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energy-saving strategies for
Water-Source Heat Pump Systems

from the editor...
Water-source heat pump (WSHP) systems are often known (unfortunately) as a "low cost" alternative. However, they have the potential to be high-performance systems, reducing operating costs for the building owner and improving occupant comfort. This EN contains a "menu" of cost-effective, system design and control strategies that can be used to save energy in WSHP systems. In general, each section can be read independently, allowing the reader to decide which strategies make sense for a given application.

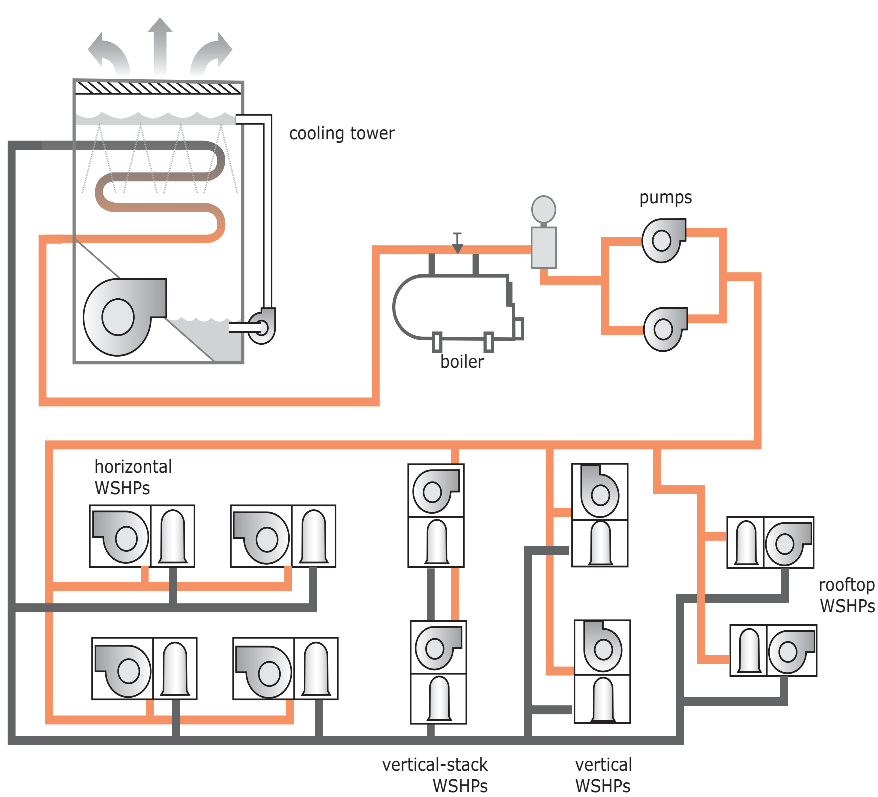
WSHP systems are used to provide comfort in a wide range of building types and climates. In this type of system, each zone has a WSHP unit that is controlled to maintain the desired temperature in that zone. All the heat pumps are connected to a common water loop (Figure 1). Also connected to this water loop are a "heat rejecter" (e.g., cooling tower or geothermal heat exchanger), a "heat adder" (e.g., boiler or geothermal heat exchanger), circulation pumps, and related accessories. Typically, outdoor air is conditioned and delivered by a separate, dedicated ventilation system.

During mild weather, such as spring or fall, the heat pumps serving the sunny side and interior of the building often operate in cooling mode and reject heat into the water loop. The heat pumps serving the shady side of the building often operate in heating mode and absorb heat from the water loop.

Heat rejected by the units operating in cooling mode is used to offset the heat absorbed by the units in heating mode. In this manner, a WSHP system provides a form of heat recovery and an opportunity to save energy by reducing the need to operate the boiler or cooling tower. For example, if the water temperature stays in the desired range—between 60ºF (16ºC) and 90ºF (32ºC)—neither the boiler nor the cooling tower need to operate.

In applications such as office buildings, heat generated by lights, people, and office equipment often results in the need to provide year-round cooling in the interior zones of the building. In these applications, the benefit of this heat recovery further reduces boiler energy use during the winter months.

Figure 1. Typical water-source heat pump system



Equipment/System Configuration Strategies

"Hybrid" systems. The WSHP system is often viewed solely as an alternative to other types of HVAC systems. "Hybrid" systems composed of water-source heat pumps and other types of HVAC equipment, however, may be best suited to meet the specific requirements of a given building.

