

Ultraefficient All-Variable-Speed Chilled-Water Plants

Improving the energy efficiency of chiller plants through the utilization of variable speed and the optimization of entire systems

Energy engineers are forever looking to reduce chiller-plant energy use, typically relying on high-efficiency water-cooled chillers, “pony” chillers, variable-frequency drives (VFDs), premium-efficiency motors, low-approach/high-efficiency cooling towers, sophisticated control strategies, and the like. In most cases, they focus on increasing the efficiency of individual components and optimizing plants based on outdoor wet-bulb temperature, condenser-water temperature, and chilled-water and differential-pressure reset. In almost all cases, they try to minimize the amount of online equipment and stage chillers based on their ability to maintain chilled-water set point (or 95-percent full-load amps). The result typically is a modest improvement in overall chiller-plant efficiency.

Average annual central-plant efficiency can be determined using the following equation:

$$\frac{\text{Wire-to-water kw per ton} \times \text{Central-plant energy use in kwh per year}}{\text{Total ton-hours per year}}$$

In this equation, central-plant energy use includes chillers, chilled-water pumps (primary, secondary, tertiary), condenser pumps, and cooling-tower fans. Figure 1 is a breakdown of typical comfort-cooling centrifugal chilled-water plants in Southern California.

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Based on the author’s experience, about 90 percent of water-cooled centrifugal central plants operate in the 1.0-to-1.2-kw-per-ton “needs improvement” range. Constant-speed equipment, decoupled pumping arrangements (mostly primary-secondary), significant mixing, oversized pumps, difficulty obtaining design chilled-water temperature, low delta-T, hunting, multiple flow and pressure problems, and systems that simply do not work typically are to blame.

To illustrate the detrimental effect constant-speed equipment has on average annual wire-to-water plant efficiency (kilowatts per ton), the following simple example is offered: A Southern California facility requires chilled water 24 hr a day, seven days a week (24/7). A central plant that

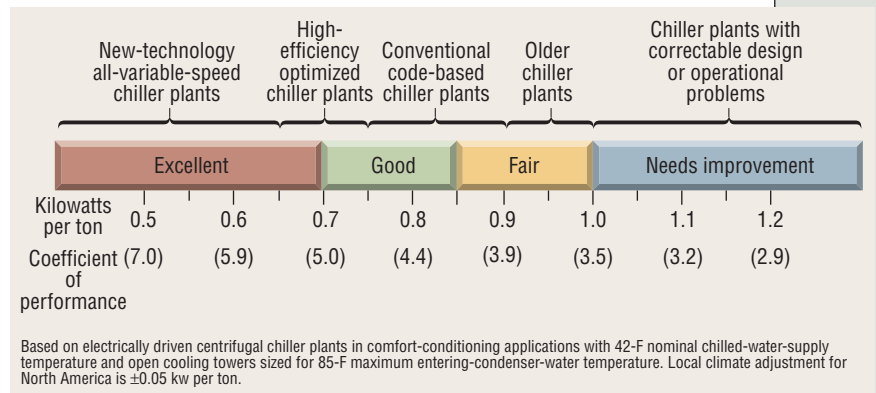


FIGURE 1. Average annual chiller-plant efficiency.

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employs a typical primary-secondary system with two 260-ton centrifugal chillers, two 10-hp constant-speed primary pumps, two 25-hp secondary pumps (with VFDs), two 25-hp constant-speed condenser pumps, and two cooling-tower cells with 10-hp fans is installed. Based on logged data from the energy-management system, the plant provides 960,000 ton-hours of cooling per year. The average annual contribution to energy use and kilowatts per ton by the lead constant-speed condenser pump alone is:

$$\text{Kilowatts per ton} = \frac{25 \text{ hp} \times 0.746 \text{ kw per hp} \times 8,760 \text{ hr per year}}{960,000 \text{ ton} \cdot \text{hours per year}} = 0.17$$

Thus, the lead condenser pump starts the plant at nearly 0.2 kw per ton. (Depending on the application, a properly controlled variable-speed condenser pump uses between 0.065 and 0.084 kw per ton.)

DEMAND-BASED CONTROL

In 2002, the author was introduced to (*HPAC Engineering* Editorial Advisory Board member) Tom Hartman's work with demand-based control.¹ The theory behind demand-based control is the Equal Marginal Performance Principle (EMPP),² which leads to the understanding that:

- System optimization is achieved when marginal system output per unit input is the same for all individual system elements.

