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Publication Date
2014-06-30

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Data and Analytics to Inform Energy Retrofit of High Performance Buildings

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May 2014

This work was sponsored by the U.S. Department of Energy (Contract No. DE-AC02-05CH11231) and the China Ministry of Housing and Urban - Rural Development and the Ministry of Science & Technology (Grant No. 2010DFA72740-02) under the U.S.-China Clean Energy Research Center for Building Energy Efficiency.

This is published as an article at Journal of Applied Energy, 126: 90-106, 2014.

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Abstract

Buildings consume more than one-third of the world's primary energy. Reducing energy use in buildings with energy efficient technologies is feasible and also driven by energy policies such as energy benchmarking, disclosure, rating, and labeling in both the developed and developing countries. Current energy retrofits focus on the existing building stocks, especially older buildings, but the growing number of new high performance buildings built around the world raises a question that how these buildings perform and whether there are retrofit opportunities to further reduce their energy use. This is a new and unique problem for the building industry. Traditional energy audit or analysis methods are inadequate to look deep into the energy use of the high performance buildings. This study aims to tackle this problem with a new holistic approach powered by building performance data and analytics. First, three types of measured data are introduced, including the time series energy use, building systems operating conditions, and indoor and outdoor environmental parameters. An energy data model based on the ISO Standard 12655 is used to represent the energy use in buildings in a three-level hierarchy. Secondly, a suite of analytics were proposed to analyze energy use and to identify retrofit measures for high performance buildings. The data-driven analytics are based on monitored data at short time intervals, and cover three levels of analysis – energy profiling, benchmarking and diagnostics. Thirdly, the analytics were applied to a high performance building in California to analyze its energy use and identify retrofit opportunities, including: (1) analyzing patterns of major energy end-use categories at various time scales, (2) benchmarking the whole building total energy use as well as major end-uses against its peers, (3) benchmarking the power usage effectiveness for the data center, which is the largest electricity consumer in this building, and (4) diagnosing HVAC equipment using detailed time-series operating data. Finally, a few energy efficiency measures were identified for retrofit, and their energy savings were estimated to be 20% of the whole-building electricity consumption. Based on the analyses, the building manager took a few steps to improve the operation of fans, chillers, and data centers, which will lead to actual energy savings. This study demonstrated that there are energy retrofit opportunities for high performance buildings and detailed measured building performance data and analytics can help identify and estimate energy savings and to inform the decision making during the retrofit process. Challenges of data collection and analytics were also discussed to shape best practice of retrofitting high performance buildings.

Keywords: analytics; data model; energy benchmarking; energy use; high performance buildings; retrofit

1. Introduction

In 2010, the U.S. accounted for 19% of the global energy consumption – more than any other country except China [1]. The buildings sector is responsible for about 41% of the U.S. primary energy use and 8% of the world's CO_2 emissions [2, 3]. Globally the buildings sector consumes more than one-third of the world's primary energy. It has been demonstrated that most existing buildings operate with various levels of deficiencies, and the problems of building energy performance are pervasive and well known [4]. Thus it is important to identify and realize energy saving opportunities in the buildings sector to reduce energy use and carbon emissions.

Currently, more and more attention is drawn to high performance buildings (HPBs), aka green, sustainable, and low energy/carbon buildings, discussed in many studies [5-7]. HPBs are buildings receiving higher rating scores under various building performance rating and labeling systems. Though such buildings are designed to be more energy efficient than other buildings, more efforts and retrofits are needed to maintain their high performance status [8, 9]. Whether there exists any deeper energy savings for HPBs and how to identify such opportunities become an important concern for not only the government, but also the building owners and facility managers.

