Using Low-Load Chillers to Improve System Efficiency

Is It Still a Good Design Choice?

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The obvious approach to system design is to ensure that the building peak loads can be met. The thoughtful engineer will apply further consideration to the part-load conditions of the building. Design-load conditions typically happen only a handful of hours throughout the year, if at all. Reflecting on this, it only makes good sense to further refine your system design so it operates as efficiently as possible at part-load conditions.

In response, some engineers will use a design in which a small "low-load" chiller runs during low-load conditions (*Figure 1*). This design benefits a large chiller system, which can operate inefficiently at low-load conditions, particularly if pumps and cooling towers must also operate. Some operators will run this chiller only at low-load conditions, while others "swing" this chiller in and out of the chiller sequence (*Table 1*). When operated in this manner, the chiller is often referred to as a "swing" chiller. In either case, the goal is higher system operating efficiency.

This article will examine the use of low-load chillers, but *not* in a "swing" application. It does so first by comparing energy use of a system design prevalent in 1999 with a system using a low-load chiller. Second, it compares a design commonly used in 2016 to three energy-saving options. Energy analysis of both hospital and office building applications will be done for seven different climate zones. This article does not cover return on investment (ROI) since installation and operating costs vary significantly.

1999 Design Year Chilled Water Plant

In 1999 the primary-secondary chilled water system design was prevalent as shown in *Figure 1*. In this system, each chiller has a constant speed chilled water pump and constant speed condenser water pump. Chilled water is distributed to air handlers via variable speed secondary pumps. Efficiencies for chillers, cooling towers, and requirements for speed modulation (variable speed drives [VSD] on cooling tower fans) are defined by ANSI/ASHRAE/IESNA Standard 90.1-1999.[1] The "standard" system design parameters from AHRI Standard 550/590-1995 are as follows:

- A design building load of 500 tons (1760 kW) is used for all locations;
- The base system has two, 250 ton (880 kW) water-cooled screw chillers; and
- The low-load chiller alternative has one, 70 ton (250 kW) chiller and two, 215 ton (760 kW) chillers.

Air economizers are modeled in those regions where they are required by Standard 90.1-1999. In humid climates, the design cooling tower leaving temperature is selected at 85°F (29.4°C). In dry climates, such as Los Angeles and Berlin, the design leaving temperature is 80°F (26.7°C).

2016 Design Year Chilled Water Plant

The 2016 base design uses variable primary flow (VPF)

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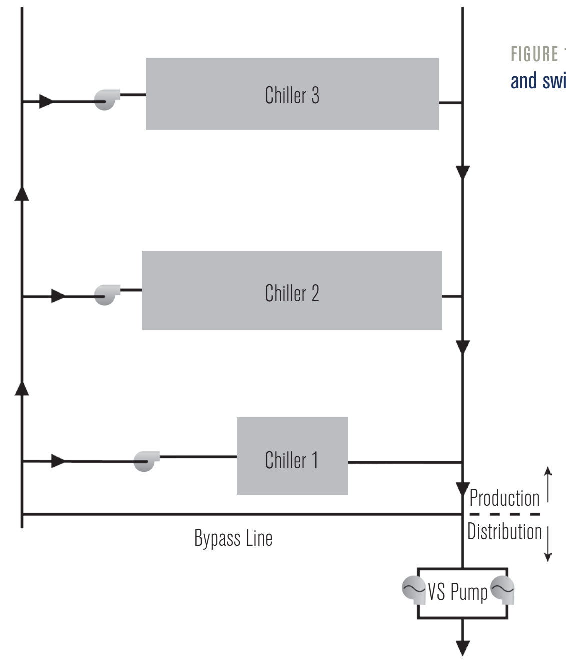

FIGURE 1 (LEFT) Primary-secondary low-load chiller system configuration. TABLE 1 (RIGHT) Low-load and swing chiller options.