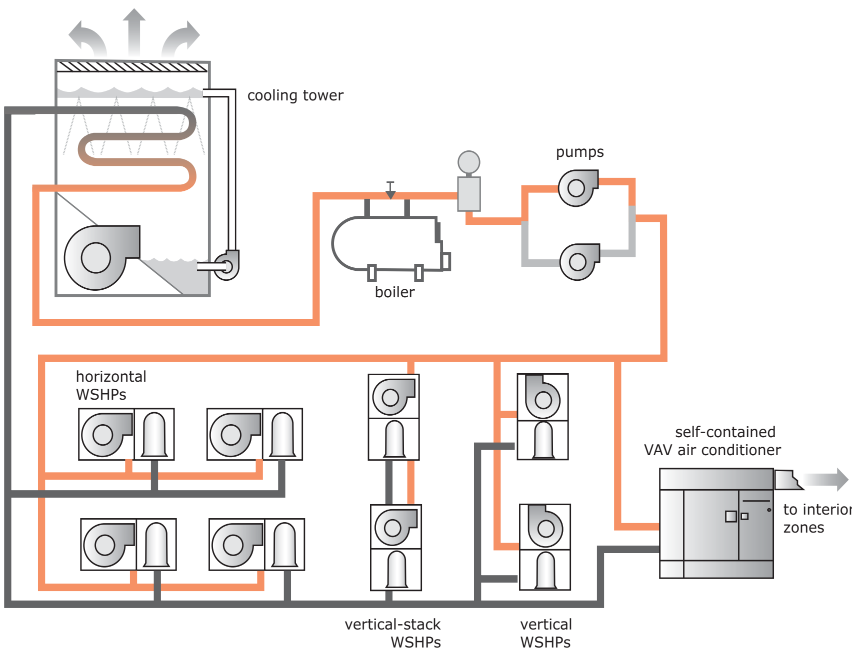


Figure 2. "Hybrid" WSHP system

While there are many possible combinations, the example hybrid system shown in Figure 2 uses variable-air-volume (VAV) self-contained units to serve the interior zones of an office building and water-source heat pumps to serve the perimeter zones. The interior zones in this type of building may have variable loads, but often require cooling year-round.

These packaged units contain a complete refrigeration circuit with a water-cooled condenser that is connected to the common water loop. The VAV supply fan varies the airflow supplied to the interior zones, resulting in significant part-load fan energy savings, while the condenser heat is rejected to the loop so that it can be absorbed by the heat pumps that are providing heat to the perimeter zones.

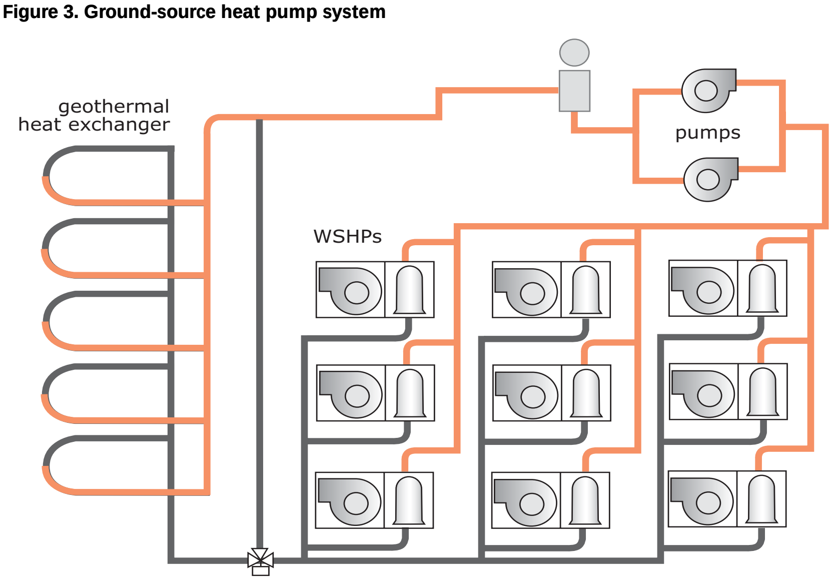


Figure 3. Ground-source heat pump system

Ground-source heat pump systems. A well-known variation of the WSHP system uses the earth as the heat rejecter and heat adder (Figure 3). Ground-source heat-pump (GSHP) systems* do not actually get rid of heat, they store it in the ground for use at a different time. During the summer, the heat pumps extract heat from the building and transfer it to the ground. When the building requires heating, this stored heat can be recaptured from the ground. In a perfectly balanced system, the amount of heat stored over a given period of time would equal the amount of heat retrieved.