In February 2011, President Obama announced the Better Buildings Initiative to make commercial and industrial buildings 20% more energy efficient by 2020 and accelerate private sector investment in energy efficiency [10]. In this aspect, California has been a leader since the inception of the Building Energy Efficiency Standards – Title 24 [11] in 1978. California buildings also received higher Energy Star scores compared with the national stock [12]. Further, more energy codes and savings targets were set in subsequent state policies, such as the Energy Action Plan [13], Assembly Bill 32 - Global Warming Solutions Act [14] which sets California's target of reducing GHG emission to the 1990 level by 2020, and Assembly Bill 758 - Comprehensive Energy Efficiency Program for Existing Buildings [15]. On the other hand, owners and managers of HPBs can also benefit from improving building operation and maintenance, reducing energy cost, extending equipment life span, and improving indoor environmental quality and employee productivity. However, it is not easy to find out the specific energy savings potential and related retrofit measures for HPBs which already employ energy efficient technologies and design strategies to reduce energy use - no low hanging fruit in this case. Although building simulations can be used to analyze energy performance and estimate savings potential of building technologies [16-21], creating and calibrating energy models is a time-consuming effort. The other approach is to measure and analyze performance of buildings. Since energy savings may lie in some specific end-uses or equipment, traditional analysis methods, based on the whole building's total energy use data from monthly utility bills, are far less adequate. Though some new approaches have been studied and implemented in real projects for a long time, such as energy benchmarking, building energy simulation, building energy monitoring, and fault detection and diagnosis, there is a lack of holistic and uniform approach for energy consultants or building managers to follow [22]. Besides, due to the lack of comprehensive and detailed monitored data, the previous studies and projects mainly focus on some aspects of the building energy performance, or portion of the building systems. For example, only energy use patterns or system operating efficiency is analyzed, only lighting system or heating, ventilation and air conditioning (HVAC) system is considered [23, 24].

There are three main reasons to study the retrofit of HPBs: (1) HPBs do not necessarily consume less energy than normal buildings [25], (2) operational changes and maintenance issues can degrade performance of energy systems [26, 27], and (3) building owners or regulations may require further energy savings. In this study, a new holistic approach using measured building performance data and analytics were proposed, for the purpose of identifying energy use patterns, operation deficiencies and then retrofit measures for major energy end-uses in existing HPBs. This study aims to shed some light on energy retrofit of high performance buildings by exploring answers to the following questions:

1. Are there energy savings in retrofitting HPBs?
2. What types of measured building performance data is needed to enable the analyses?
3. What analytics can be used to identify and evaluate energy retrofit measures?
4. What are the main challenges of using data-driven analytics to inform retrofit of HPBs?

The first section of this paper describes three types of measured building performance data which are needed to enable the analytics. An energy data model based on the ISO Standard 12655 “Presentation of real energy use of buildings” [28] is used to represent the energy use in buildings in a three-level hierarchy. Next, analytics were proposed to analyze energy use in buildings and to identify retrofit measures for high performance buildings. Then, as a case study, these analytics were applied to retrofit of a HPB in California. Finally conclusions and discussion of challenges were provided.

2. Building Performance Data

As Peter Drucker, a management thinker, said “you can’t manage what you can’t measure.” To fully understand and manage energy use and performance of buildings, good quality measured data from energy monitoring systems, building automation systems, and building energy management and control systems are crucial. Unfortunately for most buildings, only one electric meter and one natural gas meter are usually installed, and only monthly electric and gas use data from utility companies are available. This is far from adequate to tell the details of how, when and where energy is consumed in buildings, leading to a huge information gap in building operations which need detailed performance data and analytics to provide insights to improve operations, inform retrofit, and reduce energy use. It should be noted that in the U.S., smart meters with time interval electric use data are expanding rapidly, which can fill some information gap. On the other hand, data quality is always an issue in most buildings as meters and sensors lack maintenance and calibration, were installed incorrectly, or were purchased with low resolution and quality due to cost considerations.

2.1 Three types of data

There are three types of measured building data that are needed to enable energy analytics for buildings and inform retrofit decisions:

(1) energy use data

Energy use data include whole building total energy use as well as major energy end uses. Whole building energy use includes electricity and fuels like natural gas. The major end uses include indoor and outdoor lighting, plug-loads, data center, kitchen equipment, elevators, domestic hot water, and HVAC equipment such as chillers, boilers, cooling towers, fans, pumps, DX (Direct Expansion) units, and radiators for heating. Energy use data at a time interval of one hour or even a few minutes for a complete year covering four seasons is necessary for energy profiling to identify energy use patterns.

