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Water-Cooled Electric Chilled-Water Systems

There are many opportunities to achieve significant energy savings and improved occupant comfort through improved operations and maintenance practices for electric chilled-water systems. This is due in part to the fact that these systems consume a substantial amount of energy: They can account for 15 percent of a building's annual energy consumption. In addition, these systems are complex—with several interdependent subsystems—so there's a lot that can go wrong if equipment isn't properly operated and maintained. This complexity also makes it important to use an integrated systems approach to make the most cost-effective choices and to avoid inadvertently making things worse. Consider these procedures as you plan and track your chiller upgrade progress.

Operations

SYSTEM-LEVEL OVERVIEW: OPERATIONS

Consider system interactions before changing operational practices.

Some operational changes are fairly straightforward, such as turning off unneeded equipment. Others, such as those influencing sequencing or determining how many cooling towers to run, require some analysis of the available equipment and current building loads to establish parameters. Implementing chilled- and/or condenser-water temperature resets or reducing flow rates require still more forethought. Chiller plants are complex, and the efficiency and interaction of each component plays a role in determining how efficiently the entire system operates. For example, reducing chilled-water flow rates can save on pumping energy, but this requires the chiller to use more energy to produce colder chilled water. The specific flow rates and temperatures that will produce the most efficient system overall vary based on the efficiency of the chiller and pumps as well as on outdoor conditions and building loads.

Accounting for all these variables can be a daunting task. However, they can be factored into any decision by using a building energy performance simulation package—and perhaps a professional trained in its use. These computer programs perform the numerous and complex calculations needed to evaluate how buildings use energy. The most sophisticated programs

can calculate building energy consumption hour by hour for a full year. That allows engineers and designers to see how modifications to any of the building's systems—including the chilled-water system—will affect annual energy consumption. Simulation software also accounts for interactions among building components, which allows designers to experiment with a variety of combinations of strategies and determine which provide the most cost-effective approach.

Designers and their clients may seek to amortize the cost of simulating building performance by using simulations to verify savings, optimize HVAC system control, and identify malfunctions in building systems. Several HVAC equipment manufacturers also offer energy simulation software.

One approach to improving chiller plant performance through detailed analysis is described by system designers in "Optimizing Chilled Water Plant Control" (*ASHRAE Journal*, June 2007). It provides a step-by-step overview of how modeled or measured facility loads, along with calibrated chiller and component models, can be used in simulations to guide equipment selection and control strategies.

UNNEEDED EQUIPMENT

Turn off unneeded equipment.

There is no simpler way to achieve savings. Often, inspections of chilled-water systems reveal pumps, chillers, and cooling towers that are running unnecessarily. These wasteful practices are usually associated with either manual control of chilled-water equipment ("I thought you were going to turn it off") or with poorly maintained or disabled automatic controls.

To identify control opportunities, carefully observe how chilled-water equipment is operated. Some practitioners even conduct "midnight" inspections during unoccupied hours. Questions to ask include:

- Is equipment being left on when the building is unoccupied?
- Can equipment be turned on later or turned off sooner?
- Can sufficient cooling be provided with fewer chillers or pumps?

The savings potential of improving manual control efforts or installing automatic controls depends on the diligence of operators and the effectiveness of existing controls.

MAINTAIN CHILLER LOADING

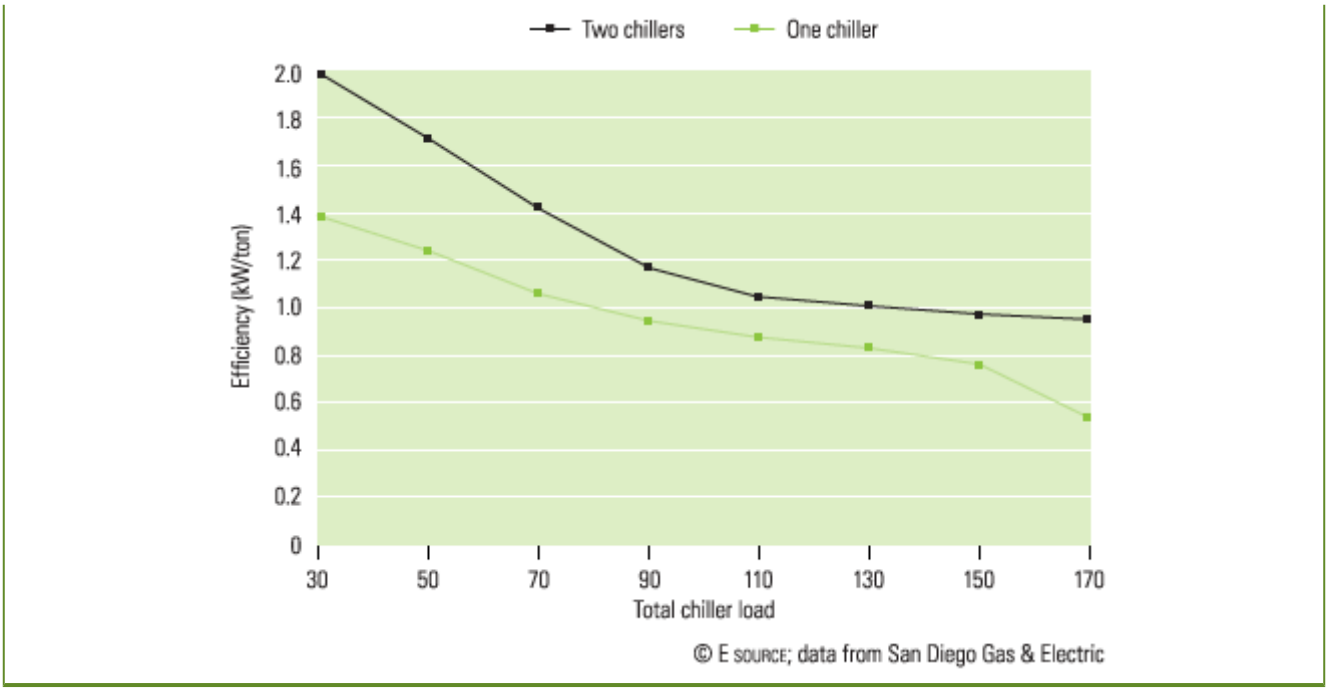
Turn chillers on or off to ensure that each is loaded appropriately to operate in its most efficient zone.

