Real Efficiencies of Central Plants

Actual wire-to-water efficiencies of six common central-plant types

By **BEN ERPELDING, PE, CEM**
San Diego Regional Energy Office
San Diego, Calif.

Far too often, claims of central-plant performance are based on projections, with very little actual "pre-" or "post-" documentation. The result tends to be that actual efficiency is considerably less than what designers and operators believe it to be.

This article will discuss ongoing studies of chilled-water plants in Southern California. The wire-to-water efficiency (kilowatts per ton) of six common central-plant types—air-cooled chiller, thermal-energy storage, large campus, hybrid, variable speed with screw chillers, and ultraefficient all variable speed with oil-less compressors—was measured on typical operating days throughout the year, taking into account all chillers, chilled-water distribution pumps, condenser pumps, and tower/condenser fans.[1] The data support an obvious, but very bold, statement: If captured, the energy being wasted by our existing-building stock could meet expected near-term electrical growth in many service areas.[2]

EFFICIENCY EXPECTATIONS

To compare the performance of central plants, excluding air-cooled-chiller plants and water-cooled plants less than 300 tons, the energy-use spectrum shown in Figure 1 was adopted. For smaller water-cooled plants, a factor of 0.1 kw per ton is added. For air-cooled systems, a factor of 0.35 kw per ton is added.

AIR-COOLED-CHILLER PLANT

A central plant serving 58,900 sq ft of hospital space and consisting of two 88-ton air-cooled chillers (two 50-hp semihermetic compressors in each unit) and three 7.5-hp constant-speed primary-only distribution pumps provides chilled water to seven air handlers with three-way pneumatic valves. The HVAC systems were installed in 1996. Figures 2 and 3 show performance data from the central plant, as well as operating conditions, on two selected days.

Problems and issues: This chiller plant aver-

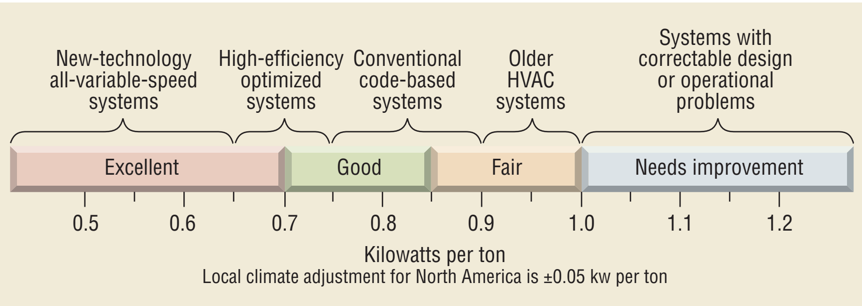

FIGURE 1. Average annual chiller-plant efficiency.

A member of HPAC Engineering*'s Editorial Advisory Board, Ben Erpelding, PE, CEM, is engineering manager for the San Diego Regional Energy Office* (www.sdenergy.org)*, a state-funded non-profit organization promoting energy efficiency. Over the last six years, he has performed more than 300 central-plant energy assessments, detailed measurement and verification analyses, and energy simulations. He can be contacted at* ben.erpelding@sdenergy.org.

Maximum dry bulb	Minimum dry bulb	Chilled-water supply	Maximum tons	Minimum tons	Average kilowatts per ton
67°F, 52% RH	58°F, 72% RH	50 to 51°F	35.7	0	1.9

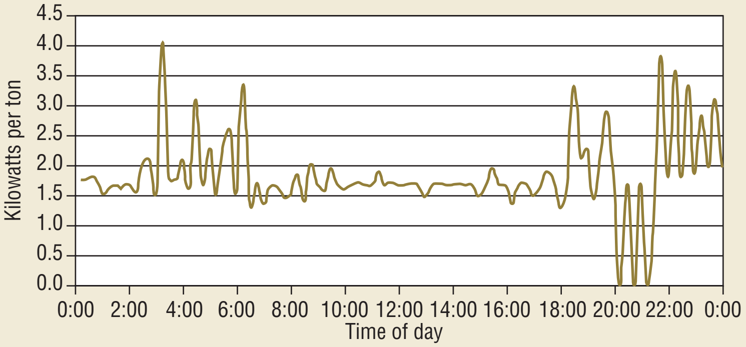

FIGURE 2. Wire-to-water total plant efficiency on Saturday, May 7, 2005.