Ground-source heat pump systems offer the potential for saving energy because they can reduce (or eliminate) the energy needed to operate a cooling tower and/or boiler. Eliminating the cooling tower has architectural and maintenance advantages, and eliminating the boiler frees up floor space in the building.

While eliminating both the cooling tower and boiler likely results in the greatest overall energy savings, for most applications it requires the largest (and more expensive) geothermal heat exchanger to account for the imbalance between heat stored and heat extracted.

For example, in a cooling-dominated climate, a large amount of heat must be rejected to the ground during the cooling season, but a much smaller amount of heat is extracted from the ground during the heating season. This imbalance can cause the temperature of the ground surrounding the geothermal heat exchanger to increase over time.

* A 2001 Engineers Newsletter (volume 30-2, "The Three E's of Geothermal Heat Pump Systems") provides more detail on ground-source heat pump systems.

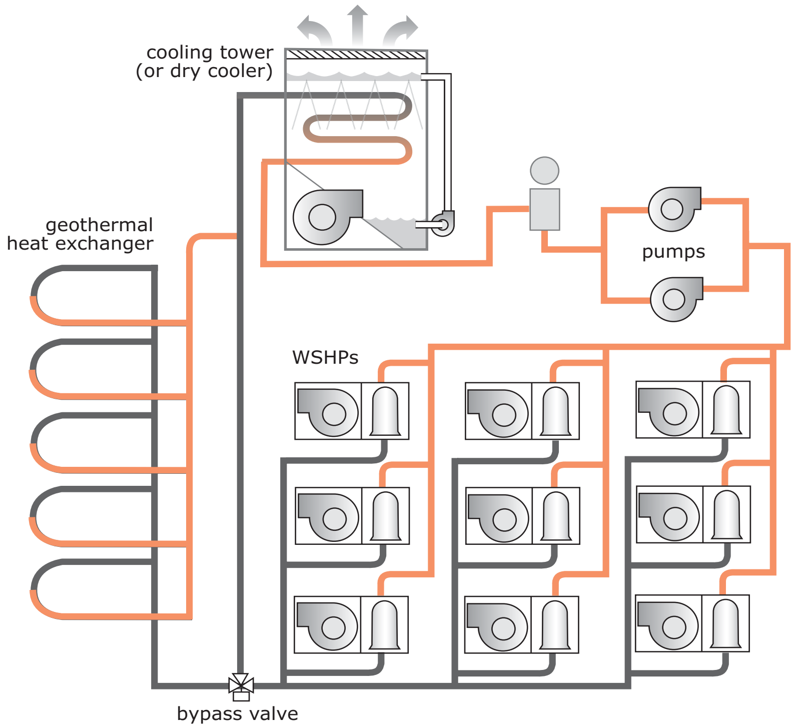
Conversely, in a heating-dominated climate, a relatively small amount of heat is rejected to the ground during the cooling season, but a much larger amount of heat must be extracted back out of the ground during the heating season. In this case, the temperature of the ground can decrease over time. In either case, future operation of the heat pumps is compromised by this change in ground temperature.

In many areas of the country, this imbalance requires the geothermal heat exchanger to be larger to prevent the ground temperature from changing over time. The first cost to install such a large heat exchanger often dissuades people from considering this approach. Using a "hybrid" approach, however, can often make GSHP systems more economical, opening up the possibility to reap the potential energy savings.

This "hybrid" approach involves adding a small cooling tower or dry cooler to the loop for a system that is installed in a cooling-dominated climate (Figure 4), or adding a small boiler to a system in a heating-dominated climate. In either case, the geothermal heat exchanger is sized based on the smaller of the two loads: for the total heat absorbed in a cooling-dominated climate or the total heat rejected in a heating-dominated climate. Then, a small cooling tower (or boiler) is added to reject (or add) the remaining heat.

This approach reduces the required size of the geothermal heat exchanger by avoiding the imbalance described previously. While the overall energy savings may not be as great as in a system with a larger heat exchanger, this approach often results in a more acceptable return on investment.