Every chiller has a range of loading conditions wherein it operates most efficiently. The efficiency of most chillers drops off dramatically at loads below 30 percent, although for some that cutoff can be as high as 50 percent—only an evaluation of the operating efficiency will tell for a particular chiller.

For example, in a loading and performance study by San Diego Gas & Electric, two 200-ton centrifugal chillers serving a 162,930-square-foot office building were found to frequently operate simultaneously at less than 45 percent capacity each. Calculations showed that savings of about 5 percent could be achieved by operating a single chiller at 90 percent load instead of both at 45 percent load. Annual energy savings would have been about 34,500 kilowatt-hours (kWh), or $3,450 per year at $0.10 per kWh. Further study revealed an additional savings of about 14,100 kWh, or $1,410 annually, from the auxiliary chilled-water and condenser-water pumps that were also shut down with the unneeded chiller. This would bring the overall savings from improved chiller sequencing to $4,860 per year (**Figure 1**).

FIGURE 1: Savings from better chiller sequencing

In this case documented by San Diego Gas & Electric, running just one chiller at 90 percent capacity instead of two chillers at 45 percent capacity could improve chiller efficiency and save almost $5,000 annually. This chiller plant used two 200-ton chillers. The chart includes all hours that both chillers operated at less than 45 percent capacity.



Standard sequencing dictates that a second chiller isn't started until the first one is nearly fully loaded. If multiple chillers are available of different sizes, the smallest should be started first. When the second chiller is started, run both of them at equal percentages until they are nearly fully loaded. Then a third chiller can be started, and so on. As the load decreases, chillers are cycled off in reverse order.

Another sequencing method uses one small chiller—called the "swing" chiller—with one or more large chillers. The swing chiller is started and runs to close to its maximum. Then it's shut down and one of the larger systems is started. In this manner, the larger system isn't started until it can operate within its maximum efficiency range. As the load increases past the maximum range of the larger chiller, the swing chiller is restarted and the two chillers carry the load until it exceeds their combined capacity. Then the swing chiller is stopped again and the second large chiller is started. As the load decreases, the chiller unloading follows the same logic. Energy consumption is reduced using the swing method by properly loading each chiller and switching off pumps and fans with their associated chillers.

For either strategy, the savings potential of running chillers at high loads will vary widely depending on chiller characteristics and the range of cooling loads exhibited by a facility. Chiller characteristics can be obtained easily from the manufacturer. In contrast, few plant operators know their building's cooling load profiles with much certainty. Fortunately, it costs little to experiment manually with sequencing strategies and to estimate savings through observation. This involves four steps:

- *Observe operation of inlet vanes or slide valves.* Inlet vanes modulate centrifugal chiller capacity and slide valves modulate screw chiller capacity. Many new chillers can display cooling capacity based on the position of these devices. If this capability is available, start logging chiller capacity using the energy management system or a stand-alone data logger. If not, find out from the manufacturer what modulating device positions are associated with 50 percent and 90 percent loading, and then log chiller capacity manually. Take note of whether chillers regularly operate below 50 percent load.
- *Sequence chillers based on capacity.* When the inlet vanes or slide valves indicate that all operating chillers are at about 90 percent load, turn on another chiller. When the operating chillers drop below 50 percent load, turn off one of the chillers. If the chillers are equally efficient but not equally sized, turn on the smallest chiller first. When it's time to shut down a chiller, turn off the smallest operating chiller first.
- *Block flow through turned-off chillers.* Close manual or automatic valves on chillers that aren't operating. Alternatively, turn off the pumps for individually pumped chillers.
- *Estimate savings.* Using information from the manufacturer, estimate the chiller load, efficiency, and power associated with each capacity level. Then estimate what the loading, efficiency, and power would have been under the original strategy. The difference between the two power estimates represents your savings.

STATIC PRESSURE RESET

Reset static pressure setting for variable-speed controls.

Variable-flow chilled-water systems modulate pump speed to maintain a constant static pressure at the most distant branch. The lower that static pressure is, the less energy the pumps consume. The question is, how low can you go? Theoretically, optimum static pressure is achieved when only one control valve is completely open. If more than one control valve is completely open, the static pressure setting is probably too low. If no control valves are completely open, energy is wasted—unnecessarily dissipated through the most-open control valve.

To reduce the static pressure setting and save pumping power, observe the chilled-water control valves during peak chilled-water demand. Peak demand usually occurs late in the afternoon on an extremely hot, humid day. This observation is easy to do when the control system monitors valve positions. However, not all control systems do this—in which case a technician must visit and observe all control valves in the system. If no chilled-water control

valves are completely open, the static pressure setpoint can be lowered. If more than one control valve is completely open, the static pressure setting may need to be raised. Of course, if a too-low static pressure setting is yielding no negative consequences (for instance, no one is complaining), consider leaving the setting alone and continue to enjoy the energy savings.

To see how to calculate savings from static pressure reset, see the “Retrofits: Valves” section. Assuming a peak flow rate of 2,667 gallons per minute, an average flow about half the fully rated flow, 3,500 operating hours, and $0.10 per kilowatt-hour, reducing static pressure by 2 feet would save about 1.15 kilowatts and $403 per year. The only cost to achieve these savings would be the labor to observe valve positions and adjust static pressure.

CHILLED-WATER TEMPERATURE RESET

Reset the chilled-water temperature based on outdoor conditions and/or feedback from chiller loads.

Where sufficient feedback is available on actual chiller loads, monitoring loads and outdoor conditions can help you fine-tune chiller system operation and maximize savings. If load feedback isn’t available, you can still use outdoor air temperature in a simpler strategy to match chiller output to the actual load. Note that this strategy is often disabled by chiller plant operators trying to rectify unrelated plant problems. To help prevent this, show plant operators how to apply and maintain this strategy and explain why it’s valuable.