ages 1.5 kw per ton annually. An inefficient chiller technology, along with constant-speed equipment, is employed with three-way valves at the air handlers. The pneumatic controls are limited to lead/lag chiller sequencing and outside-air lockout (less than 58°F). Efficiency is greatly reduced at lower loads because capacity control is limited to unloaders, cycling compressors, and on/off control of condenser fans. The kilowatt-per-ton spikes (in figures 2 and 3) occur when compressors are cycling on and off and delta-T swings between a low of 1.8°F and a high of 5.2°F.

THERMAL-ENERGY-STORAGE PLANT

An air-cooled ice thermal-energy-storage (TES) plant consists of a 300-ton air-cooled screw chiller; 26 TES tanks; a 20-hp, constant-speed glycol pump; a plate-and-frame heat exchanger; and two 40-hp, constant-speed chilled-water-distribution pumps. Figures 4 and 5 show "charge" and "discharge" performance, respectively, on consecutive days in August 2006.

The system charged the tanks at 2.20 kw per ton (506 ton-hr using 1,115 kwh). The next day, the system discharged at 0.582 kw per ton (426 ton-hr at 248 kwh). Simple math shows

Maximum dry bulb	Minimum dry bulb	Chilled-water supply	Maximum tons	Minimum tons	Average kilowatts per ton
76°F, 66% RH	69°F, 78% RH	48 to 52°F	91.2	30.6	1.4

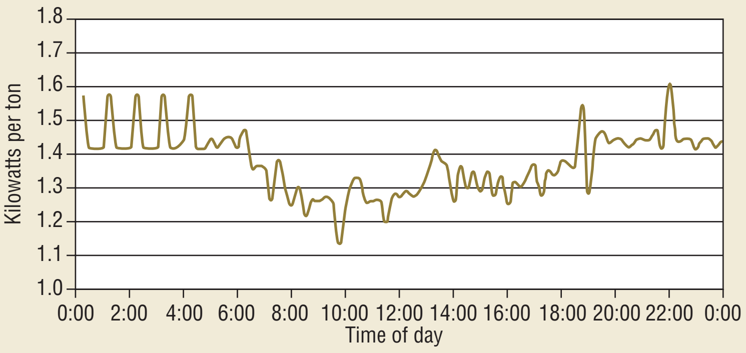

FIGURE 3. Wire-to-water total plant efficiency on Wednesday, July 27, 2005.

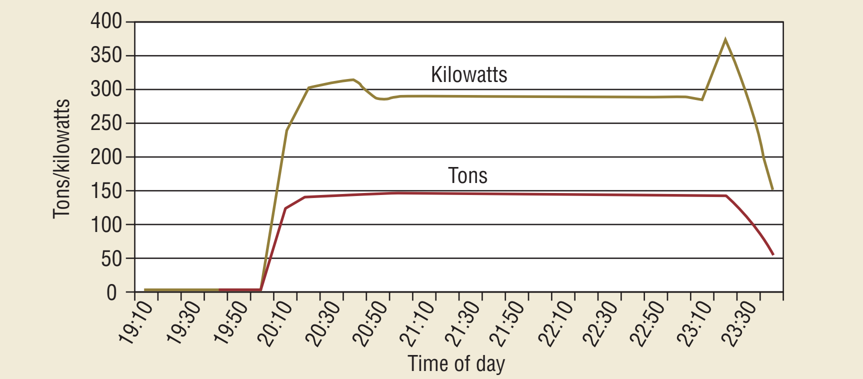

FIGURE 4. TES "charging" tons and power vs. time of day—Monday, Aug. 14, 2006.

that the system efficiency of the usable energy is about 3.20 kw per ton (426 ton-hr at 1,363 kwh). The daytime high on Aug. 15 was 84.2°F, while the previous nighttime low was 62.4°F.