Figure 4. "Hybrid" GSHP system



Variable-flow pumping. The water-circulating pumps can be either constant- or variable-flow pumps. Constant-flow pumps operate whenever the system is on, delivering a constant flow of water throughout the loop, and consuming a constant amount of energy.

Variable-flow pumps take advantage of the fact that all heat pumps in the system are not always operating at the same time. For example, when a zone needs neither cooling nor heating the compressor turns off. When the compressor turns off, a motorized, two-position valve shuts off water flow to that heat pump, so less total water flow is required in the loop. A variable-frequency drive (VFD) on the circulating pump allows the pump to unload, saving energy by delivering only the amount of water required by the operating heat pumps.

In a variable-flow system, consider installing an automatic balancing valve for each heat pump. This device helps ensure proper water flow through the heat pump (when the compressor is operating) as the system flow rate changes.

In addition, a diverting valve and bypass pipe can be added to a ground-source heat pump system to bypass the geothermal heat exchanger whenever the temperature of the loop falls within a desired range (see Figure 4). This reduces the pressure drop that the circulating pump must overcome, and saves pumping energy.

Dedicated ventilation system. In most WSHP systems, the outdoor air is conditioned by a separate, dedicated ventilation system. This conditioned outdoor air is typically delivered to the zones in one of two ways (Figure 5). The first approach is to duct the outdoor air directly to the intake of each heat pump, where it mixes with return air from the zone. The second approach is to duct the conditioned outdoor air directly to each zone. A variation on this second approach (bottom configuration in Figure 5) is to duct the outdoor air to the supply-side of each WSHP, where it mixes with supply air from the heat pump before being delivered to the zone.

Figure 5: Dedicated ventilation system configurations

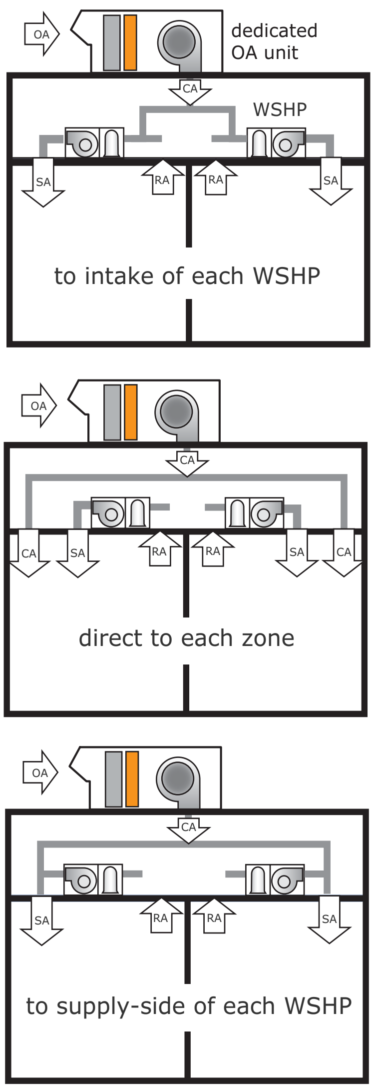
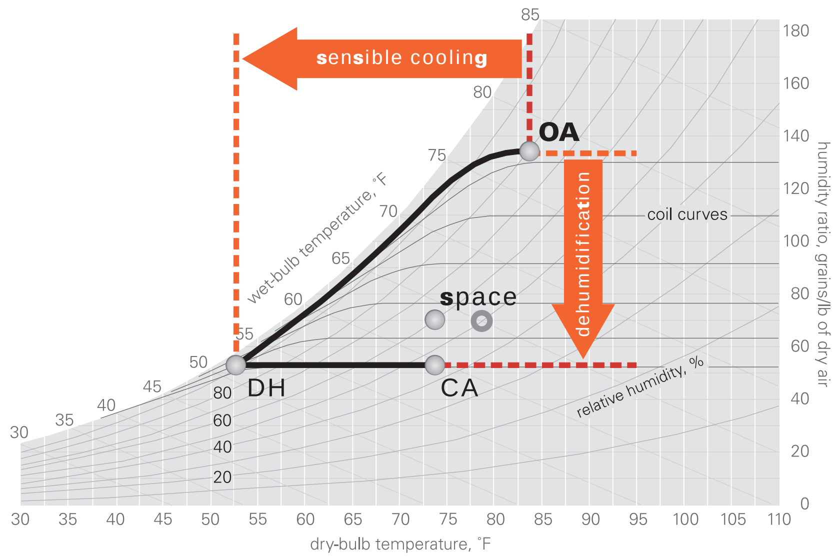


Figure 6: Sensible cooling is a byproduct of 'cold-coil' dehumidification



Depending on the climate, the dedicated OA unit may be used to cool, dehumidify, heat, and/or humidify the outdoor air. This approach allows the heat pumps to handle only the zone cooling and heating loads, not the ventilation load.