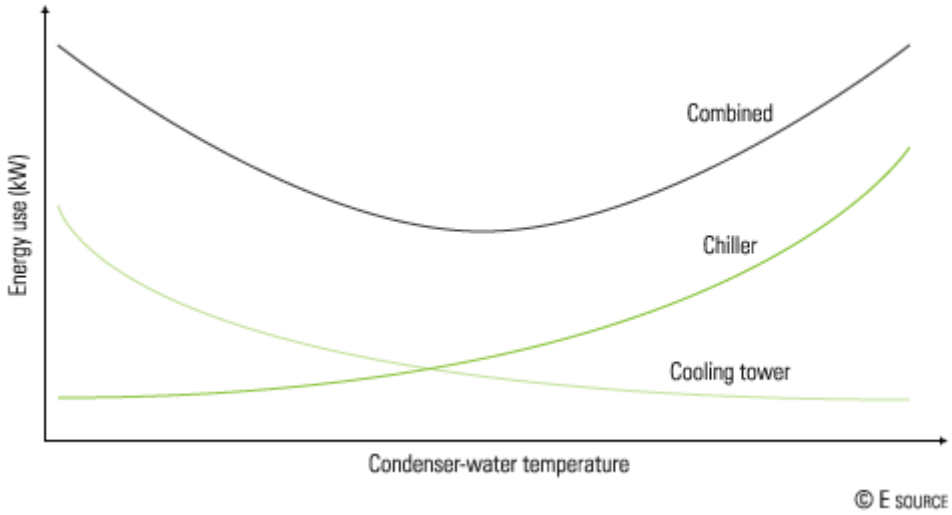
CONDENSER-WATER TEMPERATURE RESET

Reset the condenser-water temperature based on outdoor conditions.

Producing colder condenser-water temperatures reduces the energy consumed by the chiller. However, this increases cooling tower fan power. As shown in **Figure 2**, the optimum operating temperature occurs at the point where these two opposing trends combine to produce the lowest total power use. However, this point changes with outdoor conditions, so the setpoint needs to be adjusted continuously to maintain efficiency.

FIGURE 2: Finding the optimum condenser-water temperature

Chiller efficiency increases and cooling tower efficiency decreases as condenser-water temperature is lowered. The optimum operating point is found in the trough of the combined-energy curve. This point will change with operating conditions, so this analysis must be conducted for a wide range of operating conditions to determine the reset parameters.



CHILLED- AND CONDENSER-WATER FLOW RATE REDUCTION

Reduce chilled- and condenser-water flow rates to below standard conditions.

Lower either the chilled- or the condenser-water flow rates, or both, below the rates specified for standard Air-Conditioning, Heating, and Refrigeration Institute conditions. This strategy effectively works the chiller harder while saving pump energy. The energy savings from this approach can be substantial. **Table 1** displays data for an example chiller plant, showing an estimated annual energy savings of $17,000 to $37,800, depending on building location.

TABLE 1: Low-flow design raises chiller power but reduces system power

This is an estimate of savings that could be reaped in four cities by varying the condenser- and chilled-water flow rates. The chiller plant uses two 800-ton chillers, pumps that are 82 percent efficient, and motors that are 93 percent efficient.

	Chilled-water flow rate (gpm)	Condenser-water flow rate (gpm/ton)	Chiller power (kW)	Total power (kW)	Estimated annual energy use (MWh)			
					Chicago, Illinois	Lake Charles, Louisiana	Miami, Florida	San Francisco, California
Option 1	1,920	3	436	563	1,177	1,897	2,288	1,057
Option 2	1,067[a]	2	476	541	1,007	1,618	1,910	837
Percent change between options 1 and 2	–0.44	–0.33	0.09	–0.04	–0.14	–0.15	–0.17	–0.21
Savings difference between options 1 and 2 (MWh)					**170**	**279**	**378**	**220**
Annual savings ($)					**17,000**	**27,900**	**37,800**	**22,000**

Notes: Savings based on $0.10 per KWh electricity rate; MWh = megawatt-hours; kW = kilowatts; gpm = gallons per minute

a. Corresponds to a temperature increase of 8° Fahrenheit between the entering and leaving chilled water.

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COOLING TOWERS

Run as many cooling towers as possible to save on fan power.

In a way, cooling towers are the opposite of chillers: While it's good to run as *few* chillers as possible, it's also good to run as *many* cooling towers as possible. Most chilled-water plants have excess capacity, and during low-load hours, one or more cooling towers aren't operating. To make the most of existing cooling towers, simply run condenser water over as many towers as possible, at the lowest possible fan speed, and as often as possible.

Energy savings can be significant. For example, with one cooling tower we looked at, when its fan runs at half speed, the tower rejects 55 percent of its rated heat capacity but only draws 25 percent of its rated fan power. As a result, if two cooling towers run at half speed (instead of one at full speed), together they would reject slightly more heat than single-tower operation while drawing only *half* the power.

This strategy is feasible only for chilled-water systems that include multiple chillers and towers plumbed in parallel. In such systems, open all the condenser-water isolation valves at the cooling towers—and leave them open. To avoid additional pumping power costs, run only enough condenser-water pumps to maintain adequate flow through the chillers. This strategy does have one drawback: It causes additional fan cycling (between half speed and off and between half speed and full speed). This in turn leads to additional wear and tear on motors and gears. However, this problem can be avoided by adding variable-speed drives to the fans.

Maintenance

HEAT EXCHANGER TUBES

Inspect tubes annually and clean as needed, or use automatic tube-cleaning equipment.

As a chiller runs, water may leave behind scale, algae, or slime on the inside of the condenser tubes (buildup is typically not a problem in the evaporator tubes because that is a closed system). These deposits can decrease the efficiency and the capacity of the chiller by reducing heat-transfer efficiency. Periodic chemical or ozone treatments can help keep condenser tubes clear.

Another option is automatic cleaning equipment that inserts thumb-size nylon brushes into each condenser tube—catch baskets epoxied to the ends of the tubes collect the brushes. These brushes are slightly larger than the inside diameter of the tubes, so they brush the whole length of the tube as they are propelled by the water flow.

Energy and maintenance savings depend on the chemical or manual treatment that would otherwise have been used—the more deposits that would have built up, the greater the savings. For example, a condenser fouled to the point that the condensing temperature increases 5° Fahrenheit results in a 5 percent decrease in capacity and a 5 percent increase in power requirements. In some older machines, refrigerant tubes in the evaporator can become fouled by oil in the refrigerant; oil separators address this problem and are standard equipment on newer systems.