	SYSTEM DESIGN		
	BASE	LOW LOAD	SWING
	1. 250 tons 2. 250 tons	1. 70 tons 2. 215 tons 3. 215 tons	1. 70 tons 2. 215 tons 3. 215 tons
	CHILLERS OPERATING		
BUILDING LOAD (TONS)	BASE	LOW LOAD	SWING
0 to 70	1	1	1
>70 to 215	1	2	2
>215 to 250	1	2 and 3	1 and 2
>250 to 285	1 and 2	2 and 3	1 and 2
>285 to 430	1 and 2	2 and 3	2 and 3
>430 to 500	1 and 2	1, 2, and 3	1, 2, and 3

for the chilled water system, recommended temperature differences (16°F [8.9°C] chilled water and 14°F [7.8°C] condenser water) from the *ASHRAE GreenGuide*[2] as well as the resultant flow rates and constant speed condenser water pumps (which the author believes is still standard practice) (*Figure 2*). Equipment efficiency requirements of Standard 90.1-2013[3] are used (90.1-2016 had not been published at the time of writing), but chiller efficiency adjustments are as follows:

- At the lower chilled water flow rate, colder chilled water is needed to produce the same cooling effect at the air handlers;
- At the lower condenser water flow rate, the leaving condenser water temperature rises;
- Both flow rate reductions result in an increase in compressor "lift" and chiller power; and
- Therefore, chiller efficiency is adjusted for the colder chilled water temperature and the warmer condenser leaving water temperature (*Table 2*).

At the lower condenser flow rate, the water temperature entering the cooling tower is higher, and the tower becomes a more effective heat exchanger. Therefore, the design tower fan power can be reduced. This is done by using the 90.1-2013 cooling tower requirement and the condenser water flow rate to calculate cooling tower kW/ton (kW/kW) of building cooling load (*Table 3*).

Economizers are now required in all locations except Climate Zone 1 (Bangkok), and chiller and cooling tower efficiencies are more stringent. For simplicity, air economizers were modeled.

With the advent of reasonably priced variable speed drives on chillers, three alternatives are examined:

1. Install a low-load chiller.
2. Add a variable speed drive to one of the large chillers.
3. Install both a variable speed drive to one of the large chillers and a low-load chiller.

Pump efficiency as well as pump motor and drive efficiencies are the same for all alternatives.

In the 1999 system design, the primary pressure drop is 25 ft (75 kPa), and the condenser water pump head is 75 ft (224 kPa). The secondary pressure drops are 50 ft (149 kPa) for the office building and 100 ft (299 kPa) for the hospital.

In the 2016 system design, the condenser water pressure drop is identical at 75 ft (224 kPa). Since they must overcome a pressure drop through the chillers and the system, the variable primary flow (VPF) system chilled water distribution pumps use the combined pressure drop for the buildings: 75 ft (224 kPa) for the office and 125 ft (374 kPa) for the hospital (*Table 4*).

Flow rates differ due to the design parameters in the 2016 design year plant using recommendations from the *ASHRAE GreenGuide*.

Results

Chilled water plant energy use is shown for each alternative in seven different locations (*Table 5*). Energy use includes the chillers, all chilled water pumps, condenser water pumps, and cooling tower fans.

1999 Design Year Comparison

Figure 3 shows the 1999 results of the hospital and office building. Annual system energy and percent system savings are shown in *Table 5*.

Discussion

Whenever a chiller is operating, the condenser water pump uses its design power, as does the primary chilled water pump. So each hour of "low-load" chiller operation results in a 72% reduction (1 – 70/250) in the primary chilled water pump plus condenser water pump power. In addition, a smaller cooling tower fan operates. The smaller compressor may also operate more efficiently since its percent load is higher than the large, base chillers. One would suspect that locations for which there are many operating hours with only the low-load chiller operating would achieve significant energy savings.

