NEXT GENERATION ENERGY EFFICIENT TECHNOLOGIES: A CASE STUDY DEMONSTRATING TOP OPERATIONAL PERFORMANCE

The Aventine Chiller Plant Optimization

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This article includes contributions by Optimum Energy Engineering Services

INTRODUCTION

As owners contemplate major capital upgrades and investments into their existing chiller plants, several considerations become apparent and require a thorough appraisal. These primary considerations include: Age of existing equipment, existing load profile, utility rates, building occupancy and tenant use, property repositioning plan, lease type and the property's asset strategy, and others. In Aventine's case, the building was considered by most real estate professionals and owners as a relatively young building at 17 years old. The building and chiller plant still had a good five to seven years of serviceable life. The challenge in this particular case was to propose an upgrade justifying replacement of this still functioning chiller plant while asking for approximately $500k in capital expense funds. In addition to describing the technical features of this next-generation chiller plant system, this case study will attempt to integrate financial decision making attributes that assisted in the decision making process. The focus of this paper is to differentiate this technology and approach with major chiller plant upgrades.

BUILDING STATEMENT/CHALLENGE

The Aventine is a 252,000 sq. ft. multi-use building located in La Jolla, California. It is a landmark, master planned commercial development situated in the University Town Center Market of San Diego's premier financial district. Built in 1990, the Aventine includes a 217,000 square foot Class-A office building and a 23,000 square foot restaurant complex built around the Hyatt Regency La Jolla with Michael Graves & Associates as the architects.

Glenborough LLC, owner of the Aventine complex, was looking at various methods to lower its energy consumption and reduce its carbon footprint. As one of the green technologies being implemented, the chiller plant was converted to a primary-only, all-variable speed system, and the 2×300 ton chillers were retrofitted with oil-less VFD centrifugal compressors. In addition, a patented, well proven software solution was chosen to optimize the all-variable-speed plant components. The chiller plant optimization project was installed to both lower HVAC energy consumption and improve the environmental footprint of the complex.

APPROACH

Following a feasibility study in which current and future loads, new technology, energy consumption, operating flexibility, and load shedding were analyzed, a design calling for an all-variable-speed chiller plant and an all-variable-speed plant-automation solution was chosen. In looking at an install that would meet a tight schedule targeting the early months of the 2008 cooling season, the design specification called for installing four variable frequency drives, four new Turbocor compressors, and Optimum Energy's OptimumHVAC software.

The plant's existing two McQuay centrifugal chillers rated at 300 tons each were approaching 18 years old, had minimal run time on both chillers, and were rated at 0.71kW/ton using (R-500). These

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chillers operated year round supplying an adjacent, unattached 100,000 sq.ft. fitness center requiring 100 tons of cooling. Even though these chillers were inefficient and approaching the end of their useful life, their reliability and continued operation was intact, and it was determined they would be able to operate for approximately another five to eight years.

In order to capture all the savings potential of the chiller plant retrofit to an all-variable-speed system, Aventine looked at various control options with the goal of finding a solution that would be cost effective, provide higher performance than what was available with traditional control methodologies, minimize downtime, be quick to learn, and provide consistent monitoring and optimization through the life of the plant. An open protocol software solution upgrade to the existing building automation system was selected. The solution provided straightforward and stable network-based sequencing controls in response to the dynamic load requirements of the building. This demand-based control methodology allowed the plant to be optimized for energy efficiency, maximizing the savings without compromising occupant comfort.

Once a software solution and contractor were selected, all of the key stakeholders involved met to review the scope of work and coordinate execution of the project. Because of the existing plant's accessibility and flexibility with staging work, the project started in early December of 2007. With a project of this type, long lead time with equipment and supplies were reduced and an installation timeline was condensed to accommodate the need for an early 2008 start date. The software solution enabled the project to reduce field programming time to half since all programming was done prior to or done off-site.