Many dedicated outdoor-air systems are designed to dehumidify the outdoor air so it is at least as dry as the space, and then reheat it to approximately space temperature (neutral). However, when a chilled-water or DX cooling coil is used for dehumidification, a byproduct of that process is that the dry-bulb temperature of the air leaving the coil is colder than the space (Figure 6). If the dehumidified outdoor air (DH) is reheated to neutral (CA), the sensible cooling performed by the dedicated OA unit is wasted.

If the dedicated outdoor-air system delivers air directly to the individual zones, the dehumidified outdoor air (DH) can be delivered "cold," rather than reheated to neutral. The low dry-bulb temperature of the conditioned OA offsets part of the sensible cooling load in the zones, reducing the cooling energy used by the heat pumps. At design conditions, this means that the heat pumps can be sized for less airflow and less cooling capacity than in a neutral-air system.**

Compared to a neutral-air system, a dedicated outdoor-air system that delivers cold air directly to the zones (or to the supply-side of each WSHP):

- **Requires less overall cooling capacity.** The required cooling capacity of each heat pump is less than in a neutral-air system, and the required capacity of the dedicated OA unit is the same for both configurations.
- **Requires less overall cooling energy for much of the year.** By taking advantage of the sensible cooling already done by the dedicated OA unit, the cold-air system requires less cooling energy at each heat pump. The neutral-air system throws away this sensible cooling benefit by reheating the air to approximately space temperature.
- **Requires less overall fan airflow and, therefore, less fan energy.** For those zones that require seasonal cooling and heating, the supply airflow delivered by the heat pump is less than in a neutral-air

** A 2006 ASHRAE Journal article (Murphy, J. "Smart Dedicated Outdoor-Air Systems." July 2006. available at www.ashrae.org or www.trane.com) further discusses the impact of delivering the conditioned OA "cold" versus "neutral."

system, and the airflow delivered by the dedicated OA unit is the same for both configurations. (For zones that require year-round cooling, the supply airflow may need to be sized based on the warmest temperature to be delivered by the dedicated OA unit.)

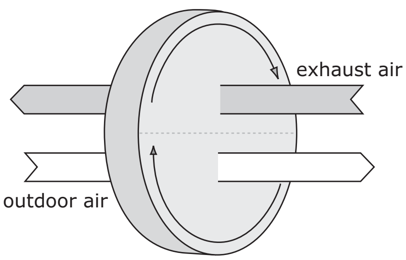
While the conditioned outdoor air should be delivered cold whenever possible, as the space sensible cooling load decreases—due to changes in outdoor conditions and internal loads—it is possible that the cold, conditioned outdoor air may provide more sensible cooling than the space requires. As a result the space dry-bulb temperature drops and the WSHP operates in the heating mode. While this may appear strange to the building operator, the few heat pumps that are operating in the heating mode absorb heat from the loop, reducing the amount of heat that needs to be rejected by the cooling tower. This likely improves system efficiency, rather than degrading it. In addition, the remaining zones continue to benefit from the sensible cooling due to the cold, conditioned outdoor air.

During the heating season, however, it may be desirable to heat the outdoor air to a temperature near the desired space temperature before delivering it directly to the zones.

Finally, if the outdoor air is delivered directly to each zone (center configuration in Figure 5), the fan inside the heat pump is no longer required to operate in order to ventilate the zone. This affords the opportunity to cycle the local fan on and off along with the compressor, saving fan energy at part-load conditions.

Exhaust-air energy recovery. A centralized ventilation system often makes it more feasible to implement exhaust-air energy recovery, if exhaust air from the building can be routed back to the dedicated OA unit.