(2) operating data of HVAC systems

HVAC systems consume a significant portion of energy in buildings. Therefore, adequate data to help understand and manage how HVAC systems operate is important to reducing their energy use. Operating data of HVAC systems include supply and return air and water flow rates, outdoor air flow rate, supply and return air temperature and humidity, damper and valve positions, operating status (on/off, loads, power, rotation speed, etc.) of HVAC equipment such as cooling and heating coils, fans, pumps, chillers, boilers, cooling towers, air economizers, and roof-top units. These operating data at small time interval such as 5 to 10 minutes are needed to analyze and pinpoint potential control and performance problems of HVAC systems and equipment.

(3) indoor and outdoor environmental data

Environmental data include indoor and outdoor conditions – air temperature, air humidity, CO_2 level, illuminance level, noise level, can be quite helpful to analyze the service level (indoor air quality, thermal, acoustical, and visual comfort) provided by a building. These data are also key to troubleshooting comfort or IAQ related occupant complaints or health problems in buildings.

2.2 Data model of energy use

The energy metering systems and energy data categorizing structures can be different from building to building. For example, lighting of a building includes outdoor lighting, emergency lighting, indoor lighting which further separates into ambient overhead lighting and desktop task lighting. Thus measured lighting energy use from different buildings can include different lighting categories and thus cannot be compared directly on an apple-to-apple basis. In other words, Building A consumes more lighting energy than Building B would not tell the details of how each lighting category or sub-system compares – a missing key information required for decision making in lighting benchmarking or retrofit. A uniform energy data model which includes major end-uses can be significantly helpful for energy benchmarking of buildings. In this study, the standard data model defined in ISO Standard 12655 [28] is adopted for end-use benchmarking, shown in Figure 1.

This model follows a hierarchy structure, from total building energy use (first tier) down to four main categories (second tier) and to each major end-use (third tier). End-uses in both the first and second tiers are described clearly in the standard. Ideally, it can be applied to most buildings, and benchmarking can be performed across buildings based on these detailed end-uses.

3. Building Performance Analytics

In order to qualify and quantify how the building energy service systems are performing and how the performance can be improved, ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) defined three progressive levels of energy audits: (1) walk-through analysis/preliminary audit; (2) energy survey and analysis; and (3) detailed analysis of capital intensive modifications [29].

To support some of the efforts defined in the ASHRAE three levels of energy audits and go beyond them to help retrofit HPBs, a suite of data-driven analytics for building energy use are proposed in this study, which are categorized into three levels and are based on measured building performance data.

3.1 Energy Profiling

As the first level of building energy analysis, energy profiling is conducted within an individual building. It can show the use pattern of both the whole building’s total energy use and each particular end-use, based on different time scales – annual, monthly, weekly and daily analysis. Besides, it can help building managers clearly see the discrepancies of energy use characteristics between different seasons, working day and non-working day, day and night, peak and base, etc.

The data required for energy profiling should include not only the whole building's total energy use, but also each major end-use, as detailed as possible. Furthermore, in order to fulfill analysis with different time scales and at typical time periods, at least one complete year of valid data with hourly or sub-hourly sampling frequency is required.

3.2 Energy Benchmarking

The second level of building energy analysis, energy benchmarking, is becoming an increasingly important approach to identifying energy saving potential. Benchmarking methods have been studied for years, while benchmarking tools or databases have been widely used, including the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) Rating System, Energy Star Portfolio Manager, Commercial Building Energy Consumption Survey (CBECS) [30], and the California's Commercial End Use Survey (CEUS) [12, 31-35]. Traditional whole-building benchmarking was extended by action-oriented benchmarking in many ways, for example, energy use of specific end-uses, and even features and efficiency characteristics of specific systems or components can be benchmarked against a stock of similar buildings in the database [36]. Thus, energy saving potential may be identified through such comparison between the case study building and its peers.

To benchmark the operating efficiencies of HVAC systems and components, real-time monitored operating data are also needed, including water/air flow rates, supply and return water/air temperatures, etc. Energy use data represented in a consistent data model such as the ISO Standard 12655 is necessary for effective energy benchmarking.

