Upgrading Chilled-Water Systems

By Mick Schwedler, P.E., and **Beth Bakkum**

In today's challenging business climate, some building owners are delaying the implementation of new building projects and concentrating on making existing buildings and systems more efficient. Within an existing chilled-water system, there are several areas of opportunity to improve energy efficiency. This article concentrates on the areas within chilled-water systems that may yield energy savings.

Options are discussed for each of the following:

- Chiller retrofits;
- Changes to pumps and flow rate;
- Examining different chilled- and condenser-water temperatures; and
- Enhancing system controls.

Each topic is examined in more detail followed by *Table 3*, which provides guidance as to which modifications may be best for three chilled-water system types.

This article does not examine economic payback; a detailed energy analysis is the best method of comparing system options and their respective economic impact *for each project*. See the sidebar, "System Analysis," for more information. In addition, Chapter 36 (Owning and Operating Costs) of the *2007 ASHRAE Handbook—HVAC Applications*, provides further information.

Chiller Retrofits

Adding a Variable Speed Drive

Variable speed drives (VSDs) can be retrofitted onto centrifugal chillers and provide energy savings if the conditions are right. It is important to understand when conditions may (or may not) warrant a VSD retrofit.

Figure 1 shows the performance of a centrifugal chiller before and after being retrofitted with a variable speed drive. It depicts chiller performance at load points between 20% and 100% for three different entering condenser-water temperatures. The results clearly show that the drive does not result in reduction of chiller

About the Authors

Mick Schwedler, P.E., is applications engineering manager for Trane, a division of Ingersoll Rand in La Crosse, Wis. Schwedler is chair of SSPC 90.1 and is a member of the Energy & Atmosphere Technical Advisory Group of the U.S. Green Building Council. **Beth Bakkum** is an information designer at Trane.

Is Drive Replacement Beneficial and Economical?	
What is the utility rate? Does it have a ratchet clause?	Since a VSD adds inefficiency, at design conditions there could be an increased demand charge for which that inefficiency incurs a significant cost penalty. On the other hand, if the chiller is oversized, the demand may be lower after a drive retrofit.
How often will the chiller operate at the reduced load and reduced condenser-water temperatures?	If the facility operates 24/7, even if the design day is hot and humid, there may be benefits due to reduced ambient wet-bulb temperatures during the fall and winter months. If the system has an economizer, many of the low-load hours with low condenser-water temperatures are eliminated since no mechanical cooling is required. In examining *Figure 1*, many of the low-load hours on the bottom two lines may well occur at times an economizer eliminates the mechanical cooling load.
How much energy is consumed by the cooling tower fans to achieve reduced tower setpoint?	This energy use may be significant and must be included in a system analysis.
Is the chiller oversized for the present load?	If so, the load reduction in conjunction with reduced condenser-water temperatures may offer significant savings.

***Table 1:** It is important to understand when conditions may (or may not) warrant a VSD retrofit.*

energy use if the tower temperature remains close to design. This could occur in a climate that is consistently hot and humid or when surface or groundwater is used in the condenser. At almost all load conditions—as long as reduced condenser-water temperature (lift) is available—there are chiller energy savings.

For example, if the entering condenser-water temperature is 65°F (18°F), the chiller savings range from 8% to 32%, depending on load. This does not include cooling tower fan energy to reach the lower setpoint.

Is the drive replacement beneficial and economical? That depends on the answers to the questions in *Table 1*.

Of course, not every chiller will perform similarly to *Figure 1* when retrofitted with a variable speed drive. Different chiller designs can benefit more or less than shown in *Figure 1*. It is critical to have performance data before and after the VSD retrofit. This allows the project team to make a decision for the specific chiller, location, and application.

Whether or not one should retrofit every chiller with a drive is primarily an economic question. Often applying a drive to one chiller in the system yields the best payback. Purchasing multiple drives is sometimes driven by the desire to "equalize run-time" on all chillers. A possible outcome of this operating philosophy is that all chillers must be rebuilt or replaced at approximately the same time.