TECHNOLOGY BACKGROUND

With Hartman Loop technology as the basis of design, Optimum Energy's OptimumLOOP integrated plant-control system and OptimumHVAC Performance Assurance service enabled Web-accessible and local plant touch screen control allowing for a user-friendly icon-driven system schematic. The online Performance Assurance service also provided quantifiable metrics covering both energy and environmental savings for the conversion. Ease of use and monitoring were important to Aventine's owners and operating staff, as well as the local utility providing a utility rebate in excess of $100,000. This rebate contributed to the overall funding for the project, enabling it to perform below the required 36 month payback period.

The technologies behind OptimumLOOP are based on three primary principles:

(1) Natural Curve Sequencing of Chillers, Pumps, and Towers

The energy performance of constant speed chillers, pumps, and towers is maximized when components are operated as closely as possible to full load. Thus, chiller plant operating strategies generally involve sequencing plant equipment to minimize the amount of on-line equipment, which is operated at full load.

By contrast, optimum performance is attained in all-variable speed chiller plants when the equipment is operating at a specific part load that depends on the current external conditions. The curve of the loading at which each variable speed component achieves maximum efficiency as the external conditions (pressure or temperature) vary is called the "natural curve" of that component.

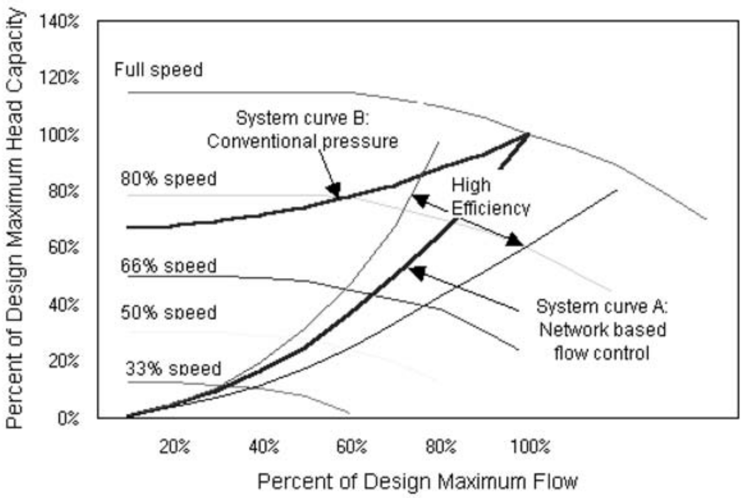
Because the Aventine converted to an all-variable speed system with VFDs, it was able to implement an optimization system. By employing a simple patented control methodology to sequence equipment based on demand, the plant is operated at all times as close as possible to the natural curves of the plant equipment contained in the plant.

Below is a diagram showing a System Curves comparison of Pressure vs. Network Based Controls, as it relates to the "natural curve" of variable speed centrifugal pumps, fans, or compressor equipment.

(2) Power-Based Speed Control of Condenser Pumps and Tower Fans

Conventional cooling tower control involves delivering a specific (sometimes reset) condenser water temperature to the chillers. This is usually delivered with constant speed condenser pumps. By contrast, an all-variable speed plant constantly modulates the tower fans and condenser pumps based on the load of the plant.

FIGURE 1. System Curves for Pressure vs. Network Based Control For Variable Speed Centrifugal Pumps, Fans, or Compressors.



(3) Network Control of Chilled Water Distribution Pumping

Chilled water distribution pumps are usually operated to maintain a specific distribution differential pressure. Sometimes this pressure setpoint is reset based on the maximum position of one or several of the valves on the loads served by the system. However, the use of minimum pressure setpoints can contribute to substantial wasted pumping energy, especially during periods of low loads that are frequent in systems operating on a 24/7 schedule.