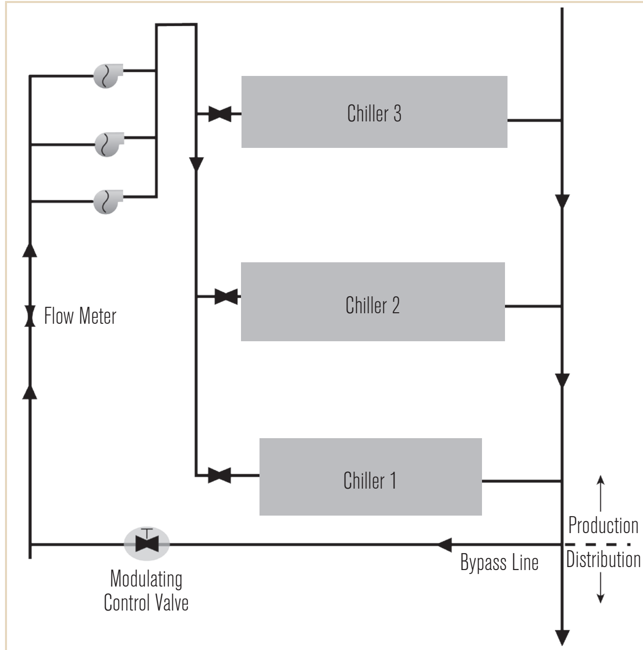

FIGURE 2 Variable primary flow low-load chiller system configuration.

TABLE 2 Chiller design parameters.

1999 DESIGN: STANDARD 90.1-1999								
90.1	TYPE	CAPACITY (TONS)	CS/VS	EEWT (°F)	LEWT (°F)	ECWT (°F)	LCWT (°F)	KW/TON (COP) (FROM 90.1-1999, 10/29/2001 REQUIREMENTS)
1999	Screw	>200	CS	54	44	85	95	0.72 (4.88)
	Screw	75	CS	54	44	85	95	0.79 (4.45)

2016 DESIGN: GREENGUIDE + 90.1-2013									
90.1	TYPE	CAPACITY (TONS)	CS/VS	GREENGUIDE CONDITIONS (°F)				KW/TON (COP) (1/1/2015 90.1-2013 REQUIREMENTS)	ADJUSTED KW/TON (COP) (SAME CHILLER AT GREENGUIDE CONDITIONS)
2013	Screw	>200	CS	57	41	85	99	0.660 (5.33)	0.735 (4.79)
	Screw	75	CS	57	41	85	99	0.750 (4.69)	0.835 (4.21)
	Screw	>200	VS	57	41	85	99	0.68 (5.17) (Path B)	0.785 (4.48)

EEWT: entering evaporator water temperature; LEWT: leaving evaporator water temperature; ECWT: entering condenser water temperature; LCWT: leaving condenser water temperature; CS: constant speed; VS: variable speed

Hospital

In the hospital, double-digit percentage savings are available in Sao Paulo, Berlin, and Minneapolis. Examination of those three climates shows the following:

- Sao Paulo is at about 2,600 ft (790 m) of elevation, fairly dry during its winter, and the temperature is fairly moderate. There are many hours of lower load operation during the weekend and nights in May through September (winter) due to the mild climate. This greatly reduces the low-load chiller condenser water pump, chilled water pump, and cooling tower fan energy use—resulting in the largest energy savings of the locations analyzed (*Figure 4*).
- In both Berlin and Minneapolis, integrated economizers led to a significant number of hours of low-load chiller operation.
- Bangkok savings occurred for a different reason than other locations. Very rarely did only the low-load chiller operate. However, the Bangkok hospital operates many hours at high-load conditions. The low-load chiller does not operate until the load is above 430 tons (1510 kW). Many hours exist when that chiller's pumps and cooling tower fans do not operate, so system energy savings are accrued.

Office

The office building has far fewer hours of nighttime and weekend operation and, therefore, fewer possible hours of low-load chiller operation. In all locations except Bangkok, the office energy savings are lower than those

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of the hospital. What is different for an office building in Bangkok? During partial occupancy over the weekend, the outdoor air conditions were sufficiently high to impose a load on the chilled water plant, and the low-load chiller operated during those hours. Another anomaly compared to the hospital savings is Sao Paulo. The office building savings are much lower than the hospital since the office has very few weekend cooling hours.