Problems and issues: Although the system is designed to charge the ice tanks with a 25°F water/glycol mixture, only 32°F to 35°F water/glycol is produced. Ice does not built up; rather, the tanks provide chilled-water storage, with only sensible energy available. This explains the low ton-hour capacity of the system and why facility engineers say that for every hour they charge, they get only 35 to 45 min of usable discharge.

Additionally:

- Time-of-use scheduling is not followed closely by building operators.
- There are clear signs (water/glycol leakage) the system is at the end of its useful life.
- Although the air-cooled chiller operates more efficiently at night (i.e., amid lower dry-bulb temperatures), the required lift is considerable because of the low water/glycol temperature.
- Through serious installation error, the chiller plant is served by a separate utility meter. This results in a separate demand charge for the plant and makes capturing the full benefit of TES—even if the plant were operating efficiently—impossible.

LARGE-CAMPUS CENTRAL PLANT

A primary-secondary-tertiary chilled-water plant designed for 3,200 tons (four 800-ton chillers) of available capacity at a 16°F delta-T serves

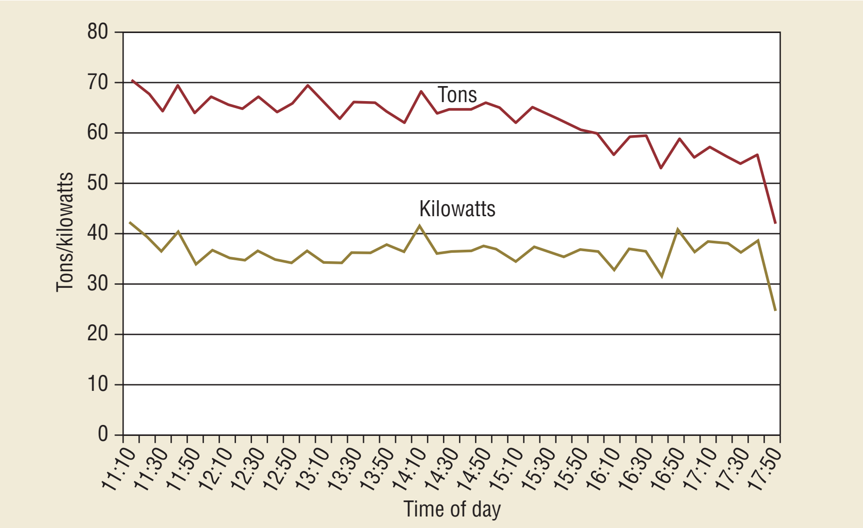

FIGURE 5. TES "discharge" tons and power vs. time of day—Tuesday, Aug. 15, 2006.

Maximum dry bulb	Minimum dry bulb	Chilled-water supply	Maximum tons	Minimum tons	Average kilowatts per ton
82°F, 51% RH	69°F, 78% RH	44 to 48°F	2,178	1,409	0.66

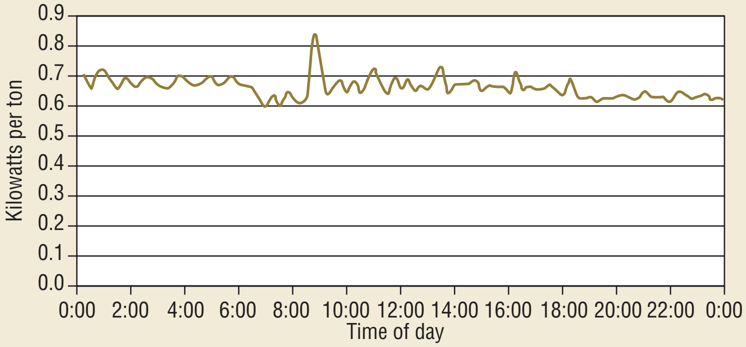

FIGURE 6. Wire-to-water total plant efficiency on Monday, June 26, 2006.

more than 787,000 sq ft of office and public spaces (all variable-air-volume air-handling units). The three 4,160-v "lag" centrifugal chillers, all condenser pumps, and all primary chilled-water pumps are constant-speed, while the secondary pumps and lead chiller are equipped with variable-frequency drives (VFDs). The cooling towers are equipped with two-speed fan motors that maintain a condenser-water-temperature set point (usually set for a 73°F basin temperature). Figures 6 and 7 show performance, as well as operating conditions, on two selected days.

