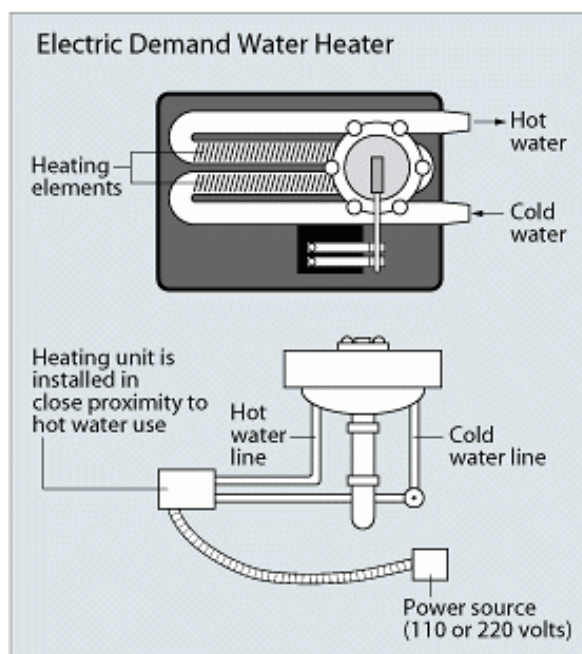


Figure 4.31: Point of Use Instantaneous Water Heater²⁷

Table 4.12: Point of Use Instantaneous Water Heater Summary

General Description	Installed close to/at point-of-use, they heat water as it flows through the devise with copper heat exchanger Only heats water when hot water is called for
Hot Water Temperature	Supply up to 140°F
Design Considerations	Does not need to cycle on and off to maintain tank water temperature, and is not subject to storage heat loss Supply up to 10 GPM
Best Application	Minimal domestic hot water demand (handwashing, breakroom, etc.) Compact size for under the sink installation

²⁷ <https://www.energy.gov/energysaver/heat-and-cool/water-heating/tankless-or-demand-type-water-heaters>

Efficiency	100% No storage loss, and minimal pipe loss
Limitation	Can't produce enough water for high DHW demand High electrical capacity may be required
First Cost	Low cost
O&M Cost	Service Life: 20 Years O&M Cost: Low to no maintenance
Technology Readiness	Readiness Level: Tier 9 – Commercialized Available Manufacturers: EcoSmart, Stiebel Eltron, InSinkErator, Rheem, others

4.3.5 Solar Thermal Water Heater

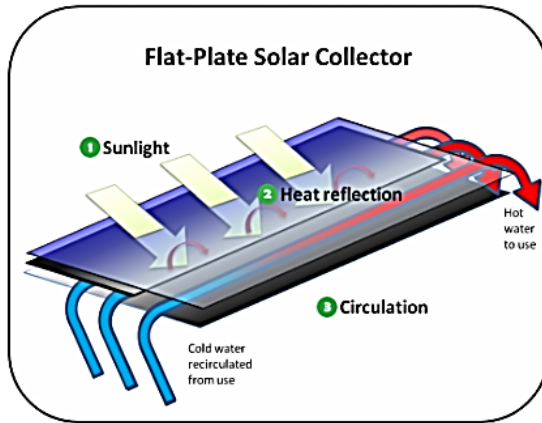
Overview

Solar thermal water heater captures the thermal energy from the sunlight and use it to generate hot water. The system has two components: storage tank and solar collectors. The storage tanks are well-insulated and is usually connected to backup heater in case there is not enough solar energy. Storage tank capacity is 1-2 gallons of water per square foot of collector area. Solar collectors come in two forms; flat plate solar collector or evacuated tube solar collector.

Table 4.13: Solar Thermal Water Heater Summary

General Description	Captures the thermal energy from the sunlight and use it to generate hot water Storage tank is well-insulated and connected to backup heater
System Options	Flat plate solar collector: an absorber panel and copper pipes attached under with water or heat transfer fluid circulating to collect the heat. Evacuated tube solar collector: perform better in cooler climates than flat plate because of lower heat loss, higher efficiency because it's able to absorb heat as the sun moves across the sky east to west
Hot Water Temperature	130°F above outside air temperature, 180°F possible
Design Considerations	South facing panels are best
Best Application	Where hot water demand coincides with solar availability (ex: pool heating)
Efficiency	60-80% of solar radiation is turned into heat energy
Limitation	Requires roof space which may not always be available Hot water production is variable by season
First Cost	High first cost
O&M Cost	Service Life: 20 Years O&M Cost: Low maintenance
Technology Readiness	Readiness Level: Tier 9 – Commercialized Available Manufacturers: SunEarth, Stiebel Eltron, etc.

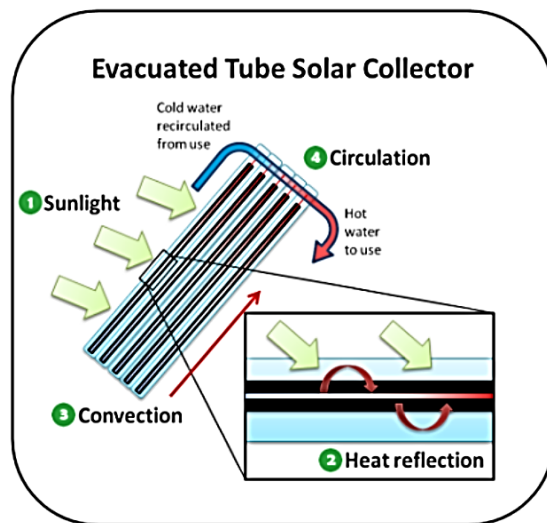
Flat plate collectors have an absorber panel and copper pipes attached under with water or heat transfer fluid circulating to collect the heat. This system is encased in metal frame housing with thick insulation to retain the heat. See below for diagram of this collector type.



1. **Sunlight:** Sunlight travels through the glass and hits the dark material inside the collector, which heats up.
2. **Heat reflection:** A clear glass or plastic casing traps heat that would otherwise radiate out. This is similar to the way a greenhouse traps heat inside.
3. **Circulation:** Cold water or another fluid circulates through the collector, absorbing heat.