TABLE 3 Cooling tower parameters.

CLIMATE	GPM/TON	EWT (°F)	LWT (°F)	WB (°F)	GPM/HP	MOTOR EFFICIENCY
1999 DESIGN: STANDARD 90.1-1999						
Humid	3	95	85	78	38.2	0.93
Dry	3	90	80	70	38.2	0.93
2016 DESIGN: GREENGUIDE + 90.1-2013						
CLIMATE	GPM/TON	EWT (°F)	LWT (°F)	WB (°F)	GPM/HP	MOTOR EFFICIENCY
Humid	2	99	85	78	40.2	0.93
Dry	2	94	80	70	40.2	0.93

2016 Design Year Comparison

The *ASHRAE GreenGuide* recommendations reduce the design pump power of the base system by using a 16°F (8.9°) chilled water ΔT and 14°F (7.8°C) condenser water ΔT. In addition, there are no primary chilled water pumps, and the variable speed distribution pump power drops quickly as the load and flow requirements are reduced. So one would expect there to be less overall savings than the 1999 design. *Figure 5* shows the summary hospital and office building results, and shows the kWh and percentage savings compared to the 2016 base.

TABLE 4 Pump parameters.

PUMP	GPM/TON	ΔP (FT W.C.)	PUMP EFFICIENCY	MOTOR EFFICIENCY	DRIVE EFFICIENCY	KW/TON
1999 DESIGN: STANDARD 90.1-1999						
OFFICE BUILDING						
CS PRIMARY	2.4	25	0.7	0.93	1	0.0174
VS SECONDARY – OFFICE	2.4	50	0.7	0.93	0.97	0.0358
CS CONDENSER	3	75	0.7	0.93	1	0.0651
HOSPITAL						
CS PRIMARY	2.4	25	0.7	0.93	1	0.0174
VS SECONDARY – HOSPITAL	2.4	100	0.7	0.93	0.97	0.0716
CS CONDENSER	3	75	0.7	0.93	1	0.0651
2016 DESIGN: GREENGUIDE + 90.1-2013						
PUMP	GPM/TON	ΔP (FT W.C.)	PUMP EFFICIENCY	MOTOR EFFICIENCY	DRIVE EFFICIENCY	KW/TON
OFFICE BUILDING						
VPF CHILLED WATER	1.5	75	0.7	0.93	0.97	0.0336
CS CONDENSER WATER	2	75	0.7	0.93	1	0.0434
HOSPITAL						
VPF CHILLED WATER	1.5	125	0.7	0.93	0.97	0.0559
CS CONDENSER WATER	2	75	0.7	0.93	1	0.0434

Discussion

In all cases except the office building in Bangkok, the savings from adding a variable speed drive to one large chiller is greater than using a low-load chiller. In addition, by installing the VSD, no additional piping, pumps, system control or cooling tower modifications are necessary. While ROI is not covered by this article, the cost of the VSD is almost certainly lower than the full cost of installing a smaller chiller with its piping and ancillary equipment.

Again, what is different about the Bangkok office building? Every weekend, low loads can be satisfied by the low-load chiller. While the VSD chiller uses less energy, the additional condenser water pump and cooling tower fan energy of the larger chiller resulted in higher system energy use. *Figure 6* shows operation for a July Saturday. For each hour in the figure, Alternative 2 (Low-Load Chiller) is on the left and Alternative 3 (VSD on One Large Chiller) is on the right.

Variable speed drive *and* low-load chiller: While further energy savings are accrued by installing both a variable speed drive chiller and low-load chiller, it's doubtful the benefit warrants the additional cost. Once again, Bangkok is an exception with the combination saving comparably more than either a low-load or VSD chiller.

Caveats

As with all analyses, one must be careful not to inappropriately extrapolate results. This section provides caveats.