COOLING TOWERS

Prevent scale formation in cooling towers.

Scaling, corrosion, and biological growth all impede tower efficiency and increase maintenance costs from the resultant condenser fouling and loss of heat transfer. These problems are accelerated by water with high concentrations of dissolved mineral salts that become increasingly concentrated during the evaporation process. In addition, cooling tower water is conducive to the growth of *Legionella pneumophila* and other pathogens that can create health problems.

Although locating cooling towers away from air intake vents can greatly reduce the risk of transmitting pathogens into the building, the typical solution to this and the other cooling tower water problems is to treat the water. Biocides can inhibit biological growth, corrosion inhibitors

can maintain equipment surfaces, and other chemicals can maintain proper pH. Finally, a significant amount of “blowdown” (deliberate water overflow) is typically used so that fresh makeup water reduces the buildup of salts and pollutants.

Although treatment chemicals are necessary for maintaining cooling towers, they are often hazardous to handle and dispose of. Chemicals also increase your operating costs. One approach from the water treatment company ProChemTech International may mitigate some of these problems. Its ElectroBrom system uses electrolysis to automatically add the biocide bromine to the tower water as needed. This eliminates the need for maintenance staff to manually perform this task—reducing their exposure risk—and could reduce the amount of chemicals used that must later be disposed of.

Some companies have attempted to develop nonchemical treatments. Magnetic-field treatments, in particular, have yet to conclusively demonstrate their value. Although there are reports that such systems have been successfully applied, there are also many observed failures. There’s no scientific explanation for how magnetic fields could influence particles and microorganisms in water to prevent fouling, so it’s impossible to predict for any given condensing-water system whether such treatment would work.

Another nonchemical treatment is ozone. It is an effective biocide, but it’s unclear under what circumstances it works well for cooling towers. In addition, it is still debated as to how—or even if—it can prevent scale buildup or corrosion. Some ozone system manufacturers even recommend using chemicals in addition to the ozone.

PUMPS

Confirm proper pump rotation.

If any two of the three power connections on a three-phase motor are reversed, the motor will rotate in the wrong direction. Reverse rotation still produces flow and pressure—but much less than rated capacity, and at very low efficiency. Occasionally, mechanics find pumps that have been spinning backward for years.

To verify pump rotation, check the pump casing or the manufacturer’s literature to determine the correct rotational direction. Then, start and stop the motor just long enough to “bump” the shaft and observe which way it turns. If the pump is rotating in the wrong direction, switch any two of the three power leads.

Retrofits

SYSTEM-LEVEL OVERVIEW: RETROFITS

Consider system interactions before undertaking retrofits.

Chilled-water plants are complex and thus present many retrofit efficiency opportunities. As a general approach, thinking upstream through possible retrofit options—starting at the balancing valves and ending at the cooling tower fan—can yield upstream capital cost and energy savings. For example, by reducing resistance in the piping system, a designer might be able to reduce capital costs by specifying a smaller pump and a smaller chiller.

However, an integrated system approach is necessary to maximize efficiency. First, it's difficult to make generalizations about specific options—creating the most cost-effective chiller plant for a particular building often requires you to consider energy and demand prices, building load characteristics, local climate, building design, operating schedules, and the part-load operating characteristics of the available chillers. Second, modifying the design or operation of one set of components often affects the performance of other components of the system. For example, increasing chilled-water flow can improve chiller efficiency, but the extra pumping power required could result in an overall *reduction* in system efficiency.

Consider the case of a designer who switched a chiller condenser-tube bundle from two-pass flow to four-pass flow. That change indeed improved chiller efficiency from 0.62 to 0.60 kilowatts per ton. But it also added 28 feet of pressure drop to the chilled-water flow stream—and thus increased the required pumping power. As shown in **Table 2**, this produced a net chiller plant energy savings at full load, but because this particular building featured a constant-flow system, at the typical 75 percent load condition there was a net plant energy-use increase. The net effect was even worse at lower loads. Although the designer had intended to reduce energy consumption through improved chiller efficiency, the "improvement" wound up increasing overall energy consumption.

TABLE 2: The perils of piecemeal chiller improvements

By not considering the interaction of all chiller components, this conversion to a four-pass flow condenser-tube bundle resulted in a net energy use increase at the more typical load

factor of 75 percent.

Component	Post-conversion power consumption changes (kW)	
	Full load	75% load
Chiller	−8.8	−6.6
Pumps	8.6	8.6
Chiller + pumps	−0.2	2.0

Note: kW = kilowatts © E SOURCE

To account for all the variables in a chiller plant, use a building energy performance simulation package to perform the numerous and complex calculations needed to evaluate how a building uses energy. The most sophisticated programs can calculate building energy consumption hour by hour for a full year. That allows engineers and designers to see how modifications to any of the building's systems—including the chilled-water system—will affect the building's annual energy consumption.

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PIPES

Insulate chilled-water pipes.

Insulation helps ensure that the chilled water only absorbs heat from the spaces where it is intended to do so.

VALVES

Remove or completely open pressure-wasting valves.

Many chilled-water systems have balancing valves, pressure-reducing valves, throttling valves, and/or pressure-regulating valves that are designed to control flow by inducing pressure drop. These valves waste energy, and there is almost always a more efficient way to control flow—such as by installing variable-speed controls, trimming the pump impeller, or staging pumps.