3.3 Energy Diagnostics

Based on the knowledge of energy use profiling and benchmarking, more efforts should be made to investigate the systems or components which are relatively less efficient and have energy saving potential. The third level of building energy analysis, energy diagnostics, is a further approach for an individual building retrofit to understand what is going on deeply inside the operating of energy services systems in buildings, especially HVAC systems, and to find out specific measures to improve. For example, great importance is attached to how efficiently each chiller, fan or pump is performing respectively, and whether the outdoor air economizer (OAE) is operating as normal and efficiently as designed [37-39]. It is important that energy diagnostics should be conducted based on the results from the first two steps, instead of being conducted for any equipment randomly, where there may be no or very limited savings. Moreover, the first two types of analysis can be integrated into energy diagnostics, the most important and comprehensive analysis.

Energy use data and operating condition data are both essential for energy diagnostics. Sometimes an even higher data sampling frequency, like 1 minute, is necessary for analyzing special equipment (e.g. a chiller or a cooling tower) which changes its status quickly.

4. A Case Study

To better understand how the analytics can be applied to retrofit of HPBs, the California State Teachers' Retirement System (CalSTRS) Headquarters building, shown in Figure 2, is taken as a case study.

4.1 Building Description

Located in West Sacramento, California, this building is a thirteen-story office tower above a five-story podium for cafés, public access areas and parking space. The mechanical room is on the top two floors. Key energy features include the use of high performance glazing, under-floor air distribution (UFAD) systems with variable speed fans and occupant adjustable diffusers, variable speed chillers, air-side economizer, demand controlled ventilation, high efficient lighting systems with manually on and dimmable lamps, and daylight controls. The building was completed in 2009 and was awarded a LEED New Construction Gold certification. It was later awarded a LEED Existing Building: Operations and Maintenance (EBOM) Platinum certification in 2011, and achieved an ENERGY STAR rating of 92 in 2012 [40, 41]. The CalSTRS Building achieved better performance than the design energy goal mainly due to the integrated design and operation strategy: (1) facility managers and building operators were brought early in the design process to provide critical inputs, (2) commissioning and retro-commissioning were done right after occupancy and before seeking LEED EBOM certification, and (3) good operation and maintenance practices to continuously improve building performance.

Since building functions are complicated and detailed end-uses can hardly be separated for the podium, only the office tower is considered in this study. The office tower has a total floor area of about 29,728 m^2 (320,000 ft^2). Building descriptions are summarized in Table 1, mainly based on site visits and interviews with the building manager. It is important to note that different HVAC systems serve the office tower and the podiums. Chillers, gas boilers and an AHU are used for the office tower, while water source heat pumps (WSHPs) are used for the podiums. However the WSHPs share the cooling towers and gas boilers for cooling and heating with the main AHU for the office tower.

4.2 Post Occupancy Survey

In 2011, a series of surveys and interviews were performed on this building by a group of researchers, focusing on the indoor environment quality (IEQ) [40]. The results show that the CalSTRS Building performs well in relation to LEED-rated buildings, all office buildings and buildings with UFAD. Occupants in this building reported being more satisfied with most of the major IEQ factors, including temperature, air quality, lighting level and so on, in this building than were their peers. However, even though relatively better than its peers, thermal comfort of the UFAD is still a major complaint in this building. Overcooling, with too much air conditioning, is quite common in this building, especially on the north side. Occupant training on how to use the diffusers of the UFAD was one recommendation by the researchers. Useful and important though it is, the research lacks detailed energy data and operating condition data to demonstrate how well the building is performing exactly. Therefore, the data-driven analytics become more significant to help answer important and detailed technical questions.

4.3 Data Collection

To conduct the three levels of energy analysis, real-time monitored data are exported from the EMS and BAS. Generally, EMS is responsible for real time monitoring and the storage of detailed energy data, while BAS is mainly used for automatic controls, fault detection and diagnostics of systems and major components. Therefore, energy use data, including major end-uses, are mainly collected from the EMS with one-hour time interval, while HVAC operating condition data and environmental condition data are collected from the BAS with a shorter time interval of 15 minutes or even one minute. Table 2 shows a list of major data points used in this study.