Figure 4.32: Flat Plate Solar Collector for Solar Thermal Water Heater²⁸

Evacuated tube collectors²⁸ have thin copper tubes filled with water or heat transfer fluid, encased vacuum-sealed glass tubes. They are typically more expensive than flat plate collectors but are more efficient and can generate higher temperature water. They perform better in cooler climates than flat plate because of lower heat loss. The tubular design also maximizes the amount of solar energy it's able to absorb as the sun moves across the sky east to west, as long as they are angled due south.



1. **Sunlight:** Sunlight hits a dark cylinder, efficiently heating it from any angle.
2. **Heat reflection:** A clear glass or plastic casing traps heat that would otherwise radiate out. This is similar to the way a greenhouse traps heat inside.
3. **Convection:** A copper tube running through each cylinder absorbs the cylinder's stored heat, causing fluid inside the tube to heat up and rise to the top of the cylinder.
4. **Circulation:** Cold water circulates through the tops of the cylinders, absorbing heat.

Figure 4.33: Evacuated Tube Solar Collector²⁸

Solar water heating uses free energy from the sun, but there are some limitations to the application:

- Large roof space may be required for DHW needs at CSU buildings
- Works best where hot water demand is during the day when solar energy can replenish the hot water tank
- Hot water production is variable by season

²⁸ EPA website <https://www.epa.gov/rhc/solar-heating-and-cooling-technologies>

4.3.6 Emerging Technology: Photovoltaic-Thermal

Overview

Photovoltaic-thermal hybrid solar collector technology is a standard photovoltaic panel with a solar thermal collector installed on the backside of the solar panel to preheat DHW. The advantage of this system is that it can produce both electricity and hot water using the same roof footprint. For all PV panel, efficiency drops as the panel temperature rises, solar thermal collector removes heat from the panels while producing warm water, providing extra benefit of improved PV efficiency. However, solar radiation is not directly used to heat water, but the heat dissipated from PV panels are used, so the solar thermal collector efficiency is low. NREL study of technology demonstration found that annual average collector efficiency ranges from 5.7 to 7.6% depending on location²⁹. PV-thermal is a relatively new technology and research is taking place to understand efficiency impacts, NREL study shows that technology is not currently economical, with simple payback between 22 to 110 years.

Table 4.14: Photovoltaic-Thermal Water Heater Summary

General Description	A typical photovoltaic system with a solar thermal collector installed on the backside of the solar panel to preheat DHW Improve efficiency of PV panel while producing hot water
Hot Water Temperature	Technology is under development, temperature and efficiency are not available
Design Considerations	South facing panels for optimal production
Best Application	Where hot water demand is during the day (ex: pool heating)
Efficiency	Technology is under development, temperature and efficiency are not available. Demonstration project shows thermal efficiency of 5.7-7.6%.
Limitation	Requires roof space which may not always be available Hot water production is variable by season
First Cost	High upfront cost
Technology Readiness	Readiness Level: Tier 7 – System Development

²⁹ National Renewable Energy Laboratory (January 2015). Photovoltaic-Thermal New Technology Demonstration. <https://www.nrel.gov/docs/fy15osti/63474.pdf>

SECTION 4.4:

Thermal Energy Storage

Thermal energy storage (TES) can be implemented at many CSU campuses to store energy for use at a later point. Like a battery, a TES can be charged and discharged daily, weekly, seasonally or annually, but instead of electricity it stores cooling or heating energy. TES allows optimization of campus system by generating heating or cooling when conditions are favorable, store it away, and supplying it when necessary. There are many benefits of incorporating a TES to an existing campus system:

- **Energy cost savings:** electricity cost in California typically varies by time of use. By shifting the generation of energy to when energy costs are low (often middle of the night), campuses can avoid high electricity demand charges when the cooling and heating needs are the highest (often middle of day or afternoon).
- **Improved operational efficiencies:** with TES installation, campus can operate chillers more efficiently at night when CW temp can be kept lower. With TES storage, campus system can be optimized to make increased use of heat recovery and waterside economizer strategies.
- **Reduced equipment capacity and first cost:** traditionally, cooling and heating equipment are sized to meet the peak load. The integration of TES offers the ability to redistribute the load so that peak demand can be significantly reduced. This offers the potential to reduce heating and cooling equipment size to meet average load rather than peak load, and therefore saving on first cost of chillers, heat pumps, or heat recovery heat pumps.
- **Provides operational flexibility:** TES operations can be adjusted to adapt to future California energy prices change, providing the flexibility to operate chilled water and hot water production during favorable times.
- **Increased reliability and resilience:** TES can provide backup capacity for cooling and heating systems and reduce the required capacity of backup generation. As campuses shift their heating generation to electricity, it's increasingly important to ensure a reliable source can meet building load, and a power outage will not have catastrophic affect to campus operations.

The followings sections will cover various TES technologies and how they be implemented at CSU campuses. There are many ways to utilize TES to best fit the needs of campus, they can be designed as partial storage for load leveling or full storage for load shifting and operated on either load-priority or storage priority depending on load conditions. See table below for summary of technologies covered.

Table 4.15: Thermal Energy Storage Technology Summary

Technology	First Cost ²	Design Considerations	Best Application	Limitation
Chilled Water Tank Storage	\$ - \$\$	Space requirement: 11-20 ft ³ /Ton-hr Design ΔT between 10 and 20°F, higher ΔT can lower tank volume is required	Campus CHW capacity is maxing out, or operating inefficiently Shifting CHW production to evening when CW temperature is reduced Using existing chillers with elevated ΔT With heat recovery plant, utilize TES as another CHW load, balance heating and cooling loads and operating heat recovery chiller more efficiently	Space requirement
Hot Water Tank Storage	\$ - \$\$	Space requirement: 11-20 ft ³ /Ton-hr Thermal loss due to higher storage temperature around 130-160°F	In heat recovery plant, make use of waste heat and store away when heating load is lower than cooling load Can reduce the capacity of heat recovery chiller because hot water can be made and stored away	Space requirement Potentially higher thermal loss
Ice-Based Thermal Energy Storage	\$\$\$ ¹	Space requirement: 2-3 ft ³ /Ton-hr Lower discharge temperature <40°F	Compact storage volume, campuses with space limitations Ice-on-coil storage tanks can be modular to allow future expansion	Requires installation of glycol chiller or ice-making equipment, making the system more complicated Glycol chiller is less efficient than standard chiller, may consume more energy
Seasonal Thermal Energy Storage	\$\$\$\$	Requires borehole or aquifer wells	Seasonal cooling/heating load with low heat recovery potential, shift heating production to overlap with cooling production Groundwater is available and ground thermal conductivity is high	Low industry familiarity Highly dependent on location and geological makeup of ground rock bed
Phase change material	Unknown (\$\$\$\$)	Technology readiness level: Tier 7	Research and development required to determine whether this is a viable application	Emerging technology, not yet in the market