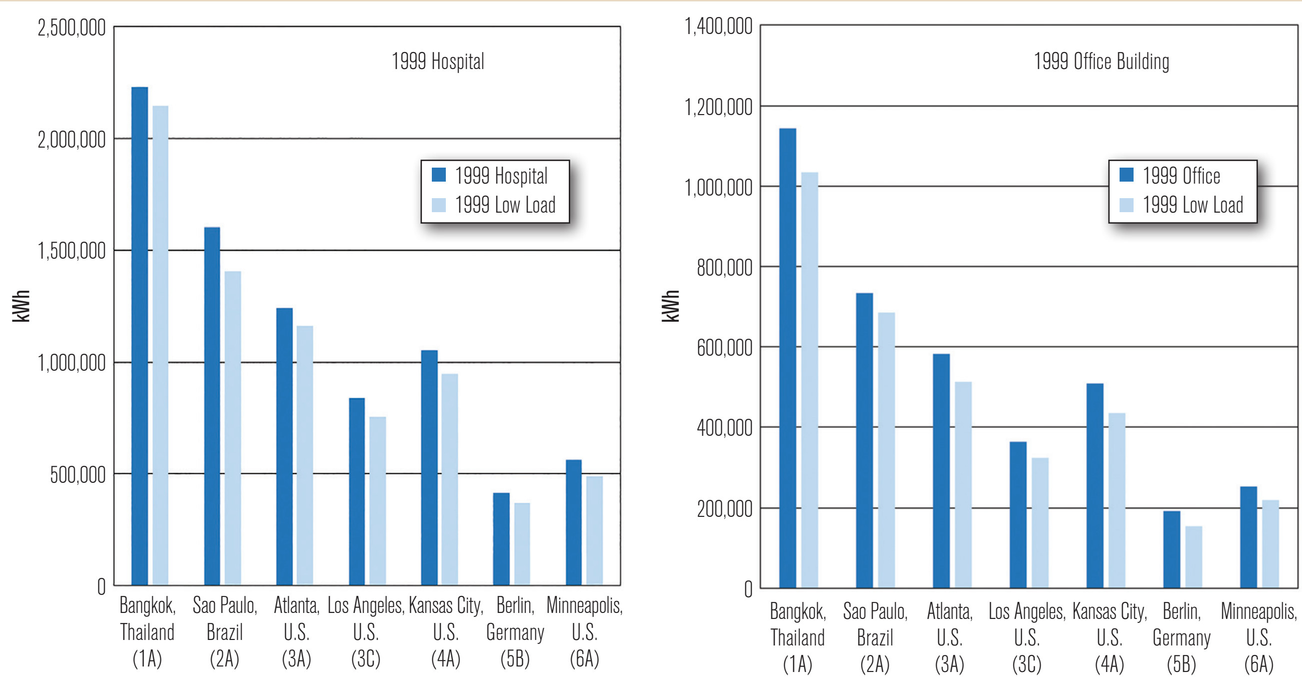

FIGURE 3 Hospital and office building results, design year 1999.

Chiller Type

Screw Chiller: A variable speed drive on a screw chiller will reduce the compressor kW if either the load is reduced or the pressure difference between the condenser and evaporator refrigerant pressures (lift) is reduced.

Centrifugal Chiller: A variable speed drive on a centrifugal chiller saves energy when it can slow down. This occurs when its lift is reduced.

The conclusions of this screw chiller analysis may *not* be true for centrifugal chillers. Analyses should be performed, especially in humid climates, to determine energy savings.

***ASHRAE GreenGuide* Condenser Water Pump and Cooling Tower Sizing:** The analysis uses the reduced condenser water flow rates recommended by the *ASHRAE GreenGuide*. This lowers the condenser water pump and cooling tower fan kW. If a higher flow rate (smaller ΔT) is used, the 2016 low-load energy savings may be closer to those of the 1999 design as ancillary equipment becomes a larger portion of the annual system energy use. If the 2016 system is designed at non-optimal flow rates, the low-load system savings will be large due to ancillary equipment savings.