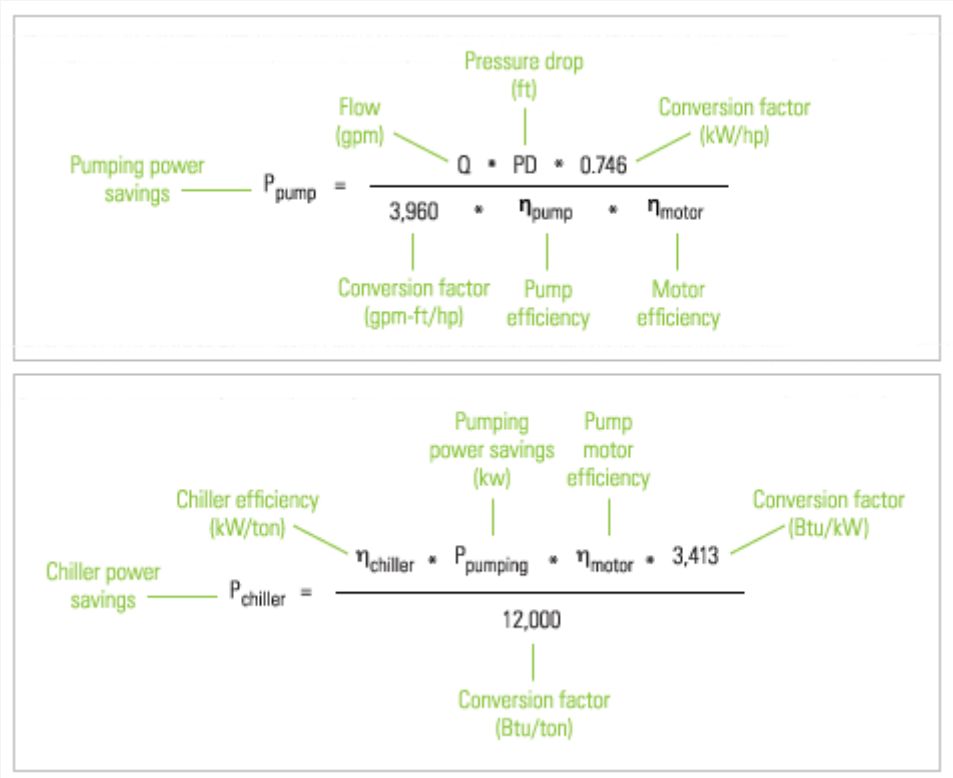
Pressure-wasting valves can be either removed or completely opened. Physically removing a valve eliminates all of its associated pressure drop, but this approach requires labor, materials, and a temporary system shutdown. Alternatively, opening a valve fully costs almost nothing—however, this approach produces less savings because the valve continues to impart some pressure drop even when fully open. Valves left in place also can still be used as shutoff valves, which does offer a maintenance advantage. To calculate savings from opening or removing pump outlet balancing valves, see the sidebar, How Much Can You Save By Opening or Removing Pump Outlet Balancing Valves? It illustrates that opening the pump outlet balancing valves on a 1,000-ton chilled-water system serving a 400,000-square-foot building could save more than 80,000 kilowatt-hours per year.

HOW MUCH CAN YOU SAVE BY OPENING OR REMOVING PUMP OUTLET BALANCING VALVES?

To estimate potential savings from removing pump outlet balancing valves, follow this procedure:

1. *Determine the flow rate and/or pressure drop through the valve.* If the valves are equipped with differential pressure ports, a field measurement will show the pressure drop. The flow rate then can be determined from the valve manufacturer's lookup table. Some valves have an exterior position scale that shows the valve's setting, which can then be converted to flow or pressure drop using the manufacturer's lookup table. Flow and pressure drop also may be found in testing and balancing reports.

2. *Determine pressure-drop savings.* Completely removing a valve eliminates its entire pressure drop. For valves that are simply opened, savings equal the pressure drop measured when the valve was set minus the pressure drop across the completely open valve. Consult the valve manufacturer's literature to determine the pressure drop across a completely open valve.
3. *Calculate pumping and chiller power savings.* Using the following equations, calculate pumping power and chiller power savings. Chiller power savings result because reductions in pumping power mean less waste heat is being picked up by the water returning to the chiller (note: gpm = gallons per minute; ft = feet; kW = kilowatts; hp = horsepower).



Add the pumping power savings to the chiller power savings to get total savings. For example, consider a 2,667-gpm chilled-water system serving a hypothetical 400,000-square-foot facility. This system is regulated by a balancing valve on its pump outlet. If opening this valve eliminates 20 feet of pressure drop, chilled-water system power would be reduced by 22.9 kW:

$$\text{Pumping power savings} \quad P_{pump} = \frac{\overset{\text{Flow}}{2{,}667\ \text{gpm}} * \overset{\text{Pressure drop}}{20\ \text{ft}} * \overset{\text{Conversion factor}}{0.746\ \text{kW/hp}}}{\underset{\text{Conversion factor}}{3{,}960\ \text{gpm-ft/hp}} * \underset{\text{Pump efficiency}}{0.6} * \underset{\text{Motor efficiency}}{0.9}} = 18.6\ \text{kW}$$

$$\text{Chiller power savings} \quad P_{chiller} = \frac{\overset{\text{Chiller efficiency}}{0.91\ \text{kW/ton}} * \overset{\text{Pumping power savings}}{18.6\ \text{kW}} * \overset{\text{Pump motor efficiency}}{0.9} * \overset{\text{Conversion factor}}{3{,}413\ \text{Btu/kW}}}{\underset{\text{Conversion factor}}{12{,}000\ \text{Btu/ton}}} = 4.3\ \text{kW}$$

$$P_{total} = \underset{\text{Pumping power savings}}{18.6\ \text{kW}} + \underset{\text{Chiller power savings}}{4.3\ \text{kW}} = 22.9\ \text{kW}$$