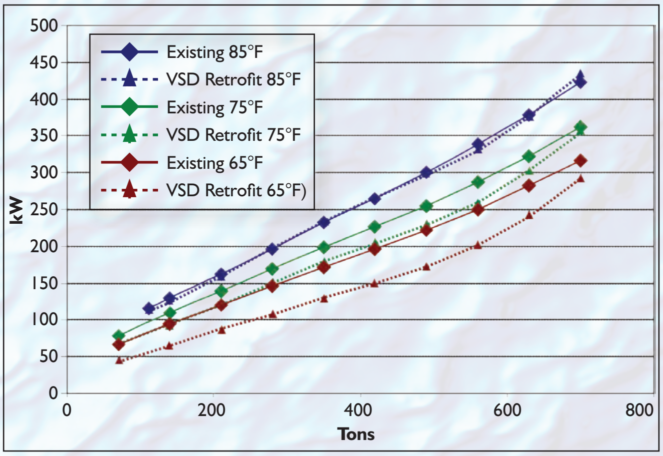

***Figure 1:** Centrifugal chiller performance before and after VSD retrofit.*

System Analysis

When considering a retrofit, properly analyzing factors that affect the economic viability of that retrofit is critical. To calculate chiller and system efficiency, ARI 550/590-2003,[1] *Appendix D*, recommends conducting a comprehensive analysis that includes actual weather data, building load characteristics, operational hours, economizer capabilities, and energy drawn by auxiliaries (cooling towers, pumps, etc.).

Considering all of these factors and the complex interactions of weather, loads, and cooling tower performance, a bin analysis is not adequate. Software tools that incorporate all of the above attributes can be used to perform a robust chilled water plant analysis in 30 to 60 minutes. In addition, the actual utility rates, not a "weighted average," and chilled-water system-level controls also should be modeled.

A comprehensive analysis enables the project team, operators, and building owner to make accurate comparisons of multiple options.

Others point out that if one chiller with a VSD is being serviced, another equipped with a VSD can operate and accrue savings. While true, the question is whether or not the savings from a short period of operating time are worth the investment. (Refer to "Number of Chillers Operating" section for more information.)

Replacing a Chiller

In cases where the present chiller operates at 0.8, 0.9, or perhaps even more than 1.0 kW/ton, replacing the chiller with one complying with the Standard 90.1-2007 requirements results in substantial demand and energy reductions. In locations with significant demand charges, the on-peak cost reductions may yield economic benefit well within the owner's cost criteria.

Replacement capacity is another important issue. Do not simply replace an existing chiller with a new chiller of the same capacity. Prior to purchasing a replacement chiller, determine the actual load the chiller must satisfy; a smaller chiller may be warranted. In many buildings, other retrofits—such as lighting systems—have already occurred. While personal computers add load, their contribution to cooling load is often overstated.[2] If data is available from an energy management system, it may be used to properly size the replacement chiller. An oversized chiller costs the customer more and may use more energy.

High Efficiency or VSD. If retrofitting a chiller with a VSD is a good opportunity (following the analysis done earlier), might it also be wise to replace a constant-speed chiller with a variable speed chiller? Perhaps, but not necessarily. Since the correct choice is dependent on economics, perform a comparison between a variable-speed-drive chiller that meets Standard 90.1-2007[3] requirements and a high-efficiency constant-speed chiller that is *equally priced*. Whichever option provides better payback using a comprehensive analysis (remember to include demand charges) is a better choice for the building owner.

Applying VSDs Properly controlled variable speed drives retrofitted to existing pumps or cooling tower fans can save energy. However, take care when applying a variable speed drive to an existing motor. Lindhorst[10] discusses the importance of motor and drive compatibility. Improper application may result in winding stresses and bearing failures. Consult the drive and motor providers to ensure compatibility. If not compatible, the motor may need to be replaced.

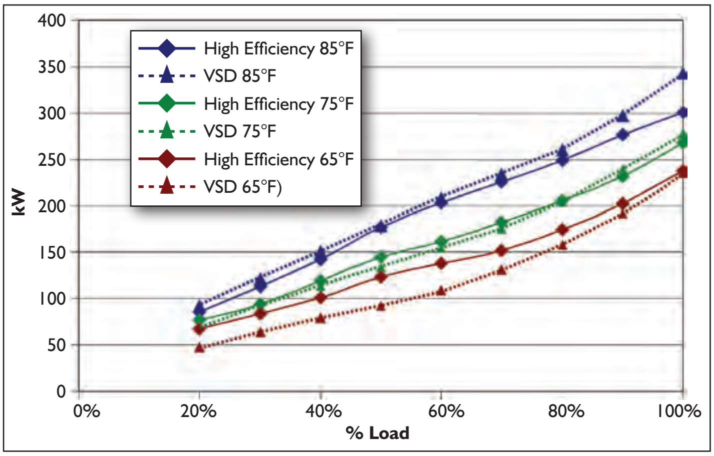

Figure 2: VSD chiller versus same price high-efficiency chiller.