- Individual-system temperatures and pressures are not directly related to optimization.

- Adaptive methods of optimization are not practical in large, complex systems that operate dynamically.

- Direct power-based control relationships provide a new direction for simpler and more-effective control of systems with all-variable-speed configurations.

Measurement and verification data from several ultraefficient all-variable-speed plants utilizing a licensed application of demand-based control show an average energy-use reduction of 54 percent over the last three years. The results point to a clear shift in the design, operation, control, and performance of central plants, the lessons being:

- Every device must be variable-speed.

- All central-plant components contribute to overall system performance. (A common control strategy is to achieve the lowest condenser-pan-water temperature possible, the thought being that the lower the temperature, the higher the performance of a centrifugal chiller. Although this can increase the performance of chillers substantially, it rarely optimizes entire

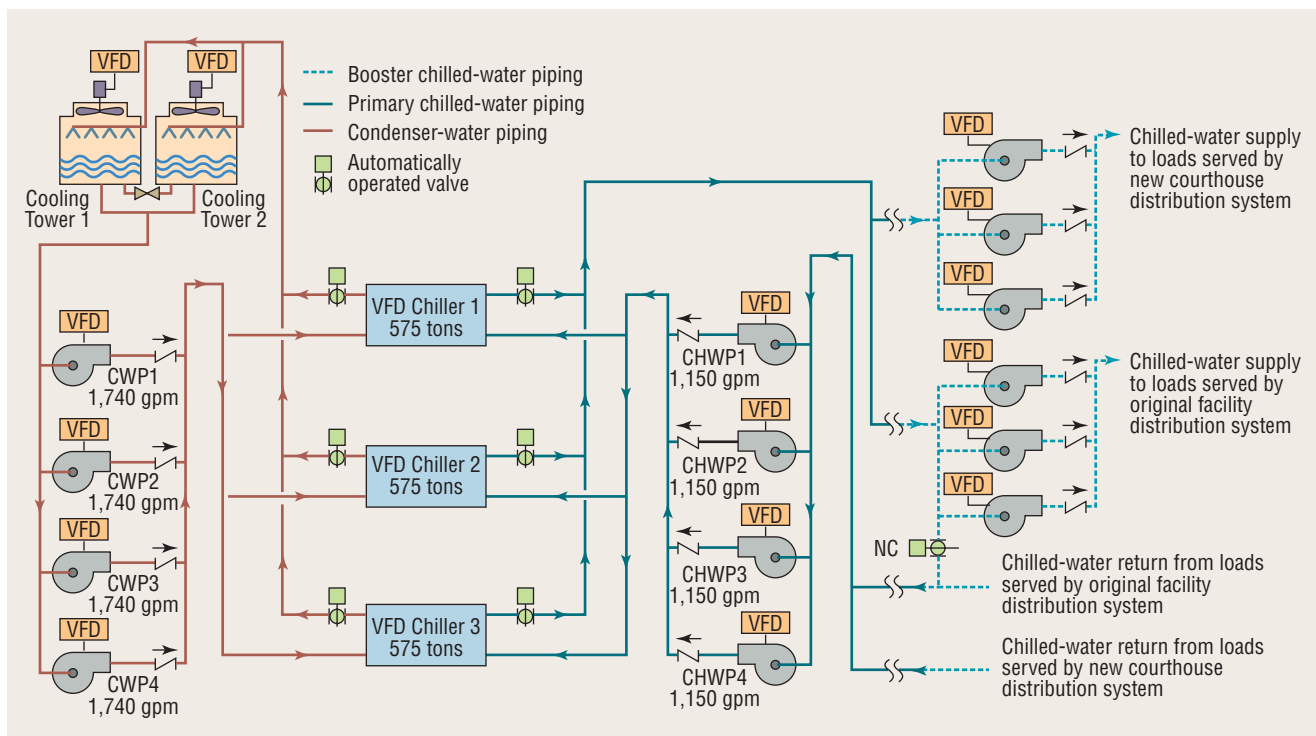


FIGURE 2. The direct-coupled distribution system at the NCRC. Multiple pumping circuits need to be connected directly in series, rather than isolated with decoupling lines. Primary/secondary systems become “primary/booster” systems, in which “all-variable-speed” pumping stations are operated in series.

central plants.) Minimizing or maximizing one component rarely results in an optimum configuration.