The OptimumLoop optimization software installed in the Aventine chiller plant utilizes a network based method of distribution pump control that is particularly effective in large distribution circuits that may have different critical flow segments under different conditions or different times. It should be noted that at all times chillers and other components are operated within their manufacturer's recommended limits. OptimumLOOP continuously monitors the chilled and condenser water flows and rates of flow change, as well as the condensing water temperature. It also limits operation to ensure these parameters remain within the range recommended by the manufacturer for the specific chiller to which the control is applied. The automatic safety shutdown circuit on each chiller is also entirely functional so that chiller protection is undiminished.

Most efficient chiller plants of this size operate at an annualized average of 0.80 to 1.1 kW per ton, employing a variable-secondary pumping system, variable-speed chillers, and variable-speed cooling-tower fans. An "ultra-efficient" plant incorporates variable-speed primary pumping, variable-speed chillers, variable-speed condenser pumps, and variable-speed cooling-tower fans, and operates at an annualized average of 0.45 to 0.7 kW per ton. All electrically driven rotating mechanical equipment in the plant is variable-speed, enabling a more precise match of equipment operating speed/load to building load, while using the least amount of energy possible.

Aside from two-speed condenser fans, the original plant system at the Aventine was constant-speed, with the components selected for peak-load operation. The chilled-water-distribution system was constant-flow, utilizing three-way control valves. This provided for good temperature control, but used more energy than necessary when in bypass position, which was 95 percent of the time. The original system operated at an annualized average above 1.43 kW per ton.

With a typical North American plant operating at part load 95 percent of the time, the Aventine's new plant-system components were selected for high part-load efficiency. In a typical part-load daytime scenario, the new variable-speed chillers operate at approximately 0.32 – 0.40 kW per ton, whereas the former chillers operated at 0.85 kW per ton. Even at full load, the new retrofitted chillers operate at close to 0.6 kW per ton, compared with the former chillers, which operated at approximately 0.71 kW per ton.

TECHNOLOGY ADVANCEMENTS WITH THE HARTMAN LOOP

The Aventine wanted to utilize Hartman LOOP algorithms and control sequences in their chiller plant upgrade, but they realized that the original technology was several years old. Optimum Energy had taken what was originally a lengthy custom process of writing code and developing control sequences for each installation, and developed a software application that integrated with the existing building automation system.

During the development process, Hartman named these "LOOP" technologies because they employ integrated "closed LOOP" controls for the entire plant. With closed "LOOP" technologies, the operation of all chillers, pumps and towers is coordinated in order to optimize total plant efficiency under all conditions. Most equipment in conventional plants operates in standalone fashion, responding only to certain temperature or pressure setpoints rather than operating in coordination with related equipment. "LOOP" is also used to describe the chilled water distribution system in this technology that involves a fully determinant, single circuit chilled water loop instead of the common but less efficient decoupled primary/secondary systems.

The Aventine selected Optimum Energy's OptimumLOOP software application to optimize the operation of its chiller plants. OptimumLOOP's next-generation technology algorithms and control sequences of chiller control enables the Aventine chiller plant to constantly adjust chilled water flow, chilled water temperature, tower fan speeds, condenser water flow, condenser water temperature, and chiller load towards reaching this "natural curve" of equipment and maximize chiller plant efficiency.

WHAT IS NEW ABOUT THESE TECHNOLOGIES?

The most significant improvement of these patented all-variable speed chiller plant and distribution systems over conventional plants is the significantly reduced energy use in comfort conditioning applications. Using Optimum Energy's OptimumHVAC software solutions, the annual energy use of the entire chiller plant usually averages **0.6 kW/ton** or less for most comfort cooling applications. This represents an annual energy reduction of 30% to 60% (depending on climate and application) below the most highly optimized conventional configurations of components of the same operating efficiencies.