Figure 7. Exhaust-air energy recovery



As an example, Figure 7 shows a total-energy wheel used to precondition the outdoor air. During the cooling season, this desiccant-coated wheel revolves between the outdoor and exhaust airstreams, removing both sensible heat and moisture from the entering outdoor air and rejecting it to the exhaust air. During the heating season, the wheel recovers both sensible heat and moisture from the exhaust air, and transfers it to the outdoor air being brought into the building for ventilation.

In many climates and building types, exhaust-air energy recovery is an effective means of reducing the energy required to cool, dehumidify, heat, or humidify the entering outdoor air. It also reduces the required cooling and heating capacity of the dedicated outdoor-air unit.

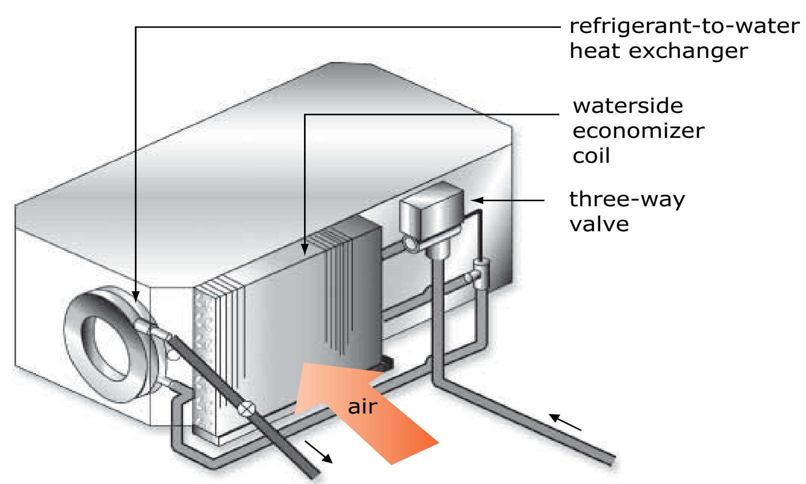
Waterside economizer. During cold weather, the heat pumps serving perimeter zones often operate in heating mode and absorb heat from the water loop, which lowers the loop temperature. If the loop water temperature is allowed to drift down further than normal—to 45°F (7°C), for example—a waterside economizer coil can be used to provide "free cooling" for interior zones.

When the loop water is cool enough, a three-way valve diverts the water through the waterside economizer coil to cool the entering air, reducing (or avoiding) the need to operate the compressor (Figure 8).

The three-way valve allows the economizer coil to be bypassed when not in use, saving pump energy. And, unlike other systems, no cooling tower energy is used to create the colder water; just the heat pumps serving the perimeter zones that are already operating in the heating mode.

Hot gas reheat for humidity control. Because a water-source heat pump typically uses a constant-speed fan with a cycling compressor, it can be susceptible to high relative-humidity levels in the zone at part-load conditions. One approach to improve part-load dehumidification in WSHP systems is to use the dedicated outdoor-air system to dehumidify the outdoor air so that it is drier than the space. But in some buildings, it may not be practical to serve every zone with the dedicated outdoor-air system.

Figure 8. Waterside economizer



Another option for controlling humidity is to reheat the dehumidified supply air with heat recovered from the refrigeration circuit in the heat pump. This is sometimes referred to as hot-gas reheat. In this configuration, the air is first cooled and dehumidified by the refrigerant-to-air heat exchanger, then reheated by the reheat coil to control not only the dry-bulb temperature, but also the relative humidity in the zone (Figure 9).

As long as the zone relative humidity is less than the desired upper limit (60% for example), the heat pump operates in the standard cooling mode and the compressor cycles on and off to maintain zone temperature. When the humidity sensor indicates that the zone relative humidity is too high, but the zone temperature is at setpoint, the reheat valve diverts hot refrigerant vapor from the compressor through the reheat coil. This allows the compressor to keep operating to dehumidify the air, while warming the supply air to avoid overcooling the zone.

Although ASHRAE Standard 90.1-2004, *Energy Standard for Buildings Except Low-Rise Residential Buildings*, limits the use of reheat using "new" energy, it allows unlimited reheat for the purpose of humidity control if site-recovered energy (such as heat recovery from the refrigeration circuit) is used as the source of heat.

Optimized Control Strategies

Night setback. To lower installed costs, some WSHP systems use simple, residential-style thermostats with no system-level controls. A non-programmable thermostat causes the heat pump to maintain the same temperature, whether the zone is occupied or not.