- The amount of equipment online should not be minimized. Existing chiller and cooling-tower heat-exchange surface area should be utilized and new sequencing strategies incorporated.

- Mixing should not be allowed.³ (All decouplers and three-way valves should be eliminated.) Every drop of chilled water should pass through a load before returning to a chiller.

- Systems should be designed so that as flow approaches zero, head requirements do as well. (This can be accomplished with the valve-orifice-area method of controlling chilled-water-distribution-pump speed,^{4,5,6} which uses percentage of open valve-orifice area to determine required chilled-water flow rate. An advantage of this intelligent-iterative-control method is that as flow goes to zero, so does required head. If pressure is not allowed to drop in proportion to

the square of flow rate, maximum energy savings cannot be achieved. This technique allows pumps to operate at their highest efficiency at all flows.)

- Ultraefficient all-variable-speed

primary-only systems are reliable and can be installed for the same cost as “standard” central plants.

- Less-than-0.5-kw-per-ton average annual central-plant wire-to-water effi-

Period	Total electricity saved, kilowatt-hours	Total peak electricity saved, kilowatts	Total electricity savings
Month 1	37,681	195	\$6,647
Month 2	132,008	120	\$14,755
Month 3	139,469	395	\$19,655
Month 4	105,087	274	\$14,450
Month 5	50,824	107	\$6,605
Month 6	100,886	102	\$11,438
Month 7	103,049	208	\$13,250
Month 8	177,140	283	\$21,650
Month 9	182,710	312	\$22,632
Month 10	48,803	229	\$8,249
Month 11	159,575	224	\$19,032
Month 12	118,818	331	\$16,662
Total	1,356,050	232	\$175,025

TABLE 1. Energy savings from the NCRC retrofit.

ciencies are attainable. (Efficiency does not take into account reductions from water-side economizers.)

- Demand-based control is much simpler than conventional control.
- The EMPP works.

CASE STUDY

An example of effective application of all-variable-speed operation to an existing chiller plant is the County of San Diego’s North County Regional Center (NCRC), which consisted of:

- 610,000 sq ft of air-conditioned space (courthouse, offices, and jail).
- Three 575-ton centrifugal chillers (1998 vintage).
- Four 20-hp constant-speed primary chilled-water pumps.
- Individual secondary chilled-water pumps (with VFDs) at each building.
- Two 850-ton cooling towers (originally with two-speed fan motors).
- Four 60-hp constant-speed condenser pumps.
- 24/7 chilled-water load.

The NCRC had a 1,725-ton constant-speed-primary/variable-speed-secondary chilled-water plant (the secondary pumps were installed in each building) that had been in operation for about five years. Although the system had been designed by an experienced firm, sized correctly, and maintained properly, the plant experienced continuously low delta-T, significant supply and return chilled-water mixing, inefficient operation at part-load conditions, and difficulty achieving design chilled-water temperatures at the air handlers. Its average annual efficiency was 1.12 kw per ton.

In November 2003, all three-way valves (14 of the 58 total valves) and decouplers were eliminated, and all of the centrifugal chillers, cooling-tower fans, primary chilled-water pumps, and condenser pumps were retrofitted with VFDs. The demand-based-control sequence was programmed into the existing energy-management system.

With the system retrofitted into a primary/booster pumping arrangement

Hour	Temp., F	Humidity, percent	Tonnage	Instantaneous power, kw	Kilowatts per ton
Midnight	65.6	75	525	168	0.32
1 a.m.	65.5	79	523	146	0.28
2 a.m.	64.3	81	507	142	0.28
3 a.m.	64.2	83	603	199	0.33
4 a.m.	63.4	85	488	161	0.33
5 a.m.	63.7	89	475	152	0.32
6 a.m.	63.2	90	911	401	0.44
7 a.m.	64.5	91	927	417	0.45
8 a.m.	67.6	86	933	411	0.44
9 a.m.	71.3	76	1,010	515	0.51
10 a.m.	74.9	68	1,031	546	0.53
11 a.m.	75.6	70	1,061	562	0.53
Noon	76.8	66	1,055	559	0.53
1 p.m.	76.5	66	1,060	551	0.52
2 p.m.	77.2	63	1,095	558	0.51
3 p.m.	77.4	62	1,100	561	0.51
4 p.m.	78.1	58	1,131	554	0.49
5 p.m.	77.6	59	1,147	562	0.49
6 p.m.	74.9	63	946	378	0.40
7 p.m.	72.8	67	814	268	0.33
8 p.m.	70.3	73	640	192	0.30
9 p.m.	67.9	69	561	157	0.28
10 p.m.	66.9	69	514	165	0.32
11 p.m.	66.1	79	619	198	0.32
Midnight	66.0	84	603	199	0.33
Total			20,276	8,723	0.43