In OptimumHVAC chiller plants, all components are variable speed; and chiller sequencing endeavors to keep chillers and towers operating at lower loads and flows. This is in contrast to conventional plant operating strategies that keep on-line equipment at high loading. To achieve these higher levels of performance, an entirely new approach to operating the equipment in chiller plants has been developed. Aside from the use of variable speed drives and the intelligence that allows these different pieces of equipment to operate in unison, the pumps, chillers, and tower fans, and plant configurations are very similar to conventional chiller plants. What is completely new is how the equipment is sequenced and operated with simple, straightforward, and stable network based controls.

In addition, OptimumHVAC Performance Assurance allows real-time monitoring of HVAC system performance and verification of equipment status using an online portal. This allows building owners and operators to track efficiency and calculate cost savings, and it tracks equipment performance over time to help identify equipment problems before they become failures.

WHY THIS SOFTWARE SELECTION WAS IMPORTANT

Chiller retrofits traditionally take several months, are extremely intrusive to the building operation, and encounter many problems associated with the programming and interface of the software. OptimumLOOP optimization software overlays onto the existing controls allowing for a quicker integration and start up. The simple direct control algorithm programming of Optimum Energy's OptimumHVAC software takes place prior to the installation of the various other control equipment enabling chiller plants immediate energy reduction and savings.

IN WHAT APPLICATIONS ARE OPTIMUMHVAC TECHNOLOGIES MOST EFFECTIVE?

OptimumHVAC technologies have been developed specifically for chiller plants that serve comfort conditioning loads. Industrial process loads may be suitable if the process loads are variable, because this technology reduces energy use only at part load conditions. Warm, dry climates usually offer the best savings opportunities, but the technologies offer significant savings in comfort conditioning applications all over the world. The energy savings spectrum can estimate percentage savings for specific HVAC applications.

WATER SAVINGS

Evaporation in cooling towers is a result of building load as well as heat produced by the inefficiencies of the chiller plant. Inefficient chillers and motors dump their heat into the condenser system, which is in turn evaporated in the cooling towers. Reducing the energy usage of the plant results in significant water savings as shown by the chart below (Figure 2). The chart shows gallons per ton-hr at different plant efficiencies (0.5 to 1.25 kW/ton) and cooling tower cycles of concentration (1.5 to 10). By solely reducing the plant efficiency from 1.43 to 0.69 kW/ton, a 20% reduction in water is possible.

Reduced water consumption directly relates to additional cost savings, reduced chemical usage, and a decreased carbon footprint.

RESOLUTION

In comparing the pre-optimization equipment with the post-retrofit equipment installed at the Aventine, several of the new devices installed included variable frequency drives (VFDs) used in most plant operations today.

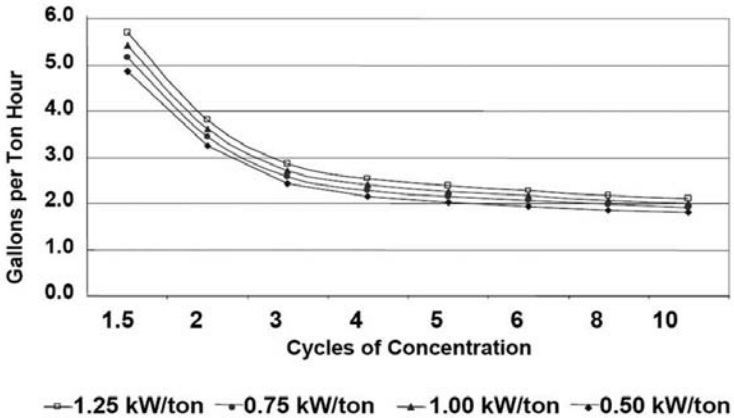
Pre-Optimization Aventine Cooling Plant Equipment

- (2) McQuay centrifugal chillers, 300 tons each and 0.71 kW/ton (R-500)
- (2) Dedicated chilled water primary pumps, 3 hp each
- (2) Chilled water secondary pumps, 30 hp each with VFDs (450 GPM)
- (1) Forced draft cooling tower, 2140 GPM (VFDs on 2 × 30 hp fans)
- (2) Condenser pumps, 60 hp each with VFDs (1070 GPM each)
- (1) Alerton direct digital control system