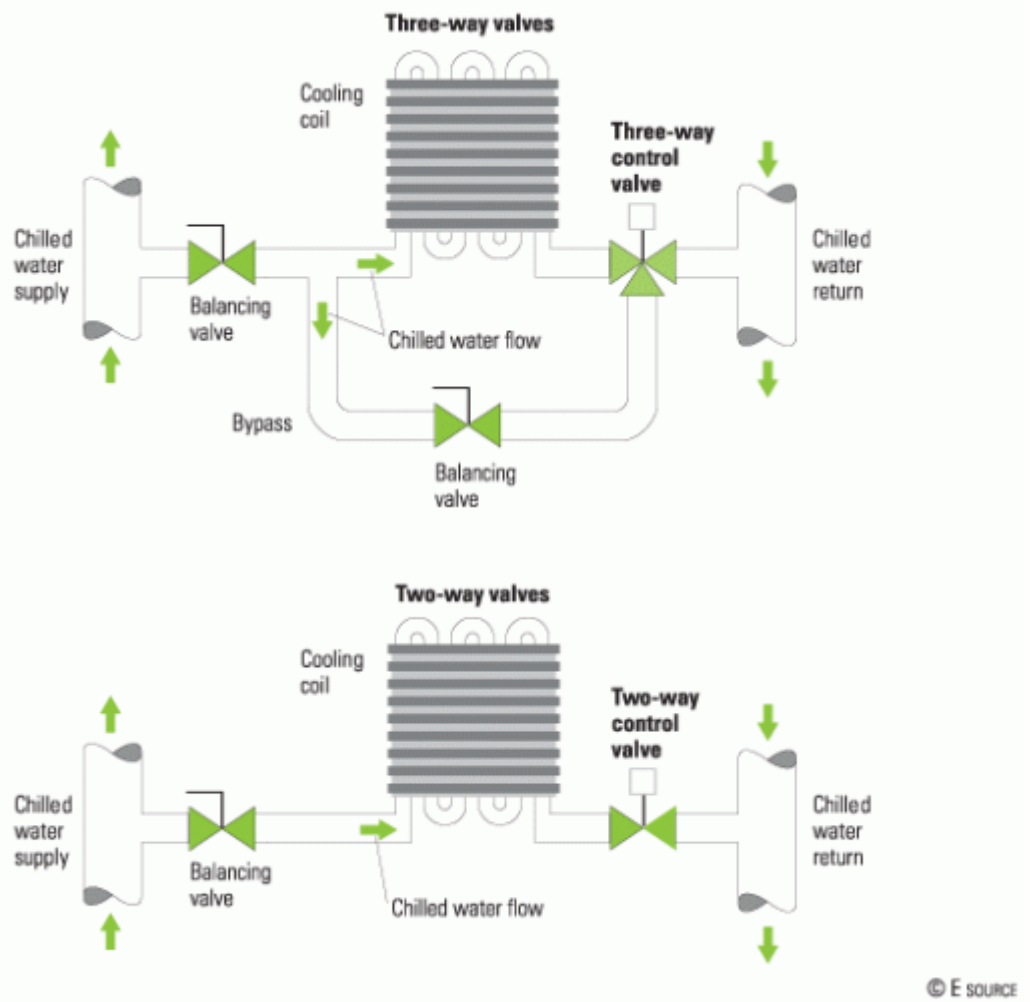
Here, chiller savings amount to about 23 percent of pumping savings—a significant secondary effect. For a facility operating 3,500 hours per year at an average electric rate of $0.10 per kilowatt-hour, this 20-foot pressure drop reduction would save 80,150 kilowatt-hours and $8,015 per year.

Convert three-way valves to two-way operation.

Traditionally, chilled-water systems have operated at constant flow with three-way control valves. These valves (**Figure 3**) direct flow through cooling coils when cooling is called for; otherwise, they bypass flow to the return stream. Three-way valve systems waste energy because the pump has to drive superfluous flow through the bypasses. Two-way valves have no bypass and simply restrict flow through the branch piping based on cooling load.

FIGURE 3: Convert three-way valves to two-way to save pumping energy

Three-way valves waste pumping energy during low-load operation because superfluous flow is pumped through the bypass pipe. Two-way valves have no bypass and can reduce pumping energy during low-load operation.



Converting three-way valves to two-way action can be as simple as closing the balancing valves on the bypass piping—as long as the three-way valves are robust enough to maintain stable operation. This strategy can save a lot of energy and money with only a little effort. If the three-way valves are not up to the task, installing new two-way valves will get the job done—although this strategy will cost more.

Once the bypasses are closed, the chilled-water flow will begin to vary with the cooling load. Often, variable-speed controls are installed on the pumps, but it's also possible to simply allow the pumps to "ride the curve." For many pumps, this means that when flow is constricted—as through the cooling coil under low-load conditions—the pressure will increase while flow and pumping power decrease. Although this method saves less energy than installing variable-

speed controls, it is the lower-cost option. Also, it's important to check with the pump manufacturer to determine the minimum allowable pump flow, and then leave enough bypasses open to ensure that the pumps never operate below that minimum.

Three-way/two-way valve conversions significantly alter system operation. Before making this change, you should take these precautions:

- *Observe control valve operation before the conversion.* Two-way systems only save pumping energy at part-load conditions, so it doesn't make sense to convert valves if all branches run at full load (with no bypass) all the time. Observe the three-way valves long enough to ensure that they are directing at least some flow through the bypass.
- *Check minimum pump flow.* "Riding the pump curve" puts the system into a high-pressure, low-flow regime. Although most pumps can handle this, consult with the pump manufacturer to determine the minimum safe pump flow.
- *Leave open enough bypasses to maintain minimum flow.* When closing down the balancing valves on the bypasses, leave enough operating bypasses to prevent the pumps from dropping below minimum flow at any time—starting with the three-way valve farthest from the pump.
- *Consider chiller flow requirements.* Chiller manufacturers recommend constant flow through their machines to prevent damage from spot freezing—although engineers debate the importance of this. Systems that have only one layer of pumping may not be able to take advantage of three-way/two-way valve conversions.
- *Confirm valve pressure ratings.* Make sure that three-way valves are rated for greater close-off pressure and dynamic pressure than the pump shutoff pressure. If not, consider replacing them with new two-way valves. One engineer experienced in these conversions recommends replacing three-way valves whenever the pump shutoff head is greater than 55 feet.
- *Open all nonbypass balancing valves.* All balancing valves that are not located on bypasses should be opened. These valves waste energy, and they also make it more difficult for the control valves to control the system.
- *Consider before-and-after metering to estimate savings.* It's difficult to know how flow will vary after a conversion unless cooling loads are measured. One relatively easy way to estimate savings is to install meters on the pumps. Measure power at least momentarily with the three-way valves in standard operation, then constantly with two-way operation. Whenever postconversion pumping power drops below the preconversion measurement,

that difference represents savings.

PUMPS

Replace standard-efficiency or oversized pumps with high-efficiency models sized for the actual load.

Pumps that are too big for the load are sometimes installed for a variety of reasons, or may have become oversized due to downstream friction-reducing retrofits. They may appear to be operating correctly because discharge valves can allow a vastly oversized pump to provide the design flow—but at the cost of significant energy waste and accelerated wear. Even if sized correctly, existing pumps can be inefficient.