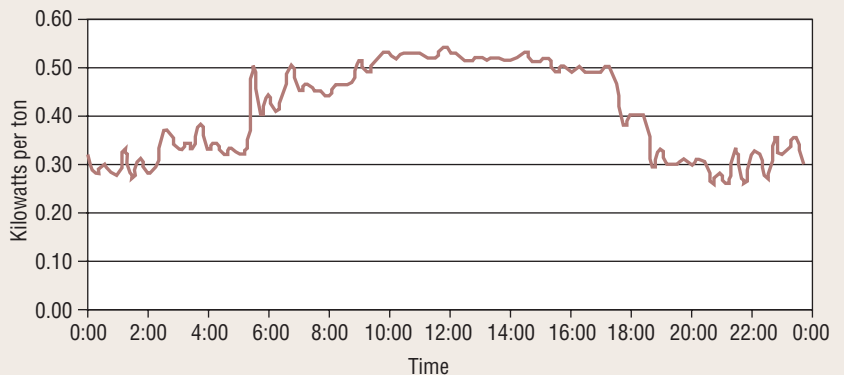


FIGURE 3. Wire-to-water total plant efficiency on Friday, July 29, 2005.

(Figure 2), the speed of operating equipment is controlled by a direct-digital-control system, ensuring optimum efficiency

at all times. Simple direct control algorithms coordinate the operation of chillers, pumps, and tower fans based on

Hour	Temp., F	Humidity, percent	Tonnage	Instantaneous power, kw	Kilowatts per ton
Midnight	67.3	81	584	193	0.33
1 a.m.	66.9	82	584	187	0.32
2 a.m.	66.4	85	617	216	0.35
3 a.m.	65.8	88	520	177	0.34
4 a.m.	65.6	90	559	196	0.35
5 a.m.	65.3	90	608	231	0.38
6 a.m.	65.2	91	502	171	0.34
7 a.m.	65.5	90	553	205	0.37
8 a.m.	68.8	84	566	204	0.36
9 a.m.	72.1	76	618	235	0.38
10 a.m.	76.5	69	672	269	0.40
11 a.m.	77.4	66	681	279	0.41
Noon	79.2	62	669	261	0.39
1 p.m.	79.2	64	733	264	0.36
2 p.m.	79.2	61	609	231	0.38
3 p.m.	78.1	64	707	262	0.37
4 p.m.	77.4	63	639	224	0.35
5 p.m.	76.3	60	602	247	0.41
6 p.m.	76.7	59	676	277	0.41
7 p.m.	72.7	75	557	223	0.40
8 p.m.	68.6	84	578	214	0.37
9 p.m.	67.6	85	602	235	0.39
10 p.m.	67.4	88	608	231	0.38
11 p.m.	67.1	88	564	203	0.36
Midnight	67.3	88	552	199	0.36
Total			15,160	5,631	0.37

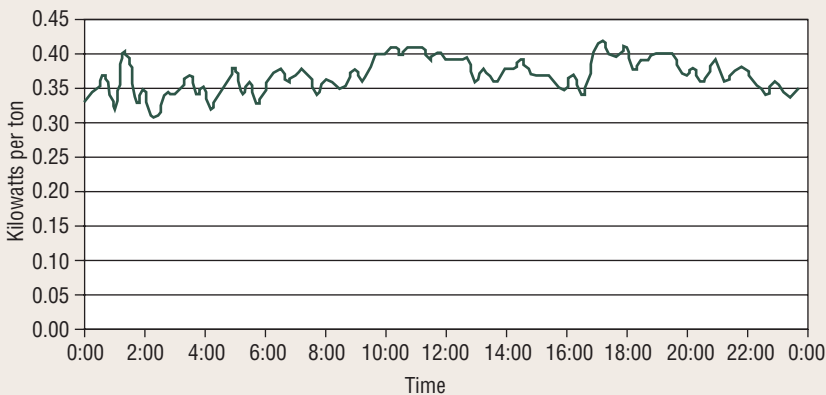


FIGURE 4. Wire-to-water total plant efficiency on Sunday, July 31, 2005.