¹. \$/Ton-hr cost for storage tank is similar or lower than chilled water tank, but additional cost for glycol chillers, these chillers can range from \$200-500/Ton
². First cost is rough order of magnitude estimates, scale is: \$ < \$100/Ton-hr, \$\$ = \$100-200/Ton-hr, \$\$\$ = higher than \$200/Ton-hr, \$\$\$\$ = much higher than \$200/Ton-hr

4.4.1 Chilled Water Storage

Overview

The most common type of TES is chilled-water storage that stores sensible energy in the form of cold water. Chilled water storage has been installed throughout the US to improve resiliency, operational flexibility and reduce peak demand on chillers. Chilled water TES is successfully implemented at many CSU campuses, and industry familiarity is relatively high. Most common chilled water storage is naturally stratified vertical cylinder made of concrete or steel. Here is the basic operating principle of stratified chilled water storage system:

- Water is stratified: warm water sits on top of cold water because cold water is naturally more dense than warm water.
- Chilled water is stored at 40-42°F (slightly lower than typical temperature of chilled water loop).
- Thermal incline is the interface between cold and warm water, this layer is usually 1-2 ft. It rises and falls depending on whether the system is in charging or discharging.
- **During charging**, warm water is pumped out from the top of the tank through diffusers, and chillers replenish the tank with cold water through bottom diffuser, the thermal incline rises
- **During discharge**, cold water is pumped out from the bottom of the tank through diffusers, and equal amount of warm water is returned from the system through upper diffuser.
- Cooling capacity is proportional to volume of water stored and temperature difference between stored chilled water and return chilled water.
- Temperature differential can be between 10 and 20°F, the higher the differential the smaller the tank needs to be. The tradeoff for elevated return water temperature needs to be evaluated against campus space requirements and chiller capacity.

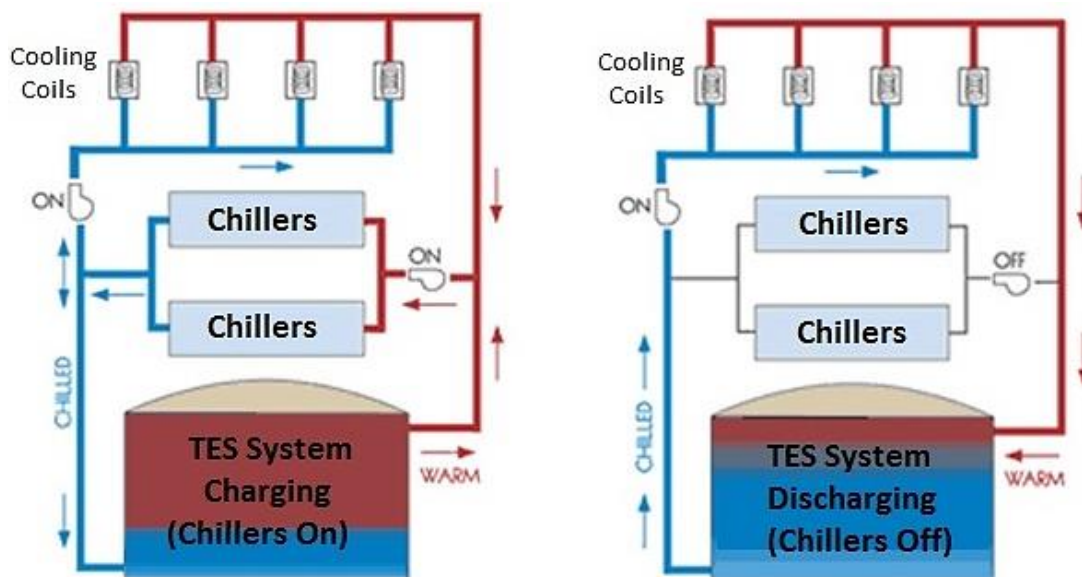


Figure 4.34: Chilled Water Thermal Storage Charging and Discharging³⁰

³⁰ <http://www.powersurety.com/reliable-chilled-water/>

Table 4.16: Chilled Water Storage Summary

General Description	Sensible energy storage, most common is naturally stratified cylindrical storage tank
Temperature	Charging: 39-42°F Discharging: 1-4°F above charging temperature
Storage Volume	11-20 ft ³ /Ton-hr
Design Considerations	Storage capacity increase with larger temperature differential between the top and bottom of the tank. 10-20°F is typical.
Best Application	Easy to integrate into campus with standard chillers to shift chilled water production
Efficiency	Low storage loss
Limitation	Large open space required
First Cost	\$30-100/Ton-hr
O&M	Low to no maintenance
Technology Readiness	Readiness Level: Tier 9 – Commercialized

Application and integration

Chilled water storage can help campus achieve load shifting from peak hours to off-peak hours. In the context of decarbonization, it can operate with heat recovery type system to optimize the production of chilled water and hot water simultaneously. When hot water needs are higher than chilled water in winter months, TES can store away the chilled water for use at a later time/day. Campus with existing TES should assess benefits of operating it differently when installing heat recovery equipment, and campus without TES should consider benefits of adding it optimize chiller operation. Large installations (3,000 ton-hr or 300,000 gallons) are usually more economical than small capacity system, hence it's a great application for CSU campus that have central chilled water.

4.4.2 Hot water storage

Overview

Hot water storage is the same technology as chilled water storage but is less commonly implemented; however, as heating technology at CSU campus shifts to electrical sources, hot water TES can also provide similar benefits as chilled water TES. They are made of reinforced concrete, insulated to reduce storage heat loss. Installation and operation are similar to chilled water TES; technology is available and industry familiarity is high.