Pre-Retrofit Plant Operations

The central plant was a primary-secondary chilled water system designed for 600-tons of available capacity at a 16°F delta-T. The lag chiller started when the lead chiller was fully loaded and once started it remained on line until loading was low. Primary chilled, secondary chilled, and condenser water pumps were sequenced with chillers on a one-for-one basis. Cooling tower fans modulated using variable frequency drives to maintain the condenser

FIGURE 2. Cooling Tower Water Usage vs. Plant Efficiency and Cycles of Concentration (Source EPA).



water temperature setpoint throughout the year (set for 70°F). The VFDs on the condenser pumps were set to maintain a 10.5 psi differential pressure across the condenser barrels (850 GPM).

The speed of the secondary pumps was modulated to meet a differential pressure setpoint as measured at the end of the distribution circuit (25 psi). A decoupling line permitted flow in either direction at the end of the primary circuit since the "stepped" primary flow was nearly always different than the continuously variable secondary flow.

Central Plant Operating Efficiency

A pre retrofit analysis showed that the Aventine central plant was providing an average annual overall chiller plant system operating efficiency of 1.43 kWh/ton-hrs, which was typical of a "Chiller Plant with Correctable Design Problems." The chillers were inefficient by today's standards, used R-500 refrigerant, and were nearing the end of their life expectancy (production of R-500, containing a mixture of chlorofluorocarbon (CFC), was halted by the clean air act on January 1, 1996). See Table 1.

The pre-retrofit plant also experienced low delta T, had oversized condenser pumps, and used excessive energy at low loads. Low loads are very frequent at this site because the central plant also serves a gymnasium that is opened for extended hours through the year.

Truly effective solutions to such problems are relatively straightforward, and extending all-variable speed principles to the chilled water plant facilitated such solutions. After completion of the optimization project, the central plant is now operating at an average annual efficiency of 0.69 kWh/ton-hrs and is in the "excellent" category of Figure 3.

Optimized Aventine Cooling Plant Equipment

- (2) Turbocor centrifugal chillers, two TT400 compressors on each machine (R-134a)
- (2) Chilled water secondary pumps, 30 hp each with VFDs

TABLE 1. Refrigerant comparison for the Aventine chiller.

Chiller Refrigerant	Ozone Depletion Potential	Global Warming Potential
R-500 (pre-retrofit)	0.605	4080
R-134a (post retrofit)	0.000	1600

*Ozone Depletion Potential (ODP) defined as a measure of destructive effects of a substance compared to a reference substance Chlorofluorocarbons have ODPs roughly equal to 1.
**Global warming potential (GWP) is a measure of how much a given mass of greenhouse gas is estimated to contribute to global warming. It is a relative scale which compares the gas in question to that of the same mass of carbon dioxide (whose GWP is by definition 1).

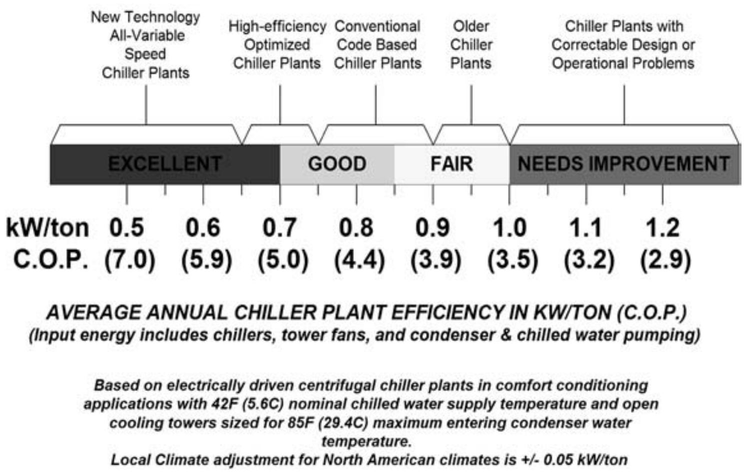


FIGURE 3. Chiller Plant Energy Use Spectrum.