Energy use data for condensing water pumps (CWPs), chilled water pumps (CHWPs) and hot water pumps (HWPs) are collected from the BAS, due to the mix and out-of-service monitoring data point in the EMS. Since the data completeness is different between these measurement points, CWPs' energy consumption was derived from run time and nominal power, while CHWPs' and HWPs' energy consumption came from direct measurement in the BAS. A data correction process was conducted for missing data and obvious invalid data, to ensure the data are complete and valid for further analysis.

Since the gas meter for the boilers is out of service, only electricity consumption data is collected and used to calculate the energy use intensity (EUI) of the CalSTRS Building in this study.

4.4 Energy Profiling

In this section, energy profiling is conducted for the case study building, including annual, monthly, seasonal, weekly and daily analysis, based on the monitored data from March 2012 to February 2013. The floor area of 29,728 m^2 is used for calculating the EUIs for both the total energy use and major end-uses.

4.4.1 Annual Analysis

Generally, the total electricity EUI during this time period is about 142 kWh/m^2a. To get an overall knowledge about how energy is used for various sub-categories of this building, annual breakdowns of EUI are shown in Figure 3, with (a) showing the breakdown of the office tower, (b) and (c) showing the further breakdowns of the two largest end uses: the data center and the HVAC system.

It is clear that the data center accounts for nearly half of the total electricity use, and HVAC (24%) takes the second place, followed by office equipment (13%) and lighting (11%), while elevator only accounts for a small part. Therefore, more attention is paid on the data center and HVAC in the following retrofit analysis.

Further inside the data center, IT equipment and computer room air conditioner (CRAC) units account for 60% and 40% respectively, while in the HVAC system, air movement is the largest energy consumer, followed by space cooling. Since gas consumption data is not included, electricity use for space heating, including boiler fans and the HWPs, is fairly small.

4.4.2 Monthly Analysis

After the annual analysis of total EUI and major sub-categories, it is imperative to go further into monthly data analysis, in order to find out energy use patterns for various end-uses. Monthly breakdowns of the total EUI and the HVAC EUI are shown in Figure 4 and Figure 5 respectively.

As can be seen, sub-categories such as IT equipment, lighting and plug-loads, which are less weather dependent, consume relatively constant energy throughout the year, while HVAC energy use changes apparently from month to month, and reaches its peak in August –probably the hottest summer month of the year.

Besides, the month-to-month variations of HVAC energy use are mainly due to the changes of electricity consumed by the AHU fans, chillers, cooling tower fans and CWPs, where the AHU fans and chillers are the two dominant consumers.

It should be noted that, due to the data in the BAS were missing during 09/13/2012 ~ 12/07/2012, the monthly energy use for the CWPs, CHWPs and HWPs during that period was estimated using available data from other periods. This approximation would not change the analysis results considering the total of such energy uses is relatively small.

4.4.3 Seasonal, Weekly, and Daily Analyses

The next level of analyses using detailed hourly energy data can further reveal energy use patterns of the building. Figure 6 shows a comparison of total electrical power, including the energy consumption in the data center, between four typical weeks in different seasons, with hourly data starting from 12:00 am on Monday. Since there is a lack of data during 09/13/2012 ~ 12/07/2012 for some end-uses, and the EUI in September is similar to that in May, a week in early September was selected as a typical week in fall, for more accurate analysis.

Generally speaking, the base load during night is nearly the same, while the peak load during daytime is higher in summer and lower in winter, except 09/03/2012 which is the Labor Day holiday in the U.S. It is obvious that energy uses during the day and night are quite different, especially on working days.

For further assessment of the energy use pattern, it is important to calculate the ratio of average load on working days to that on non-working days during a same week, and the ratio of average daytime load to average night load. Table 3 shows the ratios for the typical weeks and typical days (Wednesdays) in the four seasons, as well as their average values. Table 4 shows the comparison of the average load ratios between this building and three reference buildings (RBs) analyzed in another study conducted by the authors [42]. RB 1 (54,490 m^2) and RB 2 (39,211 m^2) are two large office buildings in Beijing, China, while RB 3 (8,316 m^2) is an office building in California, the U.S. It should be noted that the data center is excluded in such calculations for the purpose of fair comparison, as the data center in this building consumes too much energy, while its counterparts in the RBs account for small fraction of the total electricity use.