demand for cooling, which is determined by cooling-coil-valve position. Chilled-water temperature and tower leaving-

water temperature float within preset limits (i.e., 40 to 45 F for the chilled water and 60 to 85 F for the condenser)

to allow components to operate at their highest efficiency at all times. The demand-based control sequences, which replaced proportional-integral-derivative (PID) control, coordinate the operation of the condenser pumps and tower fans based on chiller power (kilowatts). The three electric chillers are sequenced on- and offline according to the “natural-curve principle,” which sets a chiller-kilowatt threshold for sequencing, based on condenser and evaporator temperature.⁷ The distribution pumps are controlled using the valve-orifice method.^{4,5,6} Because the distribution pumps are in series with the primary pumps, a power/speed relationship optimizing the operation of the entire distribution system is maintained at all times. The downstream pumps always lead, while the upstream pumps adjust to match.

The retrofit was completed and commissioned in December 2003 at a cost of \$423,700. Two years later, measurement and verification data indicate that the entire plant averages less than 0.5 kw per ton, saving the county more than \$175,000 a year (Table 1). (Three years of pre-retrofit data were averaged to provide a baseline.) With a \$205,447 incentive from the local utility, the simple payback was 1.3 year. Figures 3 to 6 show performance data from the central plant. Again, the kilowatts per ton take into account the energy use of all chillers, condenser pumps, primary chilled-water pumps, booster chilled-water pumps, and cooling-tower fans. The data were collected in 5-min increments using the building’s energy-management system.

CONCLUSION

Conventional methods of improving chiller-plant efficiency tend to focus on increasing the peak efficiency of individual components. Additionally, because the energy performance of constant-speed chillers, pumps, and towers is maximized when components are operated as close to full load as possible, these methods generally involve the sizing

and sequencing of plant equipment to fit a variety of load conditions while minimizing the amount of online equipment.

This piecemeal approach needs to be changed. Measurement and verification data confirm that the energy efficiency of a chiller plant is improved most effectively by utilizing variable speed and optimizing the efficiency of the entire system in response to the requirements of the load served by the plant. This improvement is maximized when equipment is operated at part-load conditions. Simple and reliable direct control algorithms that can be used to coordinate the operation of all-variable-speed chillers, pumps, and tower fans are available. Demand-based control through the EMPP is an effective means of operating an ultraefficient all-variable-speed chilled-water plant. Average annual wire-to-water central-plant operating efficiencies below 0.5 kw per ton are attainable.

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Hour	Temp., F	Humidity, percent	Tonnage	Instantaneous power, kw	Kilowatts per ton
Midnight	56.5	82	140	70	0.50
1 a.m.	56.7	82	124	64	0.52
2 a.m.	57.0	80	121	64	0.53
3 a.m.	55.3	81	131	64	0.49
4 a.m.	54.2	85	128	72	0.56
5 a.m.	54.4	87	122	60	0.49
6 a.m.	55.7	83	186	87	0.47
7 a.m.	56.3	83	263	113	0.43
8 a.m.	57.5	85	263	126	0.48
9 a.m.	58.4	73	278	136	0.49
10 a.m.	59.9	73	329	145	0.44
11 a.m.	60.1	69	379	174	0.46
Noon	66.4	56	519	228	0.44
1 p.m.	67.4	54	519	244	0.47
2 p.m.	66.9	61	537	263	0.49
3 p.m.	64.2	67	492	217	0.44
4 p.m.	62.4	70	439	198	0.45
5 p.m.	59.5	81	302	157	0.52
6 p.m.	57.8	86	269	129	0.48
7 p.m.	56.5	90	173	88	0.51
8 p.m.	56.0	91	159	78	0.49
9 p.m.	55.7	91	163	81	0.50
10 p.m.	54.7	91	137	76	0.55
11 p.m.	54.4	93	137	70	0.51
Midnight	54.2	93	126	62	0.49
Total			6,434	3,066	0.48