- (1) Forced draft cooling tower, VFDs on 2 × 30 hp fans
- (2) Condenser pumps, 60 hp each with VFDs (1070 GPM each)
- (1) DDC system programmed with Optimum LOOP control sequences
- (8) Air-handler "commanded" valve position feedback from all two-way chilled water control valves

The Aventine retrofit included:

1. **Install two 150-ton Turbocor compressors on each existing chiller:** The oil-less centrifugal compressor uses R-134a refrigerant, magnetic bearings (no oil), and a direct drive system (no gears). It is currently manufactured in capacities of 60–150 tons. It weighs 80% less than traditional compressors, and the direct drive system and magnetic bearings reduce noise and vibration. The compressor has an integrated variable frequency drive (VFD) and offers excellent part load performance (down to 0.32 kW/ton).
2. **Eliminate all possibility of direct mixing between chilled water supply and return:** This means eliminating all decoupling lines and three-way valves. In this era of networked DDC and variable speed control, pumping systems no longer need to be decoupled. Furthermore, the new frictionless chillers accommodate varying flows over substantial ranges without any loss of efficiency or operational stability.
3. **Focus delta T attention at each and every load:** Once decoupling lines and three-way valves have been eliminated, the only source of low delta T problems is overflow through individual loads. Overflow can occur because of improperly sized valves and varying pressure differentials across valves. It can also occur when the air side of cooling coils becomes clogged or other maintenance failures take place.

   A simple means for preventing overflow is to install a temperature sensor on the return water line at each load, and use this temperature as a limit for the control valve serving the load. When the return water temperature fails to approach the design leaving water temperature for the coil, the valve is limited from opening further. This step eliminates the problem of low delta T at the load. The simple logic that limits the valve operation can also be employed to notify the operator that a maintenance problem may be affecting the operation of the load.
4. **Revised Plant Operation:** The speed of the operating equipment is carefully controlled by the DDC system to provide cooling at optimum efficiency under all operating conditions. The decoupling line was eliminated because the variable speed controls eliminate the requirement for bidirectional and bypass flow. Simple direct control algorithms coordinate the operation of chillers, pumps, and tower fans based on demand for cooling from the air systems that is determined by cooling coil valve position. Chilled water temperature and leaving tower water temperature floats (within preset limits) allow components to operate at highest efficiency at all times.

   The OptimumLOOP optimization software coordinates the operation of the condenser pumps and tower fan speed based on chiller loading. Electric chillers are sequenced on and off line according to the "natural curve principle,"[1] which sets a chiller kW threshold for sequencing based on current operating condenser and evaporator temperature conditions. Speed of the distribution pumps is controlled according to the "valve orifice area" method.[2]

The installation of Optimum Energy's Optimum-HVAC software to optimize the central plant was projected to save thousands of dollars annually. This patented software, combined with the installation of VFD's and new Turbocor compressors, allowed the Aventine building to improve its chiller plant efficiency from 1.43 kW/ton down to 0.69 kW/ton, a significant (51.7%) improvement in overall annual central plant efficiency.

1. Chiller performance (kW/ton) versus cooling capacity with a variable speed drive is plotted for various condenser water temperatures. The loci of the curves are connected producing the chiller's "natural curve."
2. The "valve orifice method" controls pump speed by using the percentage of total valve orifice area open to determine the required flow rate. This control method allows the head to go to zero as flow rate goes to zero.