Hot water storage stores hot water at temperature 130-160°F, close to heating hot water loop temperature. With the elevated storage temperature, design needs to address potentially higher storage loss than chilled water. During discharging, hot water at the upper half of water tank is piped out to the building and lower temperature water is returned from the buildings. During charging, hot water is replenished by the campus heating system.

Table 4.17: Hot Water Thermal Energy Storage

General Description	Sensible energy storage, naturally stratified cylindrical storage tank
Temperature	130-160°F depending on campus HHW loop temperature
Storage Volume	11-20 ft ³ /Ton-hr
Design Considerations	Design needs to account for additional insulation and reduce heat loss
Best Application	Balance heating load over multiple days, can improve heat recovery operation
Efficiency	Potentially high storage loss
Limitation	Large open space required
First Cost	Slightly higher than chilled water storage to prevent thermal loss, \$30-120/Ton-hr
O&M	Low to no maintenance
Technology Readiness	Readiness Level: Tier 9 – Commercialized

Application and integration

Hot water storage presents a great opportunity to further optimize the heat recovery potential of a campus. Its benefits can be assessed in combination with chilled water TES or installed separately. For example, hot water can be generated and used to charge the tanks during optimal periods of generations, such as via heat recovery chillers operating in simultaneous heating and cooling throughout a day when cooling loads dominate on campus.

4.4.3 Ice-based Storage

Overview

Ice thermal energy storage (ITES) make use of latent heat of fusion of water, heat released during the phase change between solid and liquid state. Because heat capacity is much higher for this process (144 Btu/lb), storage density for latent heat storage is 5-15 times greater than sensible, therefore ITES requires smaller tank size (2-3 ft³/ ton-hour) compared to water storage (11-20 ft³/ ton-hour).

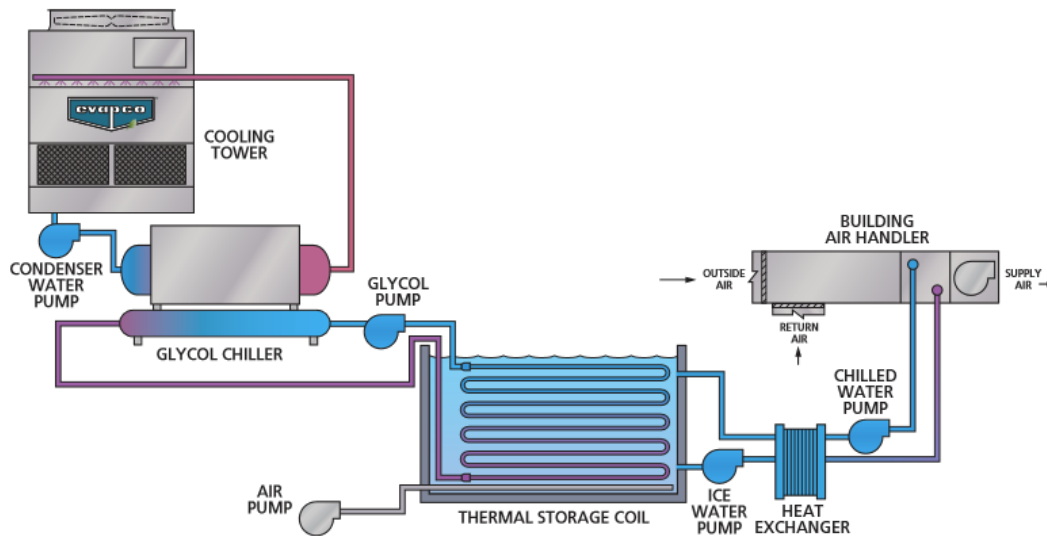


Figure 4.35: External Melt Ice-on-Coil Thermal Storage System³¹

There are several types of ice storage systems:

1. Internal melt ice-on-coil
2. External melt ice-on-coil
3. Ice harvesting

Among ITES technologies, ice-on-coil systems are more common for college campus. The system has heat exchanger coils submerged in water tank, and ice forms on the surface of the tubes. In an **Internal melt ice-on-coil systems**, during charging, cold coolant (mixture of 25-30% glycol and 75-70% water) solution at 22-26F runs through the coil and ice forms on the tubes. During discharge, warm coolant is circulated through the coil and melts the ice from inside. During this process the glycol solution is cooled and is piped to heat exchanger to extract heat from chilled water loop, producing water between 34-38F.

³¹ <https://www.evapco.com/products/thermal-ice-storage/extra-pakr-ice-coil>

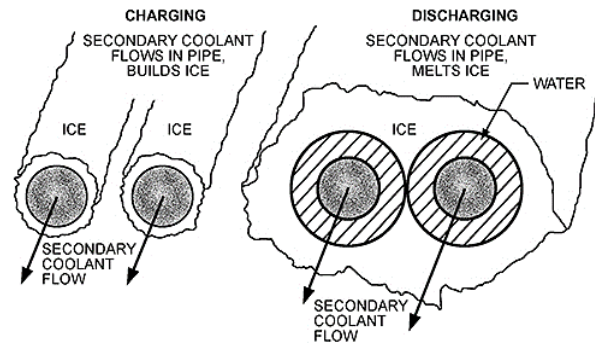


Figure 4.36: Charging and Discharging of Internal Melt Ice Thermal Storage³²

External melt ice-on-coil systems has the same coil submerged in water tank where glycol/water mixture circulates at 15-25°F temperature and ice forms on the coils. Cooling is accomplished by circulating return chilled water in the tank, melting the ice and cooling the chilled water. Because there are two fluids: water and glycol, more components may be required to control discharging and charging. But because heat is directly removed from the chilled water loop, system can produce water at 34-36°F.