One option is to replace pumps with high-efficiency units sized for the actual load. Most induction motors that drive pumps reach peak efficiency when about 75 percent loaded, and they are less efficient when fully loaded. Thus, wherever possible, size pumps so that much of their operating time is spent at or close to their most efficient part-load factor. Plotting a pump's operating condition on the manufacturer's pump curve will quickly show whether the pump is a candidate for replacement. Replacing pumps that fall well out of the efficiency bull's-eye or that are severely inefficient (less than 60 percent) may offer a good payback. To estimate savings from replacing an inefficient pump, apply the same equations used to estimate the savings associated with removing pump outlet balancing valves (see the sidebar, "How Much Can You Save by Opening or Removing Pump Outlet Balancing Valves?").

Another option is to trim the pump impeller on a lathe. Trimming an impeller reduces a pump's flow, pressure, and energy consumption. The cost of trimming is relatively small and the process can yield an extremely rapid payback—often only a month or two—provided there's no cost for downtime. The best approach is to trim the impeller during scheduled downtime or when a spare pump is available. However, if the impeller is trimmed too much, you may then have to buy a new one—which adds some obvious risk to this tactic. Note that smaller impellers allow just a bit more water to leak internally from the pump outlet to the inlet. As a result, impeller trimming sometimes causes the loss of a couple of percentage points in pumping efficiency. However, the savings in pumping power should outweigh this efficiency loss.

Before trimming an impeller, estimate the savings from this measure. First, plot the results of

a shutoff pressure test on the pump curve to verify the impeller's size. To conduct a shutoff test, run the pump against a fully closed discharge valve (this test will not damage the pump if performed briefly, with the suction valve open). The pressure developed during the shutoff should fall on one of the family of impeller curves. If the point doesn't fall exactly on one of the curves, a new impeller line can be interpolated from the others. Second, measure the pressure gain across the pump under normal operation. Lastly, use the impeller size and measured pressure to find the pump's flow and efficiency on the pump curve. Once these parameters are known, you can determine whether you should trim the pump impeller or consider replacing the pump outright.

Vary chiller and condenser flow rates based on load by using variable-speed pumps.

Installing variable-speed drive (VSD) pumps and controls enables you to use strategies that vary water flow rates in conjunction with condenser- or chilled-water temperature resets. One strategy, called *variable primary flow*, is growing in popularity because it's more efficient, simpler, less expensive to implement, and less prone to problems than others. It uses a single set of VSD pumps to circulate water through the entire chilled-water loop, including the chillers and the cooling zones. This arrangement can save energy when conditions permit by running the pumps at lower speed to capture cube-law savings, even though it works the chiller harder to produce colder water. Reducing a motor's speed produces savings proportional to the cube of the reduction. Thus, reducing chilled-water flow by 20 percent can cut pumping power by almost half. Precautions must be taken, however, to maintain minimum flow rates through the chiller to avoid freezing the evaporator vessel.

Another option is to separate the functions of chilled-water production and chilled-water distribution by using a primary/secondary piping system. Although less efficient for many applications than a variable-primary-flow system, primary/secondary systems are particularly good where the distribution system is very large, such as for a large campus. This arrangement allows you to separate distribution flows from flows through the chillers (distribution flows are high pressure by necessity due to their length—30 to 100 or more feet water gauge [wg]—and flows through the chillers must be at lower pressures because of equipment limitations—10 to 25 feet wg).

The primary pumps serve the production side (the chiller) and are constant-flow, whereas the secondary pumps are variable-flow and capture most of the available pumping energy savings by reducing their speed at part-load conditions. A bypass pipe connects the primary and secondary circuits to compensate for any flow imbalances. However, failure to implement primary/secondary systems correctly can compromise both system capacity and efficiency, so

you should obtain professional design assistance to ensure the success of this retrofit.

COMPRESSOR

Upgrade the chiller compressor.

For a centrifugal compressor, install a variable-speed drive (VSD) in applications where the load drops below 90 percent for a significant number of hours each year. This will allow the chiller to run at lower speeds under part-load conditions, thereby yielding a higher efficiency than is typically achieved by ordinary centrifugal chillers that control part-load operation with inlet vanes. However, a VSD may not be cost-effective in applications where there are extended periods with very low loads (10 percent of full load). In these cases, consider installing a separate small chiller just for these loads.

For reciprocating and screw chillers, replace the existing compressor with the Turbocor, an oil-free, magnetic-bearing compressor. New chillers using the Turbocor compressor can achieve an integrated part-load value (IPLV) of 0.3699 kilowatts (kW) per ton, as compared with an IPLV of 0.6000 kW per ton for standard screw- and scroll-based chillers. Turbocor replacements can also produce significant savings in retrofit applications.

For example, at the San Diego East County Family Resource Center, a single 80-ton Turbocor compressor replaced two reciprocating compressors on an existing air-cooled chiller after one of the reciprocating compressors failed. Before-and-after monitoring showed an efficiency gain of 0.41 kW per ton. Even though cooling loads were relatively low—1,347 equivalent full-load cooling hours (a metric used to estimate annual energy use for cooling in a building)—and the chiller was oversized by about 30 tons, the compressor replacement still yielded an estimated simple payback period of 4.7 years and an ongoing energy savings of about $8,000 per year (with incentives from the San Diego Regional Energy Office, the payback was 2.8 years).

CHILLER SOFT START

For chillers without a variable-speed drive, use low-voltage soft starters.

The motor windings of constant-speed compressors experience great stress when the chiller is first started because of the high inrush of current. Over time this can lead to motor failure. Soft starting gradually raises the voltage and current to avoid the high inrush. Soft starting

itself does not save energy, but it does enable shutting off chillers that are otherwise left running because operators are concerned about wear and tear from frequent starts.

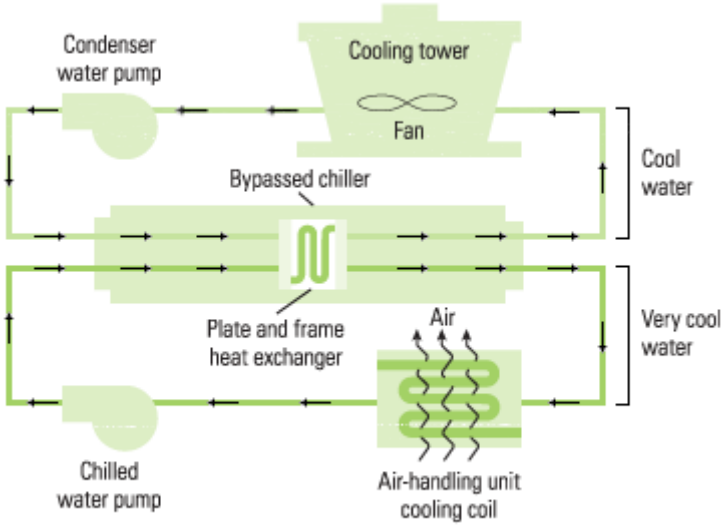
WATER-SIDE ECONOMIZERS

Install water-side economizers to allow cooling towers to produce chilled water when weather conditions permit.