CONSIDERATIONS FOR HVAC UPGRADES

Two factors are the determinants in an upgrade or retrofit decision, and both are economic in nature. The first are the metrics the building owner wants to achieve in terms of annual return on investment and overall building operating financials. The second relates to the economics of a building improvement plan. This needs to be answered by the project savings analysis and payback projections that firms like Optimum Energy very accurately provide in advance of a project implementation. With this data in hand, an owner can make a capital investment decision in the context of the project payback, and longer operating budget and value creation goals of the building.

COST/BENEFIT INFORMATION

- A utility incentive from San Diego Gas and Electric of $105,000.
- Annual cost savings totaling more than $136,000.
- Annual electricity savings of more than 637,400 kWh.
- Peak demand reduction of 37 kW.
- Annual CO_2 footprint reduced by more than 618,240 lbs.
- Annual reduction of dangerous pollutants SO_2 and NOx.
- The payback period for the entire project was under 3 years.

From the data shown in Figure 4 for the period February 1, 2008 to January 31, 2009, the plant operated at an average efficiency of 0.69 kWh/ton-hr. During this time, the plant produced 859,966 ton-hours of cooling. Figure 5 is sample screenshot of Aventine's total HVAC plant efficiency. With OptimumHVAC Performance Assurance monitoring,

FIGURE 4. Actual Aventine Performance Data: February 2008 through January 2009.

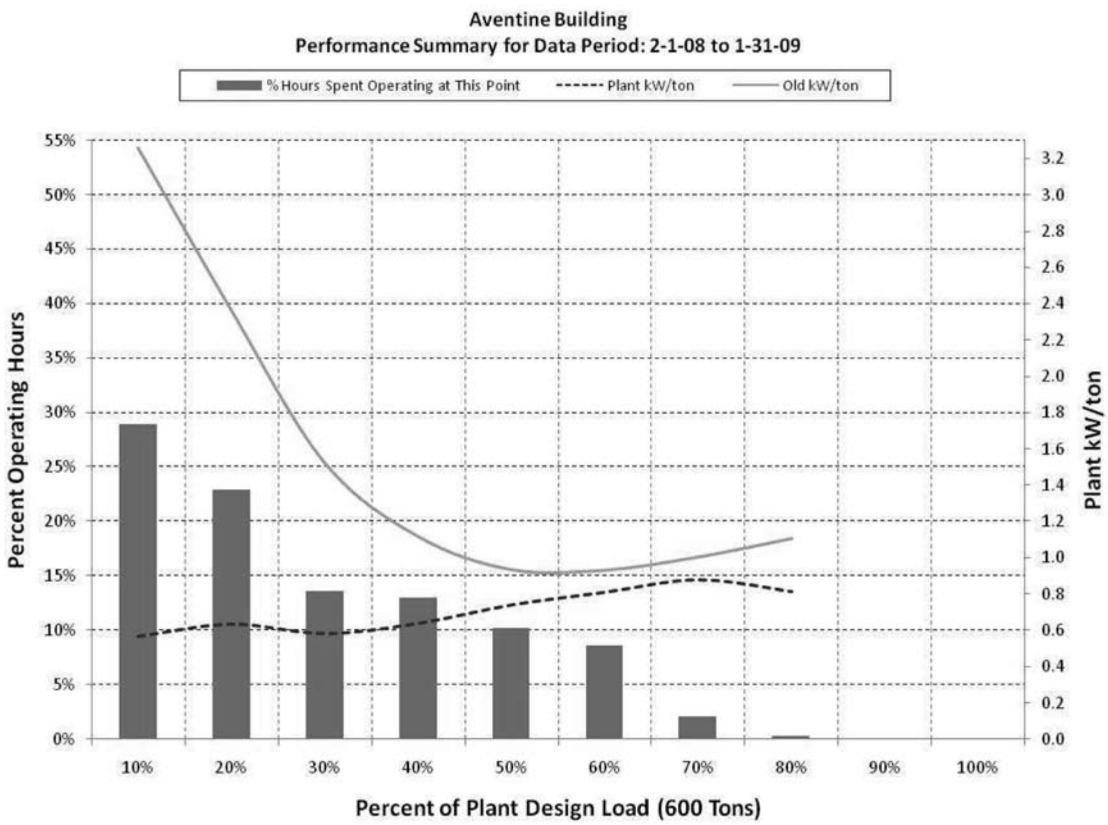


TABLE 2. CALCULATED.