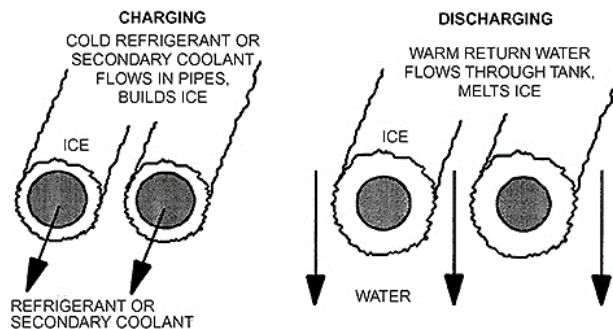


Figure 4.37: Charging and Discharging of External Melt Ice Thermal Storage³²

Ice harvesting systems are packaged system that has much higher upfront cost for ice harvester chiller, and hence is less common for college campus. 32°F water is stored in the tank and pumped to the ice harvester where ice forms on the refrigerated plate surface which is kept at 15-20°F. The ice drops into the storage tank below after reaching a certain thickness. During cooling, cold water from bottom of the tank is pump out to a heat exchanger to remove heat from the building water loop and returned to the ice harvester or directly into the tank. Ice harvesting system also requires water treatment due to the open nature of the tank, adding to O&M cost.

³² <http://www.ahrinet.org/contractors?S=141>

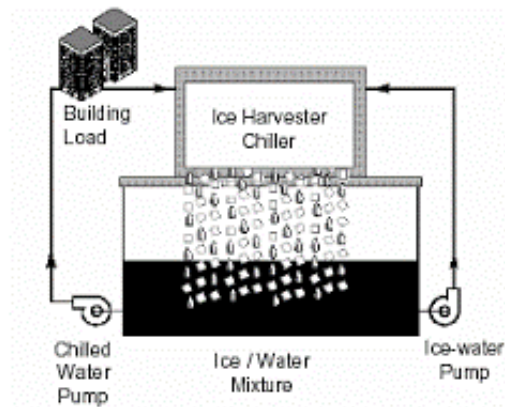


Figure 4.38: Ice Harvesting Thermal Storage³³

Table 4.18 - ICE THERMAL ENERGY STORAGE

General Description	Latent heat energy storage Discharge fluid either water or secondary coolant
Temperature	Charge Temperature: 15-26F Discharge Temperature: 34-38
Storage Volume	2-3 ft ³ /Ton-hr
Design Considerations	Require ice-making chiller or modify existing chiller to handle lower operating temperature. This chiller operates much less efficiently.
Best Application	High instantaneous discharge rates Requires much less space, can be modular to enable expansion
Efficiency	Efficiency of glycol chiller is lower than standard chiller
Limitation	Requirement of glycol chiller
First Cost	Storage tank cost is equal to or lower than chilled water storage, but additional cost for low-duty chiller (\$200-1000/Ton)
O&M	Low to no maintenance
Technology Readiness	Readiness Level: Tier 9 – Commercialized

Application and Integration

Ice thermal energy storage can be an alternative to chilled water TES for campuses that have limited space for large water tanks. However, application requires installation of glycol-based chiller or standard chillers that are selected for low temperature duty, this can increase project cost. These chillers also operate less efficiently than standard chillers that work with chilled water TES because they produce water at lower temperature.

³³ <https://www.cedengineering.com/userfiles/Thermal%20Energy%20Storage.pdf>

4.4.4 Seasonal Thermal Energy Storage

Overview

Seasonal thermal energy storage (STES) stores energy for longer period, typically for 3 or more months. STES stores heat in the summer to be used in the winter and stores cold in the winter to be used in the summer. They are sometimes coupled with solar thermal collectors as heat source. Large scale STES system is usually underground thermal energy storage, including borehole and aquifer storage. Other technologies include above ground tank storage or pit storage. These technologies have storage efficiency between 50-90%.

Table 4.19 - Seasonal Thermal Energy Storage

General Description	Sensible energy storage, stores energy for longer period via underground thermal storage (borehole or aquifer)
Storage Volume	N/A
Design Considerations	Highly dependent on availability of groundwater and geological makeup of the ground bedrock
Best Application	Campus that have extreme weather patterns, no simultaneous heating and cooling. Not likely for most CSU campuses.
Efficiency	Potentially high storage loss
Limitation	Large open space required
First Cost	High cost for installing wells or boreholes, requires available land and regulatory approval
O&M	Low to no maintenance
Technology Readiness	Readiness Level: Tier 9 Lack of industry familiarity, only implemented on the east coast for the US

Aquifer thermal energy storage (ATES) consists of a set of cold and warm wells, with hydraulic pumps and heat exchangers. Wells are contained by impermeable geological layers above and below and are separated from each other. During summer months, cold groundwater is pumped out from the cold well to heat exchangers that extract thermal energy from the campus loop, and warm water is injected into warm well. During winter months, the flow direction is reversed.

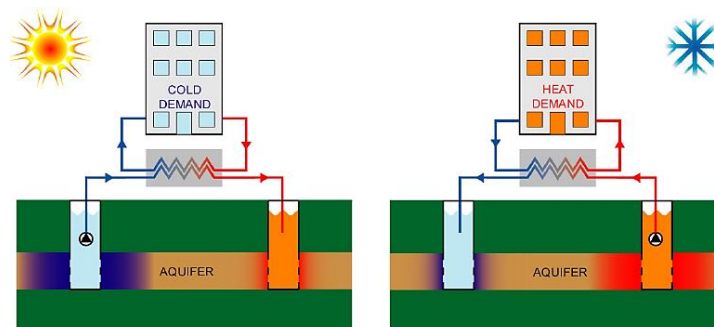


Figure 4.39: Aquifer Thermal Energy Storage³⁴

³⁴ https://www.researchgate.net/figure/Aquifer-Thermal-Energy-Storage_fig1_267300619

Borehole thermal energy storage (BTES) is like ATES but stores thermal energy in underground bedrock and transfers the heat through conduction. Vertical boreholes are drilled through the bedrocks to act as heat exchangers between circulating water (or water/glycol solution) and the ground. During the summer cooling, the flow is from the center to the outside boundaries of the borehole storage system. During the winter, the flow direction is reversed to extract the warmer water from the center. The application is not dependent on availability of aquifers and is scalable by varying the number of boreholes. Thermal conductivity is dependent on geological makeup of the ground bedrock.