Use of programmable thermostats allows each zone to vary the temperature setpoint based on time of day and day of the week. But they also allow occupants to override these setpoints or ignore the schedule altogether (by using the "hold" feature of the thermostat), thus thwarting any potential for energy savings.

A more sustainable approach is to equip each heat pump with a DDC controller that is connected to a zone temperature sensor, and then use a system-level controller that coordinates the operation of all components of the system. This system-level controller contains a time-of-day schedule that defines when the building is expected to be unoccupied. During these times, the system is shut off and the temperature in each zone is allowed to drift away from the occupied setpoint.

Allowing the indoor temperature to drift during unoccupied periods saves energy by avoiding the need to operate heating, cooling, and ventilation equipment. Figure 10 shows the potential energy savings of using night setback in an example office building that has a typical WSHP system.

Figure 9. Hot gas reheat for humidity control

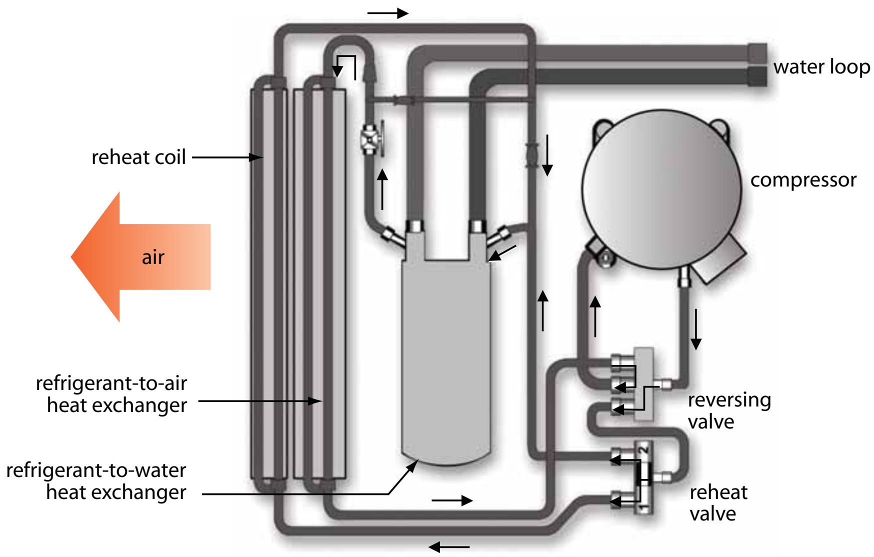
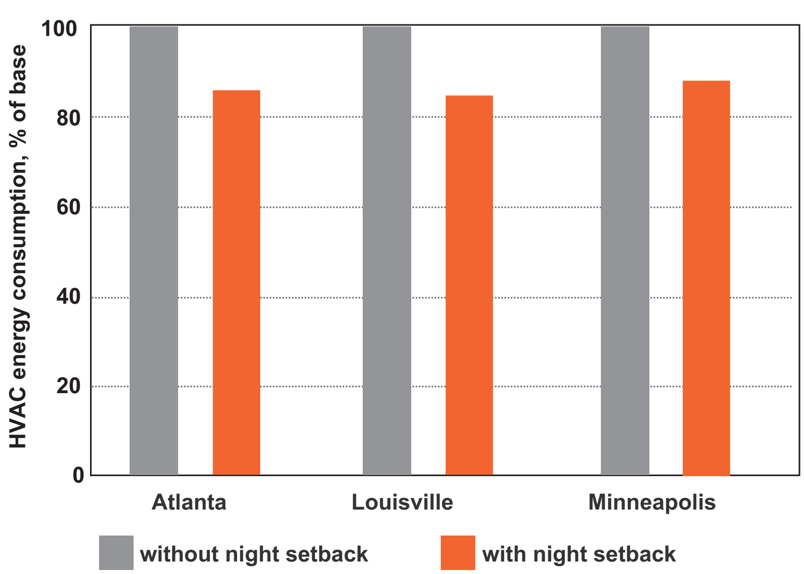


Figure 10. Energy-saving potential of night setback



Night setback reduced the overall HVAC energy use by 10% to 15% for this example building.

Optimal start. In those systems that use a time-of-day schedule to start and stop the HVAC system, the time at which the system starts in the morning is typically set to ensure that the indoor temperature reaches the desired occupied setpoint on either the coldest or warmest day of the year. The result is that, for most days, the system starts much earlier than it needs to. This increases the number of operating hours and increases system energy use.