Return on Investment: None was performed for this analysis. Do the savings warrant the change in installed

TABLE 5 Annual system savings, design year 1999.

	1999 HOSPITAL SAVINGS		1999 OFFICE SAVINGS	
LOCATION/CLIMATE ZONE	KWH	PERCENT	KWH	PERCENT
Bangkok, Thailand (1A)	84,897	3.8	108,300	9.5
Sao Paulo, Brazil (2A)	197,359	12.3	47,667	6.5
Atlanta, U.S. (3A)	80,572	6.5	68,259	11.7
Los Angeles, U.S. (3C)	83,015	9.9	40,978	11.2
Kansas City, U.S. (4A)	102,840	9.8	73,790	14.5
Berlin, Germany (5B)	45,091	10.9	37,832	19.6
Minneapolis, U.S. (6A)	72,851	13.0	33,231	13.2

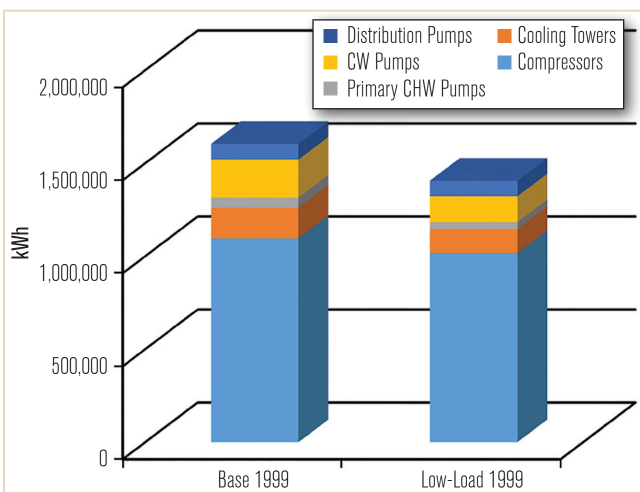

FIGURE 4 Sao Paulo hospital energy savings.

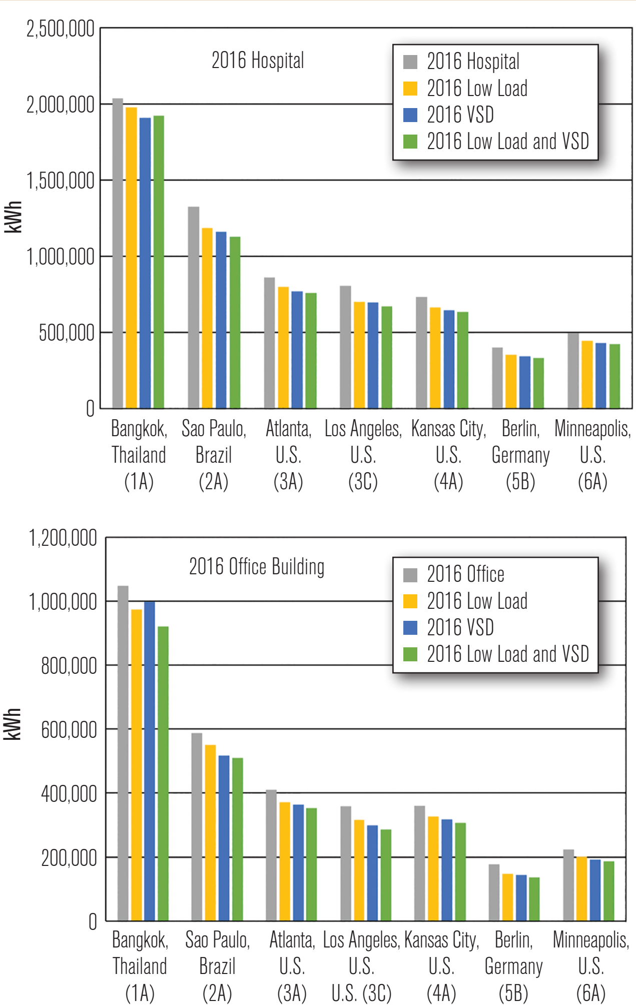

FIGURE 5 Hospital (top) and office building (bottom) results.

costs? That depends on local costs, utility rates, and labor rates, and should be investigated by the project team. It also depends if the building owner has high emphasis on energy or energy cost savings, for example, for green building rating systems.