Problems and issues: Because constant-speed equipment is used, efficiency is greatly reduced at lower loads (Figure 7). Also, secondary flow often exceeds primary flow; flow reverses through the "off" chillers (no isolation valves on the chillers) and is mixed, degrading supply-water temperature. This robs the system of its full-capacity capabilities and greatly reduces the capacity of the cooling coils. The result is premature sequencing of the chillers and increased fan speeds (and, thus, fan energy) at the air handlers. It is not unusual to see a 6°F difference between the chiller supply water and the chilled

Maximum dry bulb	Minimum dry bulb	Chilled-water supply	Maximum tons	Minimum tons	Average kilowatts per ton
71°F, 57% RH	61°F, 75% RH	44 to 48°F	1,484	388	0.95

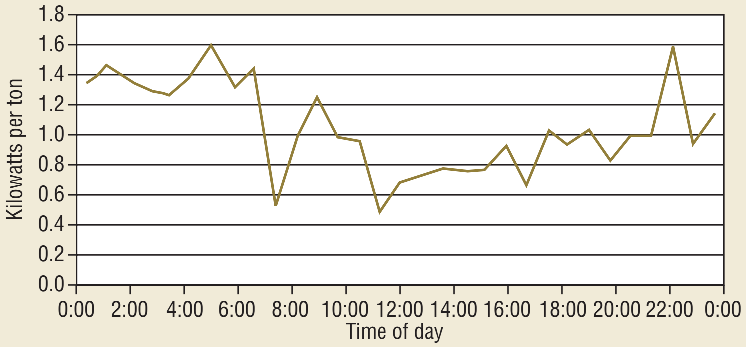

FIGURE 7. Wire-to-water total plant efficiency on Thursday, Oct. 5, 2006.

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Maximum dry bulb	Minimum dry bulb	Chilled-water supply	Maximum tons	Minimum tons	Average kilowatts per ton
72°F, 59% RH	66°F, 65% RH	45°F	534	256	0.97

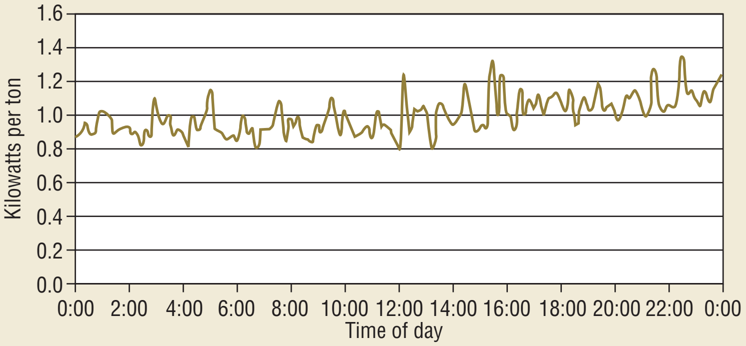

FIGURE 8. Wire-to-water total plant efficiency on Friday, Sept. 22, 2006 (both chillers on).

water entering at each coil.

This chiller plant averages about 0.85 kw per ton annually (tertiary pumps excluded). This is a reasonable level of performance compared with many contemporary plants, but well below what the owner should expect from a large state-of-the-art plant, as this is purported to be.