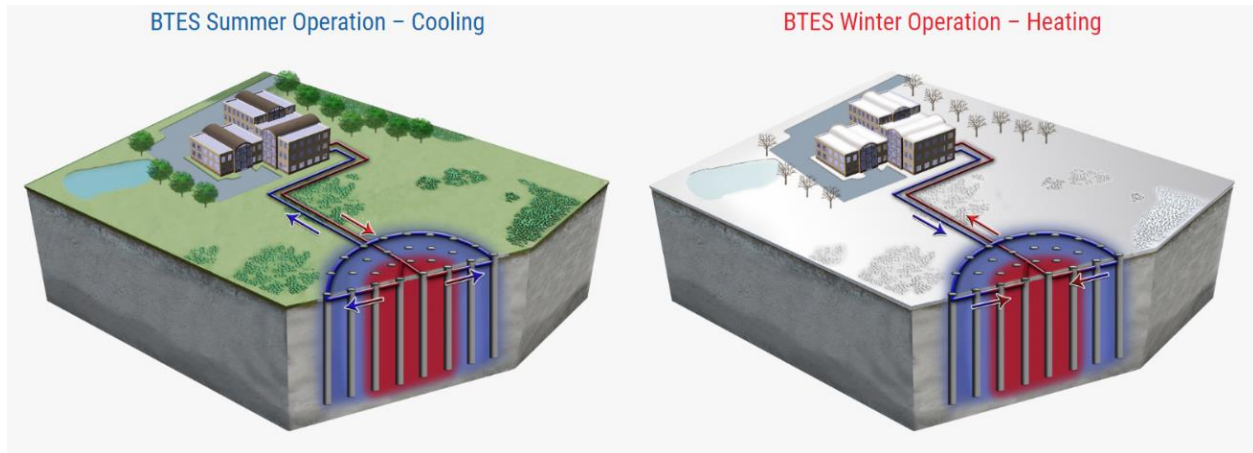


Figure 4.40: Borehole Thermal Energy Storage³⁵

Application and integration

Because of the potential high cost of installing boreholes or aquifer wells, STES is unlikely to be implemented at CSU campuses. There are a limited number of STES projects in the US, all on the east coast, but they are much more common in Europe. In the US, there is a lack of industry familiarity compared to other forms of TES. For campus where groundwater is available or where ground thermal conductivity is high, STES can be assessed as a strategy to shift heating production to overlap with cooling production.

³⁵ <https://underground-energy.com/our-technology/btes/>

4.4.5 Emerging Technology: Phase Change Material³⁶

Thermal energy storage using phase change materials (PCM) is highly researched area that can eventually produce some viable solutions for campus to consider. The concept is to make use of the latent heat when the material undergoes phase change, usually solid-liquid transformation, where the temperature of the material does not change but high amount of energy is released. PCM offers higher storage capacity than sensible heat storage. Ice thermal storage can be categorized as a type of PCM, but other PCM using salt hydrates, eutectic salt or other synthetic material are being studied extensively. The material is usually encapsulated in spherical rectangular containers that are stacked in a storage tank, and the heat transfer fluid (water) is circulated through the tank to extract heat or dump heat to the encapsulated material. The storage tank can be cylindrical like chilled water tank, or rectangular modular containers that are stackable. The modular phase change containers can be distributed along the hot water or chilled water distribution piping. Currently there are only several manufacturers that have commercialized such product, the concept is still under research.

Current research is focused on addressing challenges such as:

- High cost of high-density storage
- Low thermal conductivity and lack of thermal stability
- Phase separation
- PCM often expand/contracts when going through phase change, causing the encapsulation to erupt

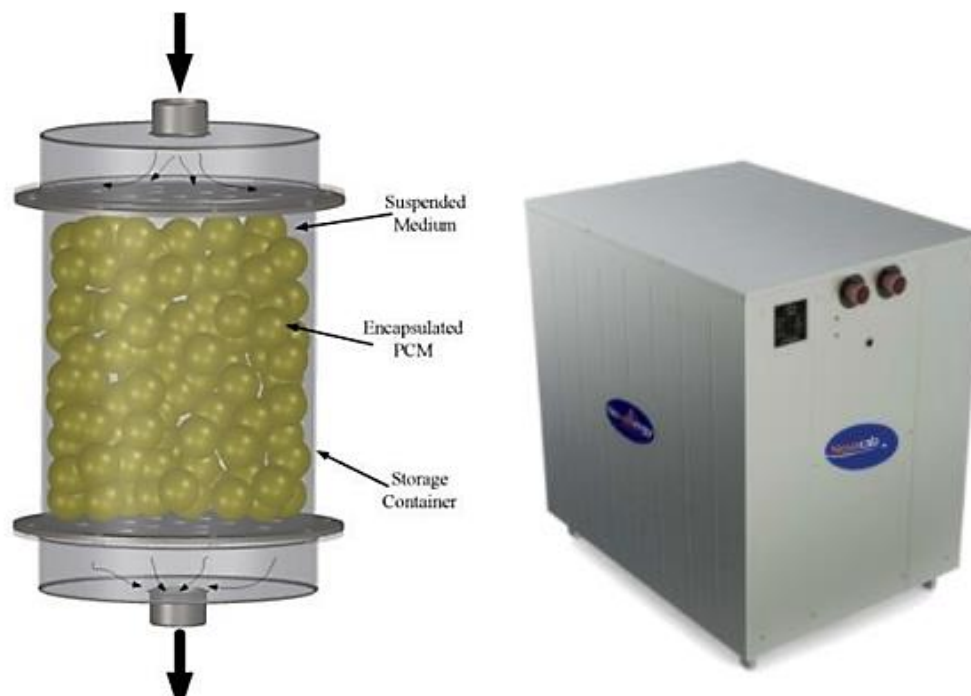


Figure 4.41: Thermal Storage with Phase Change Material^{37,38}

³⁶ Ioan Sarbu and Calin Sebarchievici, 2018. A comprehensive Review of Thermal Energy Storage

³⁷ <https://www.energy.gov/eere/solar/project-profile-innovative-thermal-energy-storage-baseload-solar-power-generation>