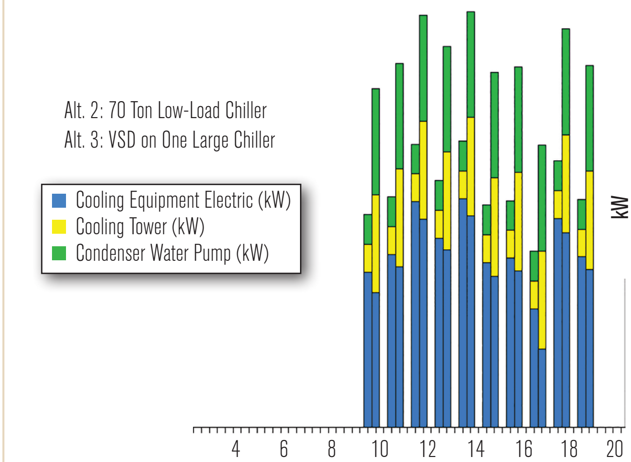

FIGURE 6 Bangkok office operation for a July Saturday. For each hour in the figure, Alternative 2 is on the left and Alternative 3 is on the right.

Conclusions

- In almost all locations, designing a system with a low-load chiller to satisfy low loads saves energy.
- However, using 2016 design practices, a system using a variable speed drive screw chiller saves more energy than the "low-load chiller" system, except in the climate that is hot and humid all of the time.
- Designing a system with a variable speed chiller and low-load chiller saves additional energy, but the additional cost may not be warranted.
- Project teams should consider asymmetric system design as an option to saving chilled water system energy.

References

1. ANSI/ASHRAE/IESNA Standard 90.1-1999, *Energy Standard for Buildings Except Low-Rise Residential Buildings*.

2. ASHRAE. 2010. *ASHRAE GreenGuide: The Design, Construction, and Operation of Sustainable Buildings, 3rd ed.* Atlanta: ASHRAE.

3. ANSI/ASHRAE/IES Standard 90.1-2013, *Energy Standard for Buildings Except Low-Rise Residential Buildings*. ■

TABLE 6 Annual system savings, design year 2016.

	2016 HOSPITAL SAVINGS						2016 OFFICE SAVINGS					
	SMALL CHILLER		VSD CHILLER		SMALL AND VSD CHILLERS		SMALL CHILLER		VSD CHILLER		SMALL AND VSD CHILLERS	
LOCATION	KWH	PERCENT	KWH	PERCENT	KWH	PERCENT	KWH	PERCENT	KWH	PERCENT	KWH	PERCENT
Bangkok, Thailand (1A)	57,665	2.8	127,306	6.3	111,027	5.5	73,744	7.0	50,263	4.8	127,746	12.2
Sao Paulo, Brazil (2A)	139,400	10.5	164,899	12.4	197,252	14.9	38,242	6.5	70,144	11.9	78,574	13.4
Atlanta, U.S. (3A)	63,182	7.3	92,423	10.7	101,523	11.8	38,814	9.5	45,299	11.1	56,352	13.8
Los Angeles, U.S. (3C)	106,761	13.3	108,262	13.4	133,400	16.6	42,774	11.9	59,158	16.5	72,703	20.3
Kansas City, U.S. (4A)	68,886	9.4	86,610	11.8	97,254	13.3	33,093	9.2	41,421	11.5	53,123	14.8
Berlin, Germany (5B)	48,018	12.0	58,989	14.7	71,269	17.8	29,450	16.6	32,686	18.5	41,509	23.4
Minneapolis, U.S. (6A)	51,493	10.4	65,398	13.2	73,906	14.9	22,757	10.2	31,366	14.0	36,849	16.5

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