Figure 2 presents the results of selecting a smaller chiller (assuming cooling load has been reduced due to lighting retrofits) and compares the performance of a 600 ton high-efficiency chiller with an equally priced VSD chiller that meets Standard 90.1-2007 requirements at ARI 550/590 standard rating conditions. Note that Standard 90.1 requires both full and part load requirements to be met, and drive losses are included in the rating.

Present Standard 90.1 requirements:

- 0.576 kW/ton full load and 0.549 integrated part load value (IPLV).

Standard 90.1 requirements as of Jan. 1, 2010 (from Standard 90.1-2007 Addendum *m*):

- Either 0.570 kW/ton full load and 0.539 IPLV; or
- 0.590 kW/ton full load and 0.400 IPLV.

An example of same price chillers at ARI 550/590 standard rating conditions gives the following performance:

- VSD: 0.572 kW/ton full load and 0.357 IPLV; and
- High Efficiency: 0.501 kW/ton full load and 0.430 IPLV.

Once again it is obvious that energy savings are accrued by using a VSD on a chiller when cooler tower-water temperature is available, that is, the refrigerant pressure differential or "lift" is reduced. This makes sense since the drive speed cannot reduce without causing the chiller to surge, unless the required compressor lift is reduced.

Given the previous information, a comprehensive analysis may show that one high-efficiency and one VSD chiller provide the best payback. In a humid environment where there are fewer hours with low tower-water temperature (such as San Juan, Puerto Rico, or Houston) two high-efficiency chillers may offer the best payback. This is true particularly when the maintenance and life-cycle replacement cost of the VSD is factored into the analysis. This again underscores the importance of performing a comprehensive analysis.

Design Parameters

When asked to retrofit a chilled-water-system, project teams often use the same design chilled-water and condenser-water flow rates and temperature differences. This is not likely to produce optimal results. Instead, judicious use of existing infrastructure—and using different flow rates and temperature differences—offers significant benefits to the building owner. The chilled-water options apply to air-cooled and water-cooled chillers.

Reducing Chilled-Water Flow Rate, Expanding ΔT

The *ASHRAE GreenGuide*[4] references the *CoolTools Chilled Water Plant Design and Specification Guide*[5] and recommends "starting with a chilled-water temperature difference of 12°F to 20°F (7°C to 11°C)." While primarily intended for new systems, this guidance can be used for many existing systems.

Reducing Pumping Energy. Significant pump savings can be realized by reducing flow rates, especially in constant-flow chilled-water systems. This may be achieved by making those flow rates variable or by developing a reduced flow rate at all times by resetting the chilled-water setpoint temperature *downward*. Hanson, et al.,[6] state:

> *A coil is a simple heat exchanger. To deliver the same sensible and latent capacity when supplied with colder water, the coil's controls respond by reducing the flow rate of the water passing through it. Because the amount of water decreases while the amount of heat exchanged remains constant, the leaving water temperature increases. Thus, by supplying colder water to the coils, a low-flow system can be applied to an existing building. In a retrofit application, it is wise to reselect the coil, using the manufacturer's selection program, at a new chilled-water temperature to ensure its performance meets the requirements.*
>
> *One possible concern of low supply-water temperatures is the ability of the valve to control flow properly at low-load conditions. A properly sized valve with good range can work well in low-flow systems. In existing systems, valves may need to be replaced if they cannot operate with the new range of flows, but the coils do not need to be replaced.*

Hanson[6] provides an example that shows that decreasing the chilled water temperature by 4°F (2.2°C) allows the existing coil to "deliver the same cooling capacity with 36% less flow, at less than half of the fluid pressure drop, with no impact on the airside system." Although the chiller uses more energy, such pump savings can significantly reduce system operating cost and should be analyzed. Centrifugal chillers should be checked to ensure they can operate at the increased compressor lift without experiencing surge.