³⁸ <https://www.novacab.com/applications>

Table 4.20 - Phase Change Material Thermal Storage Summary

General Description	Latent energy storage via phase change. Usually encapsulated PCM in a storage tank that has the heat transfer fluid.
Storage Volume	High storage capacity due to high energy density during phase change
Design Considerations and Limitations	Cylindrical solution is not yet scalable or commercialized Modular PCM containers are starting to be commercialized Research and development required to resolve material challenges
First Cost	Unknown, likely to be high cost
O&M	Unknown, likely to be medium O&M cost
Technology Readiness	Readiness Level: Tier 7

SECTION 4.5:

Low-Carbon Heat Sources

As discussed in previous sections, heat pumps and heat pump water heaters require a source of heat that can be rejected to a high-temperature area. The same heat source can also act as heat sink to absorb unwanted heat in the cooling process. Heat can be provided from a range of different sources and this section is an overview of the different sources of heat available to CSU campuses. To assess different heat sources, a few things should be considered for them to be viable solutions:

Temperature

- In order to optimize system efficiency, heat sources should minimize lift, the difference between entering source and leaving supply water temperature. The lift on the system may vary depending on heat pump application, and therefore analysis should be completed to ensure the minimum source temperature will still provide efficient operations.
- If the lift on a system becomes too great, a heat pump will not be capable of rejecting enough heat to the high-temperature area, resulting lower than optimal supply temperature. Low temperatures may also result in frosting of condenser coils.
- Heat sources that have low temperature variation will provide the most stable system operation.

Availability

- Ideally, heat sources should always be readily available with little to no variation in flowrates. Heat pump condensers operate most efficiently when there is a consistent and uninterrupted flow.

Cost

- Heat sources should not increase the cost of system operation significantly, installation cost should be one of the main considerations.
- Transferring heat from a source that will subsequently require reheating will increase energy consumption and costs. Optimal heat sources will not result in additional operational costs to the system.

Table 4.21: Low-Carbon Heat Sources³⁹

Options		Suitability		Availability		Cost		Temperature		Common Practice	
Category	Heat Transfer Medium	Heat Source	Heat Sink	Location	Coincidence with need	Install	O&M	Level	Variation	Use	Limitation
Air	Outside Air	Good	Good	Universal	Continuous	Low	Moderate	Varies	High	Very common	Defrosting and supplemental heat required for low temperature applications Heating efficiency and capacity decreases with decreasing outdoor air temperature
	Exhaust Air (ventilation)	Excellent	Fair	Excellent	Excellent	Low to moderate	Low	Excellent	Very low	Very common	Insufficient for typical load, only works as energy conservation measure Potential O&M cost if exhaust air has dirt or greasy
	Industrial Process heat or exhaust	Fair to excellent	Varies, often impractical	Varies	Varies	Varies	Generally low	Varies	Medium	Varies	Laboratory process heat is limited on most campuses
Water (HVAC)	Condensing Water (Heat Recovery Heat Pump)	Excellent	Poor to good	Varies	Varies with cooling load	Low	Moderate	Favorable as heat source	Depends on source	Available	Suitable only if heating need is coincident with heat rejection
	Building water loop	Good	Good	Excellent	As needed	Low	Low to moderate	As Designed	As Deigned	Very common	Suitable for medium or large buildings Loop supplemental heating may be required as heat source and heat rejection may be required as heat sink
Geothermal	Ground Water (Well)	Excellent	Excellent	Practical depth varies by location	Continuous	Low if existing well or shallow wells used, costly otherwise	Low, but periodic maintenance and testing required	Generally excellent, varies by location	Low	Common	Water disposal and permit requirements; may require double-wall exchangers; may foul or scale Groundwater quality testing is required to ensure cleanliness.
	Surface (lakes, river, ocean)	Excellent for large bodies or high flow rates	Excellent for large bodies or high flow rates	Limited, depends on proximity	Usually continuous	Depends on proximity and water quality	Depends on proximity and water quality	Satisfactory	Depends on source	Available, particularly for fresh water	Often regulated or prohibited, may clog, foul or scale
	Ground-Coupled (Buried or submerged fluid loops)	Good if ground is moist, poor otherwise	Fair to good if ground is moist, poor otherwise	Depends on soil suitability	Continuous	High to moderate	Low	Good	Low	Rapidly increasing	High initial cost for ground loop
Other	Tap (municipal water supply)	Excellent	Excellent	Excellent	Continuous	Low	Low energy cost	Excellent	Very low	Uncommon	Use or disposal may be regulated or prohibited, may corrode or scale
	Waste (sewage or grey water)	Fair to Excellent	Fair, varies with source	Varies	Varies, may be adequate	Depends on proximity, high for raw sewage	Varies, may be high for raw sewage	Excellent	Low	Uncommon	Usually regulated, may clog, foul, scale or corrode
	Solar	Fair	Poor/ Unacceptable	Universal	Highly intermittent	Extremely high	Moderate to high	Varies	High	Very limited	Supplemental source or storage required

³⁹ Developed based on ASHRAE Handbook 2016 HVAC Systems and Equipment 9.3, tailored to be CSU specific

4.5.1 Air

Air is very commonly used as heat source in HVAC, an air-source heat pump is an example of this system type. The benefit of using air as source of heat is that it's always available and abundant. However, the drawback is that outside air temperature is always variable throughout the year. As described in earlier sections, systems that use air as heat source experience capacity and efficiency penalties when outside air drops below 32°F. Heating efficiency decreases as outside air drops, which is when heating is needed most. In these cases, supplemental heating using electric resistance coils are common. The possibility of frost build-up on outdoor air coils when temperature is low, and humidity is high is another limitation on using outside air as heat source.

Where available, building exhaust and process exhaust can also serve as source of heat, but due to the limited availability on most CSU campuses, they are utilized only as an energy efficiency measure by using energy recover ventilation.

4.5.2 Geothermal

The earth makes for a great heat source because of its relatively stable temperature throughout the year. Ground temperature remains between 50°F and 60°F year-round in California and is warmer than outside air during the winter and cooler than outside air during the summer. These properties make the ground a better heat source compared to ambient air, and equipment using ground as source have higher efficiencies in cold weather. Both open loop and closed loop systems require significant excavation work which can add to project cost, local regulations can also be a limiting factor on whether this can be implemented.