HYBRID CENTRAL PLANT

A hybrid[3] primary-secondary chilled-water system designed for 1,200 tons of available capacity at a 10°F delta-T serves a hospital. The centrifugal chiller (600 tons), condenser pumps, and primary chilled-water pumps are constant-speed, while the cooling-tower fans and secondary pumps are equipped with VFDs. The direct-fired natural-gas absorption chiller (600 tons) is operated primarily on winter nights (when the electric chiller cannot handle the low loads of the hospital) and throughout the summer (24/7). The electric chiller is operated on winter days and throughout the summer (24/7). Cooling-tower fans operate to maintain a condenser-water-temperature set point, which usually is set at an 81°F basin temperature. The plant uses considerably more energy than was projected during de-

Maximum dry bulb	Minimum dry bulb	Chilled-water supply	Maximum tons	Minimum tons	Average kilowatts per ton
60°F, 55% RH	53°F, 82% RH	46°F	183	78	0.93

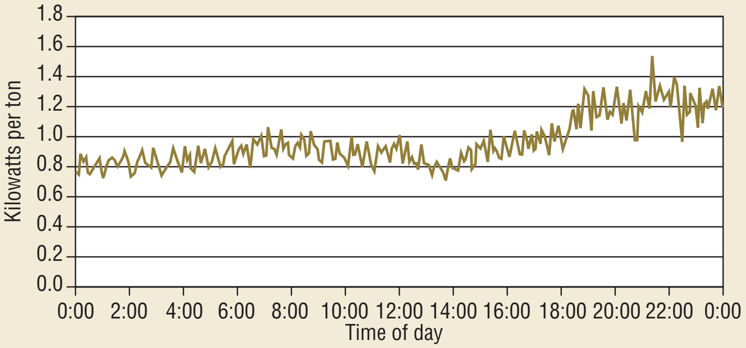

FIGURE 9. Wire-to-water total plant efficiency on Saturday, Dec. 16, 2006 (only the absorption chiller operating).

sign. Figures 8 and 9 show electrical usage only; they do not reflect the 0.2 therm of natural gas per ton-hour of cooling used by the absorber.

Problems and issues: Problems associated with this hybrid system—low delta-T (usually, 4°F to 7°F in a 10°F design), inability to fully load chillers, significant mixing, decoupled pumping, oversized pumps, the use of constant-speed equipment[4]—are quite universal. Without fail, the second chiller is brought online at much lower-than-expected loads, and the efficiency of the plant suffers considerably.

That electric and absorption chillers in hybrid systems typically share a condenser header presents another problem. With centrifugal chillers, the lower the condenser-water temperature, the greater the operational efficiency; absorption chillers, on the other hand, generally require higher condenser-water temperatures for stable operation. The result is a relatively high (usually, a minimum set point of 80°F) condenser supply temperature throughout the year and the centrifugal chillers using much more energy than needed.

VARIABLE-SPEED SCREW-CHILLER PLANT

A 2-year-old primary-secondary chilled-water system designed for 440 tons of available capacity at a 12°F delta-T features two 220-ton high-efficiency screw chillers with 0.539-kw-per-ton full-load and 0.487-kw-per-ton non-standard-part-load values. The two 15-hp cooling-tower fans, two 25-hp condenser pumps, two 10-hp primary chilled-water pumps, and two 25-hp secondary pumps are equipped with VFDs. Figures 10 and 11 show plant performance on two typical days.

Problems and issues: Although it was designed to be 21-percent more efficient than required by Title 24 of the California Code of Regulations, the plant averages 1.2 kw per ton annually. The high kw-per-ton spikes in Figure 10 occur when the second chiller comes online, while the high spikes in Figure 11 occur when the chiller trips off at low load and the pumps still operate. Unfortunately, there was a disconnect between the design, the intent, and the commissioning of the facility; other than for the secondary pumps, control sequences were not added to the energy-management system to make the system variable.

ULTRAEFFICIENT ALL-VARIABLE-SPEED PLANT WITH OIL-LESS COMPRESSORS

A 750-ton central plant serving jail, office, and court facilities was installed in 1998. In 2005, the system was retrofitted with oil-less centrifugal compressors on both the 450-ton and 300-ton chillers and VFDs on all condenser pumps, chilled-water pumps, and cooling-tower fans. Decouplers were eliminated, all valves were converted to two-way direct digital control, and demand-based controls were integrated into the existing energy-management system. Figures 12 and 13 show performance data and operating conditions.