Increasing System Capacity Using Existing Infrastructure

Increasing System Capacity Using Existing Chilled-Water Pumps and Pipes. Instead of using lower chilled-water temperature to reduce flow rate and pump energy, colder chilled-water can be used to increase the capacity of the chilled-water system while re-using the existing infrastructure (chilled-water pumps and pipes). Since the existing coil uses 36% less flow when supplied with a lower water temperature, the existing pump can be used to provide chilled water for new air handlers that are part of a building expansion. If the chiller is being replaced, the new chiller can be selected to provide 40% to 60% additional system cooling capacity using this concept.

Increasing System Capacity Using Existing Towers and Condenser-Water Pumps and Pipes. When increased cooling capacity is needed and the chiller is being replaced, judicious use of existing infrastructure is a powerful retrofit tool. Schwedler and Bradley show that the "existing cooling tower, condenser water pipes,[8] and condenser water pump can deliver at least 50% more

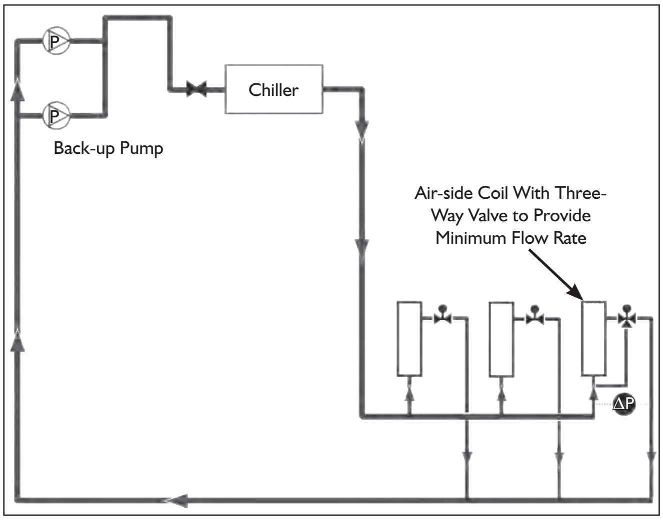

Figure 3: Variable primary flow (VPF) system using three-way valves to ensure chiller minimum flow rate.

cooling capacity." This is done by selecting the existing tower and new chiller at higher temperatures (e.g., 88°F to 103°F [31°C to39°C], rather than 85°F to 95°F [29°C to 35°C]). Using this concept may well bring an "over-budget" job back into budget.

Variable Flow Considerations

Converting Constant-Flow Systems to Variable Flow

It may be beneficial to convert a constant-flow system to variable flow. Generally, the most economical way to do so is by using the variable primary flow (VPF) concept, since a VSD can be applied to the pump (provided the pump and drive are compatible). This article only addresses a few issues with respect to applying VPF to existing systems. See the references for more information.[9,13,18]

While there are many issues that should be considered, three are paramount with respect to the chiller:

- Confirm with the chiller manufacturer that the existing unit controls can tolerate variable evaporator flow. If not, consider a control retrofit.
- Provide system hardware and controls that keep the evaporator flow rate between the minimum and maximum allowed by the manufacturer.
- Ensure that system flow rate *changes* are below the threshold allowed by the manufacturer.

Many new VPF applications provide flow-sensing devices, and a separate bypass line with a control valve to maintain the chiller's minimum flow rate. In an existing plant, minimum flow can instead be maintained by using an adequate number of three-way valves to ensure that the chiller's minimum required evaporator flow rate is always met. In *Figure 3,* this simple approach reduces pumping costs while providing the chiller with enough chilled water, and it's simple in retrofit applications whether there is a single chiller or multiple chillers, since the three-way valves are part of the existing infrastructure.

Be careful applying VPF to an existing system with chillers differing in size, or chillers with differing evaporator pressure drops. Flow variations may cause operational issues, and sequencing and loading of chillers can be especially challenging.

Variable Condenser Water Flow. Some project teams consider varying condenser water flow to reduce system energy use. This concept has been successfully implemented, but is not in widespread use today. The difficulty is that varying condenser-water flow results in chiller and cooling tower performance changes—and those changes are in opposite directions; that is a reduction in cooling tower energy and condenser water pumping energy results in increased chiller power since the leaving condenser water temperature and condenser refrigerant pressure both rise. So, implementation is difficult. While several articles address varying flow rate through the condenser and across the cooling tower, few give specific implementation guidance. Baker, et al.,[11] provide a method to vary condenser water flow rate that has been successfully implemented on a number of projects.