Under the right conditions, water-side economizers can save a lot of energy. In cool, dry climates, they can provide more than 75 percent of the cooling requirements (in warm climates they may provide only 20 percent). The most common type is an indirect economizer that uses a separate heat exchanger, typically of the plate-and-frame type (**Figure 4**). It allows for a total bypass of the chiller, transferring heat directly from the chilled-water circuit to the condenser-water loop. When the wetbulb temperature is low enough, the chiller can be shut off and the cooling load may be served exclusively by the cooling tower. Typically, plate and frame heat exchangers are sized for about 50 percent of the load. However, sizing them for up to 100 percent of the load can extend their operating temperature range by 8° to 10° Fahrenheit in some climates for just the added cost of additional plates.

FIGURE 4: Maximize savings with an indirect water-side economizer

Inserting a heat exchanger between the cooling tower and air-handling unit enables the controls to bypass the chiller when outdoor temperatures are low enough.



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CHILLER REPLACEMENT

Replace an old or oversized standard-efficiency chiller with a properly sized high-efficiency water-cooled unit.

If the existing chiller is nearing the end of its life or is in need of substantial maintenance, consider retiring it early to capitalize on the savings that a new high-efficiency model can provide. The annual energy cost for operating a chiller can be as much as one-third of its purchase price, so even a modest improvement in efficiency can yield substantial savings and attractive paybacks.

For example, paying an extra $6.00 per ton for each 0.01 kilowatt per ton (kW/ton) improvement to raise the efficiency of a 500-ton chiller from 0.60 kW/ton to 0.56 kW/ton would increase that machine's first cost by $12,000. But it would also reduce operating costs by $3,000 per year, yielding a four-year simple payback (assuming 1,500 equivalent full-load hours and an average electricity price of $0.10 per kilowatt-hour, including demand).

If a decision is made to replace an existing chiller, select one that will be most efficient under the conditions it is likely to experience. Even though chiller performance can vary dramatically depending on loading and other conditions, designers frequently select chillers based on full-load, standard-condition efficiency. However, chillers spend most of their operating time at 40 to 70 percent load under conditions that are often considerably different from standard conditions.

To select the chiller that will have the lowest operating costs, determine what the actual operating conditions are likely to be and then consider how efficiently the unit will operate under those conditions. This can be particularly fruitful if the existing chiller is already oversized or if load reductions achieved by upgrading other building systems, such as swapping out inefficient lighting with high-efficiency equipment, allow the chiller to be downsized.

COOLING TOWERS

Install plumbing to connect multiple cooling towers or multicell towers in parallel and variable-speed drives to control cooling tower fans.

As outlined in the Operations section, this step allows the chiller plant to use excess cooling

tower capacity at part-load conditions and save fan energy. For applications with multiple same-size fan motors that are run simultaneously, one variable-speed drive sized for the total motor load can be used.

SYSTEM PERFORMANCE TRACKING

Set up a monitoring system to calculate and track component and system efficiency.

Building operators have achieved energy savings of 10 to 25 percent by using a monitoring system to measure, record, and analyze chilled-water system efficiency on an ongoing basis. By watching for changes or anomalies in trend log data, you can identify malfunctioning or inefficient equipment. For example, by monitoring the difference between refrigerant and water temperatures (the approach temperature), the control system can sound a warning when the condenser becomes fouled—allowing it to be cleaned in time to save downtime and energy.

Furthermore, monitoring systems can help you critically evaluate new operating strategies and identify those with the best overall efficiency. For example, monitoring can help to:

- Develop different cooling tower temperature setpoints to minimize the influence of cooling tower fan power on overall plant kilowatts per ton (kW/ton) while still maintaining excellent chiller efficiency.
- Alter the rate at which the chilled-water temperature setpoint can be reset depending on whether chiller load is increasing or decreasing at the time. This could reduce chiller cycling as well as energy waste from changing the setpoint too much, too quickly.
- Raise the allowable setpoint for chilled-water temperature during certain conditions to improve chiller efficiency. Although this could incur some penalty in pumping energy, on a net basis it could improve overall plant efficiency.

Most large cooling equipment sold since 2000 is under microprocessor control and is already sensing nearly all the information necessary to calculate chiller efficiency. If all the controls are from a single manufacturer or comply with a single communications protocol, then efficiency tracking should be highly cost-effective. If the controls cannot communicate, note that the cost of upgrading them to do so can vary widely—so the cost-effectiveness must be evaluated on a case-by-case basis.

An important decision for building operators is to determine which trend logs will be useful for tracking and improving efficiency. It pays to explicitly request the right trends early on and to work with the installing contractor to ensure that appropriate historical trends are set up when the system is first programmed. Once the contractor is off the job, it will usually be a hassle to get someone back to update the programming. Trend logs commonly used to optimize chiller plant efficiency include:

- Chiller kW/ton
- Ancillary system kW/ton
- Total chiller plant kW/ton
- Total chiller plant kW/ton versus load
- Total chiller plant kW/ton versus outside air temperature

These trend data can inform how to alter several parameters to achieve better system efficiency:

- Chilled-water supply temperature and flow rate
- Condenser-water temperature and flow rate
- Number and sequence of chillers in operation
- Cooling tower cells in operation
- Cooling tower fan speed

Note that to provide useful results, tracking sensors must be able to provide measurements of consistent accuracy over an extended period. Without this repeatability, it will be difficult to assess how plant efficiency may be changing over time—because it won't be possible to discern an actual change in efficiency from an inaccurate measurement. For this reason, specify sensors that provide both accuracy and repeatability. Fortunately, the two usually go hand in hand.

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