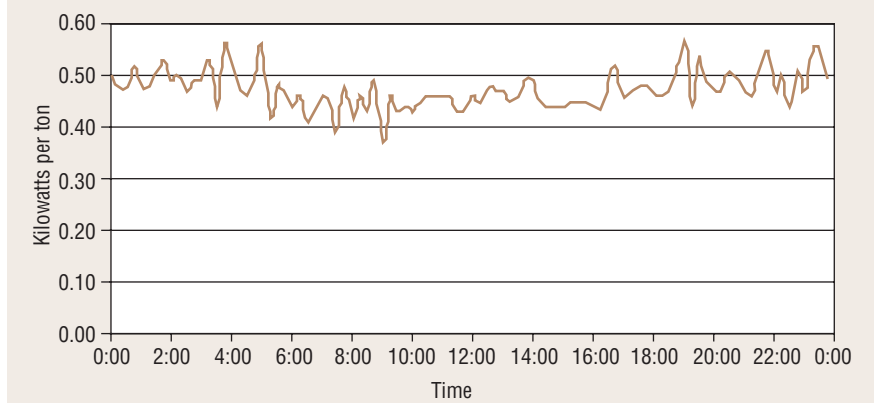


FIGURE 5. Wire-to-water total plant efficiency on Friday, Nov. 4, 2005.

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 5) Hartman, T. (2003, October). Presenting intelligent iterative control: PID replacement for setpoint control (pt. 2). *HPAC Engineering*, pp. 9, 10.
 6) Hartman, T. (2003, November).

Hour	Temp., F	Humidity, percent	Tonnage	Instantaneous power, kw	Kilowatts per ton
Midnight	55.4	93	115	58	0.51
1 a.m.	56.0	90	121	57	0.47
2 a.m.	55.6	89	99	56	0.57
3 a.m.	53.2	91	108	59	0.54
4 a.m.	54.8	94	92	48	0.52
5 a.m.	54.1	94	117	57	0.49
6 a.m.	54.1	95	151	62	0.41
7 a.m.	55.6	96	134	64	0.48
8 a.m.	56.7	91	219	74	0.34
9 a.m.	59.6	89	168	77	0.46
10 a.m.	63.1	75	190	95	0.50
11 a.m.	65.2	68	204	100	0.49
Noon	71.5	51	235	111	0.47
1 p.m.	74.6	45	246	128	0.52
2 p.m.	70.4	63	261	136	0.52
3 p.m.	64.8	76	290	145	0.50
4 p.m.	62.4	83	223	114	0.51
5 p.m.	60.9	87	185	106	0.57
6 p.m.	59.5	89	209	102	0.49
7 p.m.	60.1	89	164	94	0.57
8 p.m.	58.1	90	160	86	0.54
9 p.m.	56.9	92	129	72	0.56
10 p.m.	56.0	94	119	67	0.56
11 p.m.	55.1	94	132	73	0.55
Midnight	54.4	94	137	67	0.49
Total			4,209	2,108	0.50

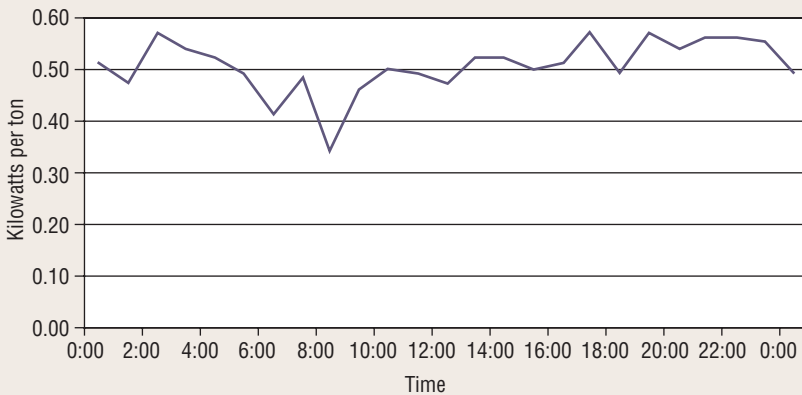


FIGURE 6. Wire-to-water total plant efficiency on Sunday, Nov. 6, 2005.

Presenting intelligent iterative control: PID replacement for setpoint control (pt. 3). *HPAC Engineering*, pp. 9, 10.

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