Converting P-S Systems to Variable Primary Flow

Variable primary flow is becoming a popular choice for new systems, often due to reduced installed costs. Some system owners also consider converting their existing primary-secondary (P-S) systems to VPF. The operational savings are related primarily to pump energy, but the savings are not large in most cases. As Taylor[13] points out, there may be an advantage to "over-pumping" chillers to allow them to more fully load. "Over-pumping" chillers is also possible in many primary-secondary systems with manifolded primary pumps. By operating more pumps than chillers, the flow rate through chillers rises, allowing the P-S system to "over-pump" chillers.

To convert existing P-S systems to VPF, the following are just some of the changes that occur:

- Primary (chiller) pumps are removed.
- Distribution (secondary) pumps and/or the bypass line are re-piped to send water through the chillers.
- The distribution pumps must now overcome the additional pressure drop through the chiller evaporators. If the original distribution pumps were oversized, they may have enough excess head capacity to meet the new requirements. If not, they must be replaced.
- The bypass line may need to be resized, since the bypass in a primary-secondary system is much larger than the pipe needed to provide chiller minimum flow rate in a VPF system. Also, the valve installed in the smaller bypass line offers better control.
- Flow measurement devices must be added.

Given the significant cost required to make these changes, and minimal advantages, conversion of a well-operating primary-secondary system to a VPF system may not provide the economic payback a building owner desires.

Controls

Many chilled-water systems are operated manually. A well-engineered and commissioned chilled-water system controller allows proper sequencing, monitoring, and response to system diagnostic issues. Library routines available from a number of control providers can be customized for the specific plant with help from the present operators. While savings are hard to quantify, automated chiller plant control frees building personnel to work on other building components or tasks. However, there are control options that save energy and operating cost.

Number of Chillers Operating

An oft-asked question is whether it is more efficient to operate two chillers at a lower load or a single chiller at a higher load. This is likely in response to data supplied by all chiller manufacturers based on ARI 550/590-2003.[1]

Table 2 shows full and part load data used to calculate integrated part load value for the 600-ton (2110 k/W) chiller at standard rating conditions. Often people compare the 100% load 0.572 kW/ton to the 50% load 0.308 kW/ton. At first glance, the chiller operating at 50% load seems almost twice as efficient as it is when operating at 100% load. However, these ratings are also at two different entering condenser-water temperatures (ECWT), making this an invalid comparison.

As discussed in the "Chiller Retrofit" section, a VSD reduces chiller energy when compressor "lift" is reduced. During actual chiller operation, the cooling towers provide the same water temperature. Therefore, a valid evaluation must compare chiller kW *at the same ECWT*, whether one chiller is operating at 100% load, or two chillers are operating at 50% load.

So when is it beneficial to operate more than one chiller? *Figure 4* depicts a two-chiller plant with equally sized chillers.

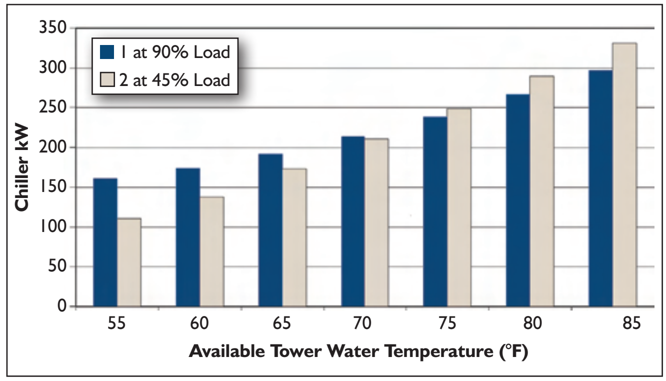

Figure 4: Chiller only kW at 45% plant load. (Operate one or two chillers?)