Generally, higher load ratio indicates higher energy efficiency in terms of operating pattern of the whole building. Given the constant nighttime base load of the CalSTRS Building, the ranking of day to night load ratios represents the ranking of the daytime peak load. The lower load ratio of working day to non-working day in Fall is mainly caused by the holidays, on which less energy was consumed than expected. According to the average load ratios in Table 4, the CalSTRS Building is much more efficient than the three peer buildings, indicating that more unnecessary equipment are turned off at night and on non-working days in this building. However, in terms of the load ratios of working day to non-working day, the superiority of this building to its peers is not obvious enough, which indicates some energy saving potential exists for this building by turning off more unneeded equipment at weekends.

Another observation from Figure 6, the total energy use usually experiences an obvious increase during night, from midnight to early morning, especially in September. To better understand the driving factors of such phenomena, the energy use of major sub-categories in a typical September week is shown in Figure 7. It can be seen that the nighttime increase was caused by HVAC, and the HVAC also consumed relatively high energy use at weekends unexpectedly. Besides, while IT equipment and CRAC units in the data center consumed constant energy throughout the week, the energy used by lighting, plug loads and elevators seem to follow the daily working schedule.

Since HVAC has such a significant influence on the variation of the total energy use, it is imperative to break down HVAC energy use further into sub end-uses. Hourly data of the HVAC's major end-uses on a typical weekday and weekend in September are shown in Figure 8 and Figure 9 respectively.

It is obvious that the nighttime power increase on weekdays was mainly caused by AHU fans, with exhaust fans having a little influence as well. This is due to the night purge, which occurs when indoor air temperature is much higher than outdoor air temperature, using outdoor air to cool down the building at night and reducing cooling load at daytime. In fact, night purge is quite common in this building, sometimes for pre-cooling and sometimes for pre-heating, according to the control strategy.

Most HVAC end uses, especially AHU fans and chillers, reach their peak at 3~4 PM, contributed to the peak HVAC energy use in the afternoon. It can also be observed that AHU supply and return fans as well as exhaust fans began operating at around 5 AM on both weekdays and weekends, about five hours earlier than other equipment. This drives the higher energy use for air movement. Energy use can be reduced if the exhaust fans are operated with VFDs instead of on/off schedules.

As for the weekend, the HVAC system still operated, though at lower power. There might be potential to turn off or turn down some HVAC equipment during the weekend to save energy. For example, operating one supply and return fans when only one floor is occupied.

4.5 Energy Benchmarking

4.5.1 Benchmarking with peer buildings

To better understand how efficiently the CalSTRS Building is performing among its peers, benchmarking was conducted mainly against the CEUS database which contains 2790 commercial buildings in California. There are 31 buildings selected from the CEUS database as the peer group of the CalSTRS Building. All of the 31 buildings are large-sized office buildings, over 13,935 m^2 (150,000 ft^2), and were constructed after 1991.

First of all, shown in Figure 10, the 31 sample buildings are ranked based on annual total electricity use intensity, ranging from 100 to 460 kWh/m^2, with a median value of 173 kWh/m^2. Though the annual EUI of CalSTRS Building, 143 kWh/m^2, is much lower than that of the samples' median value, it is still larger than about 20% of the samples, indicating there is energy saving potential for this building.

One step further, the end-use benchmarking between the CalSTRS Building and the average level of the samples is shown in Figure 11, with (a) showing four major sub-categories of the whole building and (b) showing three sub-categories of HVAC. According to the end-use labels in the CEUS database, office equipment, instead of plug-loads, was adopted in the uniform benchmarking against the peer group. It is clear that the annual EUIs for HVAC, lighting and office equipment of the CalSTRS Building are much lower than the average levels of the samples. However the sub-category "Other" shows the opposite results, mainly because "Other" in the CalSTRS Building includes not only elevators, DHW pumps and so on, but also the high-energy-consuming data center. Further in depth, the discrepancy of HVAC energy use is mainly caused by space cooling, while energy used by air movement in the CalSTRS Building is nearly the same as the samples' average level, shown in (b).