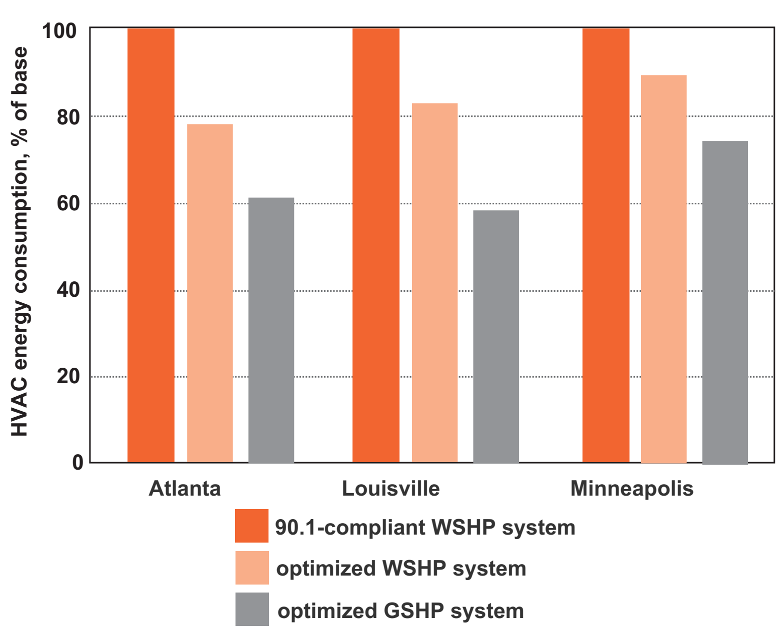
An alternative approach is to use a strategy called optimal start. The system-level controller is used to determine the length of time required to bring each zone from the current temperature to the occupied setpoint temperature. Then, the controller waits as long as possible before starting the system, so that the temperature in each zone reaches occupied setpoint just in time for occupancy.

This optimal start strategy reduces the number of hours that the system needs to operate, and saves energy by avoiding the need to maintain the indoor temperature at occupied setpoint even though the building is unoccupied.

Loop temperature optimization. A system-level controller should be used to operate the water circulation pumps and coordinate cooling tower and boiler operation. To maximize the energy-related benefits of a WSHP system, the loop water temperature should be allowed to float across a wide range—between 60ºF (16ºC) and 90ºF (32ºC), for example.

Further, communicating system-level controls offer the opportunity to optimize the loop water temperature in an effort to minimize overall system energy consumption. In the cooling mode, the compressor in the water-source heat pump is more efficient if the entering water temperature is cooler. However, making cooler water often requires the cooling tower to use more energy. A smart, system-level controller can reset the loop temperature setpoint to minimize the combined energy consumed by the heat pumps and cooling tower under the current operating conditions.

Figure 11. Energy-saving potential in WSHP systems



Summary

The impact of any energy-saving strategy on the operating cost of a specific building depends on climate, building usage, and utility costs. Building analysis tools (like TRACE™ 700) can be used to analyze these strategies and convert energy savings to real operating cost dollars that can be used to make financial decisions.

Figure 11 shows the potential energy savings of using several of these strategies in an example office building with a WSHP system. The "base" WSHP system complies with ASHRAE 90.1-2004, so it includes night setback control, variable-flow pumping with a VFD, and a total-energy wheel on the dedicated outdoor-air unit. The optimized system adds optimal start and loop temperature optimization to the system-level controls, and the conditioned outdoor air is ducted directly to each zone (rather than to the inlet of each heat pump). Delivering the OA directly to each zone allows it to be delivered "cold" (rather than reheated to neutral) during the cooling season, and allows the fan in each heat pump to cycle off with the compressor when that zone does not require either cooling or heating.

The optimized WSHP system reduced the overall HVAC energy use by about 20% for this example office building in Atlanta, by 15% in Louisville, and by 8% in Minneapolis. If the system is converted to a ground-source heat pump system, the energy savings increases to 37% in Atlanta, 40% in Louisville, and 24% in Minneapolis.

There is a real potential to create high-performance WSHP systems, which reduce operating costs for the building owner and improve occupant comfort.

By John Murphy, applications engineer, Trane. You can find this and previous issues of the Engineers Newsletter at www.trane.com/engineersnewsletter. To comment, e-mail us at comfort@trane.com.

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