Open loop system directly pumps either underground water or surface water to building where heat is exchanged with chilled water or hot water loop, then used water is pumped back to the source. Because this system is open to contamination, water quality needs to be properly addressed in designing these systems and local restrictions will dictate whether open discharge is acceptable. Open-loop heat pump (groundwater/surface water) water flow rate is dictated by heat pump capacity, usually in the range of 2-4 gpm/ton. The well and pump must be large enough to supply the water needed by the heat pump. In open systems, periodic inspection and cleaning of heat exchangers is necessary to avoid mineral deposits, adding to O&M cost.

Closed loop system can be ground-coupled where it circulates a mixture of antifreeze and water in pipes buried underground to extract heat from or reject heat to the ground soil. Closed-loop systems can also be direct expansion, where refrigerant is circulated through underground copper coils that acts as ground-to-refrigerant heat exchangers. These direct-expansion applications are more limited compared to ground-coupled system. Close-loop heat pump capacity determines the amount of piping needed, typically in vertical configuration 270-350 ft of piping per ton of heat pump capacity. For horizontal configuration, 400-600 ft of piping per ton of heat pump capacity. Examples of closed-loop system are geothermal water-to-water heat pump (Section 4.2.2), geothermal water source heat pump (Section 4.2.3), and borehole thermal energy storage (section 4.4.4). A closed-loop system will require less maintenance because they are sealed and pressurized.

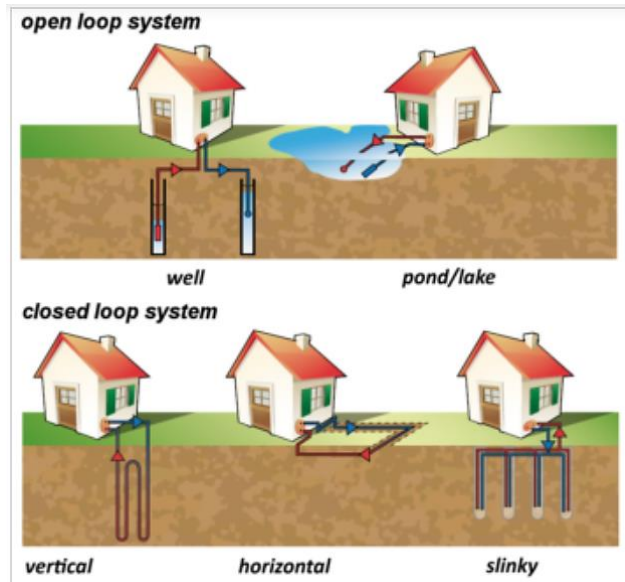


Figure 4.42: Open Loop and Closed Loop Geothermal System⁴⁰

4.5.3 Solar

Solar energy can be a good source of heat when available, but the challenge is that they are often intermittent, so would require supplemental heat. Solar thermal captures high temperature heat from the sun and use it for space and water heating. Typical applications include pool heating, water heating, and supplement other heat sources in space heating. However, the collector area required for space heating is very large for CSU campus heating load, and thus may not be practical. The system uses solar collectors that are either flat plate or evacuated tubes. Photovoltaic-thermal technology is emerging that combines electricity generation of photovoltaic panels with hot water generation of solar thermal but is not yet economically viable. For more information about using solar energy, please see Sections 4.3.5 and 4.3.6.

4.5.4 Building Heat

The concept of heat recovery is using heat generated within building that would otherwise be wasted to reduce the requirement for additional heat generation elsewhere on campus. Within a building, heat sources for space or water heating include condenser water loop, chilled water return loop, sewer, and exhaust system. When there is simultaneous heating and cooling load, recovering rejected heat from building processes can be highly efficient. Technologies using heat recovery were discussed in Sections 4.2. All CSU buildings have some potential to capture buildings' waste heat, therefore each campus's heat recovery potential should be studied by assessing simultaneous heating and cooling profiles. A high-level study of campus simultaneous heating and cooling potential is provided in Section 6: Simultaneous Heating and Cooling Study.

⁴⁰ <https://iwae.com/resources/articles/open-loop-vs-closed-loop-geothermal.html>

4.5.5 Waste or Municipal Water

Process hot water or sewage water can be another source of heat that would otherwise be wasted. Sewage pipes usually have higher temperature, using a heat exchanger, some of this heat can be captured and heat water either for domestic water or space heating. Currently, there are major barriers to the application of wastewater heat recovery because of lack of regulation and guidelines on implementation from local government, however this technology is a potential option for campuses looking to fully decarbonize their heating systems.

As with groundwater, incoming municipal water is supplied at a relatively constant temperature throughout the year. A heat exchanger or water-to-water heat pump can be used to capture this heat and distribute it throughout the building. However, potable water supplied from the city is rarely used because municipal restrictions applies to discharge of the water. Although the only change in the water into the heat exchanger and out is a slight temperature increase, government regulations remain the main barrier for implementation.

4.5.6 Biogas

Recently there has been lots of discussion around using biogas as direct substitute for natural gas. Biogas (also known as biomethane) is a form of biofuel which includes solid, liquid and gas fuel from biomass. It is derived from organic waste materials such as food and animal waste, using anaerobic digesters. Biogas is then processed to become pipeline grade natural gas; it's considered renewable because it originates from organic sources.

There are a few barriers for using biogas as decarbonizing strategy:

- Limited quantity of biogas, there is insufficient biomethane to substitute for current natural gas demand. The limitation on the availability of biogas makes it difficult to implement as a scalable solution. As there isn't enough biomethane production available to displace natural gas usage.
- Biogas is associated with premium cost that's difficult for CSU to absorb
- Source of biomethane (i.e. cow manure and landfill) is inherently high emitters of GHG or high polluters

While biogas emits less GHG than natural gas, there are still many barriers for it to become suitable solution for decarbonization. Priority should be placed on converting space heating and water heating to electricity and reserve biogas for sectors that are more difficult to decarbonize. Afterall, biogas is extremely costly compared to electrification technologies such as heat pumps and heat recovery chillers covered in earlier sections.