Similarly, EUI rankings for some major sub-categories are shown in **Figure 12**, along with the CalSTRS's EUI and the samples' median value. It can be inferred that much more energy saving potential lies in the air movement than in any other major sub-category. In addition, the better performance of lighting is consistent with the survey results in [40], showing occupants' appreciation of natural lighting in this building.

4.5.2 Data Center Benchmarking

Since the data center consumes nearly half electricity of this building, much larger than the ratios of most other buildings, it is essential to conduct benchmarking dedicated for the data center, in order to see whether there is retrofit opportunity to save energy.

In this field, the power usage effectiveness (PUE), defined as the ratio of total data center energy consumption to the IT equipment energy consumption, is becoming a widely-used metric for assessing overall data center energy use efficiency [43, 44]. According to the Uptime Institute's 2012 Data Center Survey, the PUE of the global average of respondents' largest data centers is between 1.8 and 1.89 [45]. In the meantime, some benchmarks, shown in Table 5, were provided by Lawrence Berkeley National Laboratory (LBNL) for their database, with an average PUE of 1.83 [46].

Based on the definition, the annual average PUE of the CalSTRS Building is 1.66, with a highest monthly average PUE of 1.89, which occurred in February. It is clear that the data center in this building performs normally, with the PUE located between the Standard and Good. Though, there still exists some energy saving potential for this data center, when compared with the average PUE of large Google data centers, about 1.1 all year around [45]. Assuming that the average PUE of this data center was reduced to 1.1 from 1.66, while IT equipment's energy use stayed constant, then about 696,000 kWh of electricity might be saved per year.

Besides, more efforts should be made to reduce energy used by IT equipment, such as replacing inefficient servers, powering down servers when not in use, increasing part load ratio of servers, consolidating servers, and so on [47].

4.6 Energy Diagnostics

4.6.1 Chiller

Though space cooling of the CalSTRS Building consumes less electricity than its peers, some abnormal phenomenon can be found when data is collected and analyzed with higher sampling frequency, especially for the two centrifugal chillers. Figure 13 shows one chiller's performance on a typical weekday in spring, with one-minute time interval. Both the power and the part load ratio (PLR) are displayed for the chiller, which was operating alone during that time. Though the chiller is equipped with variable speed drive (VSD), frequent and intense cycling lasting for a fairly short time occurs during periods of low loading such as the beginning run times in the morning, sometimes cycling off after only several minutes, which is harmful to the equipment's efficiency and life span as well. Not until the afternoon did the chiller begin maintaining operating normally for a longer time. More seriously, the frequent cycling is quite common for a single chiller's operation, when cooling load is low, including not only transition season, but also some weekends in summer. Therefore, it is essential to figure out how often such phenomena may occur, and to what extend the low PLR may influence the chillers' COP and power.

Based on the 15-minute data, the PLR frequency distribution histogram for the whole cooling season (from February to September) is shown in Figure 14, separating the situation that only one chiller was operating and the situation that both chillers were operating together. The PLR here represents the ratio of total cooling load to the rated cooling capacity of one chiller. It can be seen that the PLR is lower than 1 for most of the time, and lower than 0.5 for nearly half of the time. The two frequency peaks for PLR occur in 0.2~0.5 and 0.8~1.0 respectively.

Meanwhile, the relationship between the PLR and COP is shown in Figure 15, indicating a relatively high COP when PLR is equal to or greater than 0.6, compared with the rated COP of 7.6. However, the COP goes down sharply as the PLR decreases. It can be much lower than the rated COP when the PLR is below 0.4, which accounts for about 36% of the time in a cooling season. Considering the equipment's efficiency and service life, it is suggested that one of the two chillers be replaced with a smaller one. Then the cycling phenomena can be reduced and COP can increase due to higher PLR.