Plant kW/ton	% Design Load	% Hours Spent Operating at this Point
0.57	10%	28.9%
0.64	20%	23.0%
0.58	30%	13.6%
0.64	40%	13.0%
0.74	50%	10.2%
0.81	60%	8.7%
0.88	70%	2.1%
0.82	80%	0.3%

TABLE 3. Plant Averages for the Year and Annual Savings.

Plant kW/Ton	0.69	kW/ton
Plant Tonnage	144.1	Tons
% of Total Load	24.02	%
Returning Condenser Water Temp	75.0	°F
Leaving Condenser Water Temp	70.5	°F
Chilled Water Return Temperature	54.0	°F
Chilled Water Supply Temperature	45.8	°F
Ton-hrs produced	859,966	Ton-hrs
Chiller #1 Total Run Hours	3,562	Hrs
Chiller #2 Total Run Hours	3,428	Hrs
Total Energy Savings for year	637,418	kWh
Total CO2 Savings	662,277	lbs

Aventine's building operators are able to see at any given time via the Web how the plant is operating. At the time this screenshot was taken, one chiller was enabled, as well as several pumps and fans, and overall chiller plant kW/ton was 0.414. This is one of several dashboards that provide measurement and validation of HVAC system performance, including real-time energy usage, energy and carbon savings, and component monitoring, as well as trend data that helps with preventive maintenance.

The tables on this page show the percent of time operated over the range of loads. Entering condenser water temperature from the cooling tower varied between 60°F. and 85°F. while chilled water supply temperatures are variable between 42 and 48°F. Annual savings were calculated at 637,418 kWh or $136,142, a 51.7% reduction in chiller plant energy from February 2008 to January 2009. The facility carbon footprint was reduced by more than 618,240 lbs.

UTILITY SAVINGS

The utility data below, obtained from the San Diego Gas & Electric (SDG&E), is for the period beginning February 1, 2008 and ending January 31, 2009. Energy cost savings were recorded at $136,035 as compared to the previous year's total. This translates into a $0.63 cent per sq.ft. reduction in operating expenses.

TABLE 4.

Month	Cost '07-'08	Cost '08-'09	Cost Savings
February	$51,452	$38,226	$13,226
March	$47,792	$37,436	$10,356
April	$46,841	$37,772	$9,069
May	$47,081	$39,994	$7,087
June	$47,322	$37,870	$9,452
July	$54,433	$44,246	$10,187
August	$63,954	$42,528	$21,426
September	$61,390	$48,044	$13,346
October	$49,740	$44,159	$5,581
November	$46,768	$38,805	$7,963
December	$63,043	$37,742	$25,301
January*	$41,936	$38,896	$3,040
TOTALS	$621,753	$485,718	$136,035

*Estimated cost from annual average

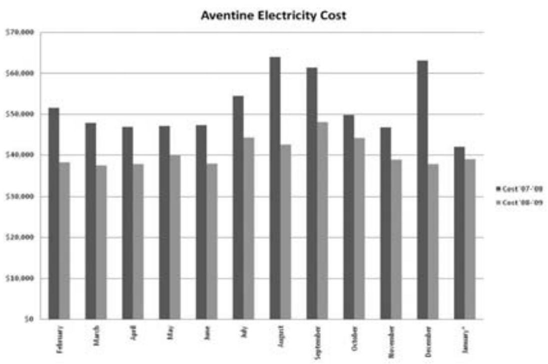


FIGURE 5. Performance Assurance Dashboard for the Aventine Plant: Total plant efficiency.