Problems and issues: Although new staging strategies needed to be developed, the modular oil-less compressors went far in increasing part-load efficiencies, as this significantly oversized (partly because of redundancy issues) plant averages less than 0.55 kw per ton

Maximum dry bulb	Minimum dry bulb	Chilled-water supply	Maximum tons	Minimum tons	Average kilowatts per ton
82°F, 51% RH	69°F, 78% RH	42 to 44°F	263	62	0.94

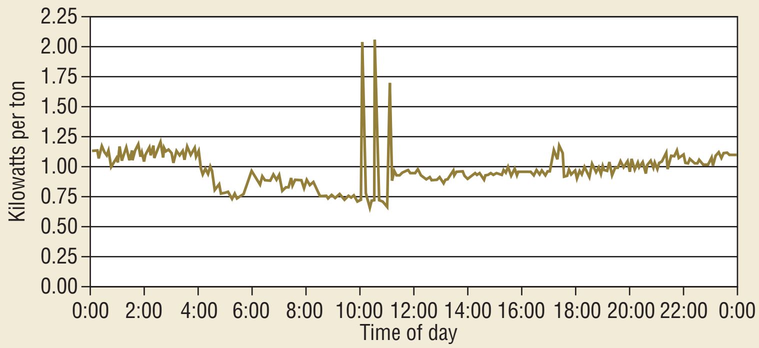

FIGURE 10. Wire-to-water total plant efficiency on Monday, June 26, 2006.

Maximum dry bulb	Minimum dry bulb	Chilled-water supply	Maximum tons	Minimum tons	Average kilowatts per ton
68°F, 67% RH	61°F, 78% RH	40 to 47°F	97	2	1.34

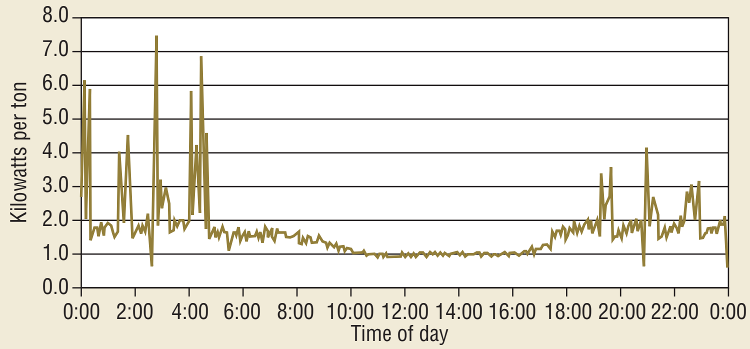

FIGURE 11. Wire-to-water total plant efficiency on Tuesday, May 16, 2006.

Maximum dry bulb	Minimum dry bulb	Chilled-water supply	Maximum tons	Minimum tons	Average kilowatts per ton
82°F, 51% RH	69°F, 78% RH	45 to 48°F	373	60	0.58

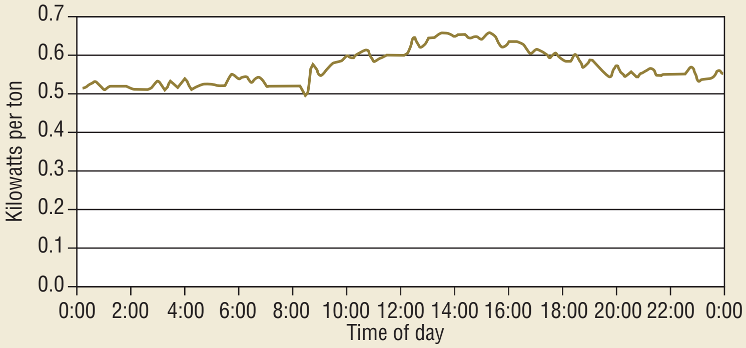

FIGURE 12. Wire-to-water total plant efficiency on Monday, June 26, 2006.

annually. The key to success was the incorporation of a system and support to ensure performance is monitored and shared with plant-design- and operation-team members. The system saves the owner more than $100,000 a year.[5]

CONCLUSION

Surveys of hundreds of chiller plants reveal that a great many plants are wasting a lot of energy. By extending all-variable-speed principles to chilled-water plants,[6] however, substantial energy savings (over 60 percent, in some cases) can be achieved. Beyond variable speed, we need:

• Codes based on chiller nominal efficiency (full-load kilowatts per ton) to be changed. ANSI/ASHRAE Standard 90.2-2004, *Energy-Efficient Design of Low-Rise Residential Buildings*, and Title 24 of the California Code of Regulations should emphasize part-load efficiencies (IPLV/NPLV rating).