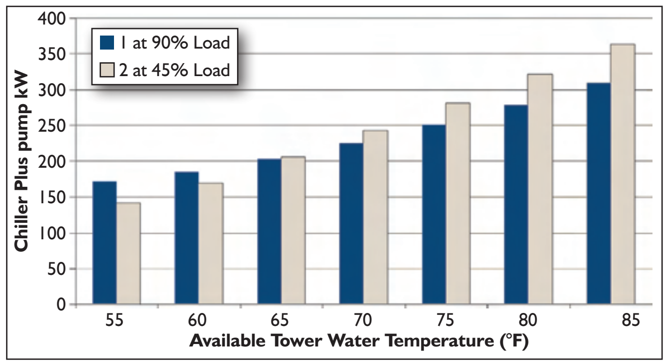

Figure 5: Chiller plus pump kW at 45% system load. (Operate one or two chillers?)

Load	Weighting	ECWT	kW/Ton
100%	0.01	85°F	0.572
75%	0.42	75°F	0.420
50%	0.45	65°F	0.308
25%	0.12	65°F	0.372

VSDs improve with part lift performance so running two chillers with VSDs at part load seems more efficient than one chiller at double the same load, but they are at different condenser water temperatures.

Table 2: A closer look at IPLV (VSDs and centrifugal chillers.)

In this example, a VSD is supplied for both chillers. As previously discussed, this may not be the best economic choice.

Above 50% plant load, both chillers must operate, so the decision to operate one or two chillers is valid only below 50% *plant* load. *Figure 4* shows chiller-only kW at 45% plant load, when the options are to operate a single chiller at 90% load or two chillers at 45% load each. If only chiller power is considered, operating two chillers does not reduce overall chiller kW unless tower-water temperature is 70°F (21°C) or below.

When the pump power required to move water through the evaporator and condenser is considered (*Figure 5*, Page 26), operating two chillers rather than one is not beneficial until the tower-water temperature is less than 65°F (18°C). (Pump operation is VPF for the chilled-water system, and a constant speed condenser-water pump for each operating chiller.)

The benefit of a VSD chiller depends significantly on the cooling-tower-water temperature available. What happens at different load points? For example, Taylor provided guidance that running two VFD chillers is more efficient up to 35% plant load, but this did not examine the effect of varying tower-water temperature at different plant loads.

Figure 6 shows that at almost all system load and tower-water temperature points, operating only one chiller is beneficial. From this we observe that:

- At 45% plant load: operate one chiller until tower temperature below 65°F (18°C) is available;
- At 40% plant load: operate one chiller until tower temperature below 60°F (16°C) is available; and
- Below 35% plant load: operate one chiller, as Taylor[12,13] states.

Given this information, it appears that operating two VSD chillers is seldom beneficial. As discussed previously, a better option may be to choose a "same price" high-efficiency chiller rather than a second VSD chiller.

Chiller-Tower Optimization

Operating at the real-time optimal cooling tower setpoint has been shown

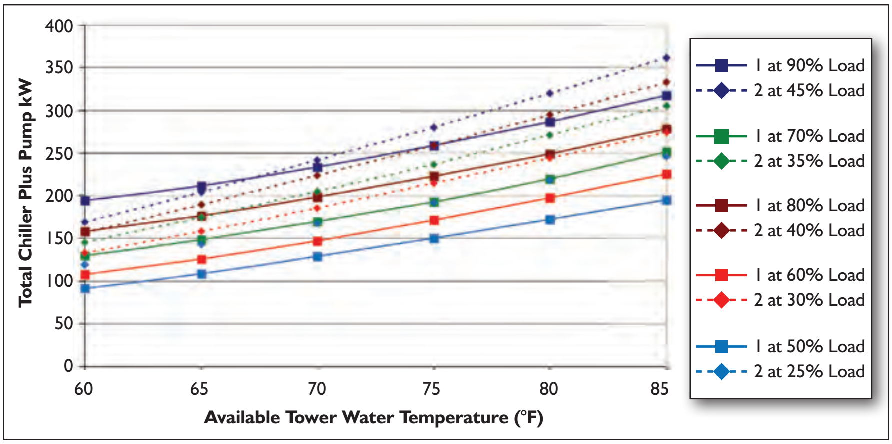

***Figure 6:** Performance comparison. (Operate one or two chillers?)*

Options for Upgrading Chilled Water Systems

	Small Constant Flow Air Cooled	**Large** Vintage, Constant Flow Water Cooled	**Primary Secondary** Water Cooled
Chiller			
VSD Retrofit	N/A	Likely	Likely
Replacement			
High Efficiency	Likely	Likely	Likely
VSD	N/A	Likely	Likely
Design Parameters			
Chilled Water			
Reduce Chilled-Water Flow	Likely	Likely	Likely
By Reducing Pumping Energy	Likely	Likely	Likely
By Increasing System Capacity Using Existing Infrastructure	Likely	Likely	Likely
Condenser Water			
Increase System Capacity Using Existing Infrastructure	Likely	Likely	Likely
Variable Flow			
Convert to Variable Primary Flow (VPF)	Likely	Likely	Unlikely
Variable Condenser Water Flow	N/A	Perhaps	Perhaps
Controls			
Chiller Plant Control	Perhaps	Yes	Yes
Operate Fewer Chillers	Yes	Likely	Likely
Chiller-Tower Optimization	N/A	Yes	Yes
Chilled-Water Reset	Likely Reset Upward	Likely Reset Downward	Likely Reset Downward
Pump Pressure Optimization	Yes	Yes	Yes

***Table 3:** Guidance for three chilled-water systems.*

to decrease the overall system energy use. Papers and articles by Braun and Diderrich; Cascia; Crowther and Furlong; and Schwedler[14,15,16,17] discuss cooling tower setpoint control. Crowther and Furlong[16] estimate that when compared with a 65°F (18°C) constant cooling tower setpoint baseline, chiller-tower optimal control of variable speed drives on cooling tower fans results in the following chilled-water plant savings for an office building:

- Chicago: 6.3%
- Las Vegas: 4.7%
- Miami: 8.0%

As shown by Schwedler,[17] requirements for determining real-time optimal cooling tower setpoint include a variable speed drive on the cooling tower fan, sensors (possibly including an outdoor humidity sensor), and a control system.

Chilled-Water Reset

In small, constant-flow chilled-water systems, appropriate *upward* chilled-water reset reduces chiller energy. Consider humidity sensing in a critical space(s) to ensure the chilled-water reset does not cause moisture issues. Alternately, examination of reducing the design flow rate through use of a colder chilled-water setpoint is warranted.

In variable-flow plants, resetting of chilled-water temperature *downward* may decrease water flow rate and pump energy, and more than offset the additional chiller energy. See the "Reducing Chilled-Water Flow Rate" section for more information.

Pump Pressure Optimization

Fan pressure optimization is a staple of variable air volume (VAV) systems and has been required by Standard 90.1 since 1999 on communicating direct digital control (DDC) VAV systems. The fan static pressure setpoint is reset to maintain the "most open damper" at a position that minimizes system energy use (e.g., between 65% and 75% open). This significantly reduces fan operating energy. The same concept is being applied to pumping systems using the position from DDC water valves to reset pump static pressure. Standard 90.1-2007 Addendum *ak*, which will be part of Standard 90.1-2010, requires pump pressure optimization on many variable-flow chilled-water systems with DDC valves. The foreword of Addendum *ak* states:

> *Resetting the pressure setpoint can save a significant portion of annual pumping energy. It will also save chiller energy because of the reduction in pump heat going into the chilled water. No additional hardware is required to implement temperature and pressure setpoint reset in a DDC system. Some additional control programming and commissioning is required. Furthermore, the cost to implement the resets will go down over time as engineers and contractors gain experience and controls manufacturers improve their products.*

Dealing With Low ΔT

This article concentrates on the chilled-water system and does not discuss the impact of the air handler or coils on the chilled-water system. However, as Taylor points out, low ΔT can cause significant chilled-water plant operating issues and increased energy use. Taylor[12] separates issues into three categories.

Three Reasons Why Plants Operate Badly

- Causes that can be avoided;
- Causes that can be resolved, and once resolved, may result in overall operating savings; and
- Causes that cannot be avoided (but may be mitigated).

Clearly, causes that can be avoided should be avoided.

Solving Operations Problems

- Providing proper setpoints and controls calibration;
- Eliminating use of unnecessary three-way valves;
- If retrofitting air handlers, select coils properly;
- Properly selecting control valves (changing if necessary);
- Ensuring coils are piped properly;
- If tertiary pumps are used, making sure they are properly piped and controlled; and
- Controlling process loads.

Especially if there are only a few air handlers, time taken to mitigate low ΔT can significantly increase the chilled-water plant efficiency.