• Continuous performance monitoring. In the U.S. Green Building Council's Leadership in Energy and Environmental Design for New Construction and Major Renovations (LEED-NC) green-building rating system, monitoring should be mandatory, with certification dependent on performance goals being met.

Maximum dry bulb	Minimum dry bulb	Chilled-water supply	Maximum tons	Minimum tons	Average kilowatts per ton
67°F, 57% RH	60°F, 65% RH	48 to 51°F	172	40	0.42

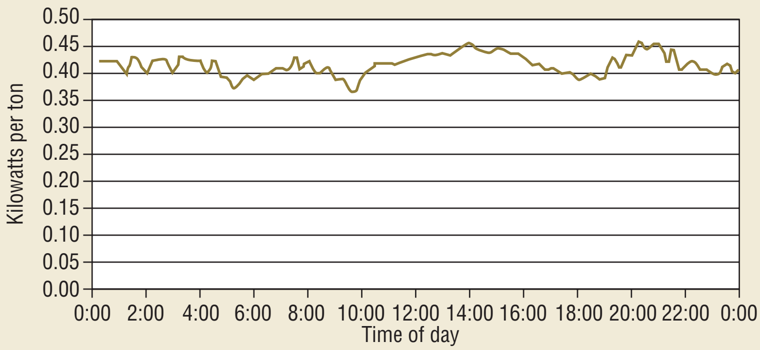

FIGURE 13. Wire-to-water total plant efficiency on Tuesday, Oct. 31, 2006.

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• Ways to measure performance beyond thousands of British thermal units per square foot per year or HVAC power density,[7] which often give a false sense of an energy-efficient building or design. Real-time operating and monthly/yearly average kilowatts per ton should be utilized for all new central-plant designs.

• Networked-based controls. Many engineers still design systems under the outdated notion of system isolation and independent control of plant equipment.[8] All HVAC components need to be coordinated and new relational-control strategies implemented.

Engineering firms that ensure the chilled-water plants they design are meeting performance goals—not just producing design flow and supply-water temperature—should be commended. More firms should offer performance-based designs. Every chilled-water-plant designer's goal should be to guarantee annual average energy consumption of 0.5 kw per ton or less.

NOTES

1) The data are representative of typical operation. All of the plants were designed by reputable engineering firms.

2) Hartman, T. (2007, February). The perfect energy resource. *HPAC Engineering*, pp. 13, 15.

3) The absorption chiller is served by a 20-hp primary pump (1,490 gpm), a 40-hp cooling-tower fan, a 75-hp condenser pump (2,750 gpm), and a 100-hp variable-speed secondary pump (3,600 gpm).

4) Hartman, T. (2002, April). All-variable speed chilled water distribution systems: Optimizing distribution efficiency. *AutomatedBuildings.com*. Retrieved from http://www.automatedbuildings.com

5) Juvenile hall's water-cooled chillers retrofitted with oil-less compressors. (2006, May). *HPAC Engineering*, pp. 68, 69.

6) Erpelding, B. (2006, March). Ultraefficient all-variable-speed chilled-water plants. *HPAC Engineering*, pp. 35, 36, 38, 40-43.

7) Kavanaugh, S.P., Lambert, S., & Devin, N. (2006). HVAC power density: An alternate path to efficiency. *ASHRAE Journal*, *48*, 40, 41, 44, 45, 47, 48.

8) Hartman, T. (2000, October). *Network based control: An imperative for green office buildings*. Paper presented at APEC in Taipei, Taiwan. Available at http://www.hartmanco.com/pdf/pre15.pdf