Application of Options

Not all options should be considered for all applications. *Table 3* gives general guidance about which of the opportunities discussed previously may be advantageous given the costs and benefits. Since installations differ, the options are summarized for three general categories of plant size and type:

- Small, constant-flow, air-cooled, chilled-water systems;
- "Vintage" large, water-cooled, chilled-water plants that are constant flow and water-cooled; and
- Primary-secondary systems: either air- or water-cooled.

Gradations used are:

- Yes: Very likely to reap benefits;
- Likely: Consider this because it's likely to reap benefits;
- Perhaps: May or may not reap benefits;
- Unlikely: Unlikely to reap benefits; and
- N/A: Not applicable.

There are always exceptions to the guidance in *Table 3*. After performing a comprehensive analysis, system designers, operators, and owners may find that on a specific job, the application of a strategy listed as "unlikely" saves energy in their particular application.

Summary

It is clear that a significant number of opportunities are available in existing chilled-water systems, including chiller retrofit or replacement, examining design parameters, considering variable flow, and implementing control strategies. Whichever options are considered, remember to examine them using a "comprehensive analysis" that takes into account simultaneous loads, detailed utility rates, weather, operational parameters, and all the ancillary equipment. Always remember that "the meter is on the system" and compare system, not component energy use. Tools are available that allow this analysis to be performed in 30 to 60 minutes. By taking advantage of those tools, the owner is provided with better information to make a good decision.

References

1. Air-Conditioning, Heating and Refrigeration Institute. ARI Standard 550/590-2003, *Performance Rating of Water-Chilling Packages Using the Vapor Compression Cycle.*

2. Komor, P. 1996. "Cooling Demands from Office Equipment and Other Plug Loads: Less Than One Watt per Square Foot." *ESOURCE*, TU-96-9.

3. ANSI/ASHRAE/IESNA Standard 90.1-2007, *Energy Standard for Buildings Except Low-Rise Residential Buildings.*

4. ASHRAE. 2006. *ASHRAE GreenGuide: The Design, Construction, and Operation of Sustainable Buildings*. 2nd ed.

5. Taylor, et al. 2000. *CoolTools Chilled Water Plant Design and Specification Guide*. Lawrence Berkeley National Laboratory and Pacific Gas & Electric Company.

6. Hanson, S., M. Schwedler and B. Bakkum. 2009. Chiller System Design and Control. Applications Engineering Manual. Trane.

7. Schwedler, M. and B. Bradley. 1995. "Tower water temperature—control it how???" *Engineers Newsletter* 24(1). Trane.

8. Schwedler, M., and B. Bradley. 2001. "Uncover the hidden assets in your condenser water system." *HPAC Engineering* (11):68 – 75.

9. Schwedler, M. and B. Bradley. 2002. "Variable-Primary-Flow Systems Revisited." *Engineers Newsletter* 30(4). Trane.

10. Lindhorst, P. 1998. "Motor and drive compatibility: A Must." *Electrical Construction & Maintenance*. http://ecmweb.com/mag/electric_motor_drive_compatibility/.

11. Baker, M., D. Roe, M. Schwedler. 2006. "Prescription for chiller plants." *ASHRAE Journal* 48(6):H4 – H10.

12. Taylor, S.T. 2002. "Degrading chilled water plant Delta-T: causes and mitigation." *ASHRAE Transactions*. (1):641 – 653.

13. Taylor, S.T. 2002. "Primary-only vs. primary-secondary variable flow systems." *ASHRAE Journal* 44(2):25 – 29.

14. Braun, J.E., G.T. Diderrich. 1990. "Near optimal control of cooling towers for chilled water systems." *ASHRAE Transactions* 96(2):806 – 813.

15. Cascia, M. 2000. "Implementation of a near-optimal global set point control method in a DDC controller." *ASHRAE Transactions* 106(1):249 – 263.

16. Crowther, H., J. Furlong. 2004. "Optimizing chillers & towers." *ASHRAE Journal* 46(7):34 – 40.

17. Schwedler, M. 1998. "Take it to the Limit…Or Just Halfway?" *ASHRAE Journal* 40(7):32 – 39.

18. Waltz, J.P. 1997. "Don't ignore variable flow." *Contracting Business* (7):133 – 144.