To estimate the energy savings of such a retrofit measure, the concept of DCOP and ICOP was introduced to deeply analyze the chillers' performance [37]. Considering different influences of internal and external factors, COP can be described as the product of DCOP (internal efficiency) and ICOP (ideal efficiency), defined by:

$$ICOP = \frac{T_{ev}}{T_{cd} - T_{ev}} \qquad (1)$$

$$DCOP = \frac{COP}{ICOP} \qquad (2)$$

Where T_{ev} and T_{cd} in Equation (1) represent the chiller evaporating temperature and condensing temperature respectively. While ICOP is mainly driven by outdoor environment, DCOP is strongly related to PLR. Based on existing studies and practical experience in engineering, DCOP can be described as a quadratic function of PLR for centrifugal chillers, as in this case [37]. Shown in Figure 16 is the correlation between DCOP and PLR for the whole cooling season with the 15-minute data, when only one chiller is operating. The trend line of the scatter plot is also displayed as well. Based on this performance curve, DCOP can be estimated when PLR is given. As mentioned before, if one of the two 375-ton chillers was replaced with a smaller chiller, with half of the current cooling capacity, the new PLR would be larger than before, and hence improving the DCOP, providing that the correlation between DCOP and PLR stays the same for this type of chillers. According to the cooling load's frequency distribution and the DCOP ~ PLR correlation, the integrated DCOP of the two chillers might be increased to 0.48 from 0.41 for the whole cooling season, when proper control strategy was adopted. For example, as the cooling load increases, the new smaller chiller runs first to meet low loads until its full capacity is reached, then it is the larger chiller's turn to meet the load until its 100% capacity, and finally the smaller chiller is also turned on so that both chillers operate together.

Therefore, providing the other factors remained the same as before, integrated COP would increase by 15%, and thus total energy use of the chillers would decrease by about 14%, saving about 18,507 kWh of electricity per year.

4.6.2 AHU Fans

As shown in previous sections, air movement, especially AHU fans, accounts for a large part of the building's total electricity use and shows energy saving potential when benchmarked with the CEUS database. However, when the fan system efficiency is taken into account, the AHU system seems to perform well, shown in Table 6 [35], and much better than designed, shown in Table 7. Therefore, although the AHU fans consumed significant amount of electricity, they are highly efficient.

According to operating data, the supply air temperature of the UFAD system is always greater than 17.2℃ (63℉) during the cooling season, much higher than that of traditional air conditioning systems. It leads to a smaller temperature difference between the supply air and the return air, and hence contributes to higher air flow rate and greater energy use of the AHU fans.

As the night purge caused the earlier starting and longer operating hours of the AHU fan system, it was recommended to further investigate the control strategy. According to the building manager, adjustments have been made on the original night purge. The activation setpoint and deactivation setpoint of indoor air temperature were raised to 32.2℃ (90 °F) and 26.7℃ (80°F) respectively, in order to limit the number of times night purge is activated and to reduce the amount of night purge runtime. Besides, the high energy use of the AHU fans is also consistent with the overcooling issues reported by some occupants. Though there may still be limited air movement when a diffuser in the UFAD system is closed, occupant training on how to use the diffusers may help reduce fan energy use while alleviating some discomfort as well [40].

Furthermore, to understand the fans' efficiency more specifically, the performance of the AHU fan system (including four supply fans and two return fans) throughout the whole year is shown in Figure 17. Both power and supply air flow are normalized by their design values. With the minimum static pressure (SP) setpoint at about 250 Pa (1.0 inch of water gauge), the SP setpoint reset seems normal, when compared with the DOE-2's modeled curve with the same minimum SP setpoint of 250 Pa. However, by contrast to the curve with minimum SP setpoint at 0 inch, representing perfect reset, the actual operation is less efficient, as nearly all data points lie above the ideal curve. And the efficiency difference becomes larger as the airflow decreases. Besides, the default curve of variable speed fans in DOE-2 is also shown in this figure, demonstrating the significant discrepancy between original design and actual operation [48, 49].

Meanwhile, the histogram of supply air flow shown in Figure 18 shows two peaks, located in 0.2~0.3 and 0.6~0.7 respectively, demonstrating the system often runs at part load conditions, with lower efficiency. It is estimated that up to 22% of the fan energy, 136,257 kWh of electricity, can be saved per year, if perfect SP setpoint reset can be achieved in actual operation.

4.6.3 Outdoor Air Economizer

Since it is common to see different types of failures in most outdoor air economizers (OAE), it is crucial to investigate the OAE performance in this building. Figure 19 shows the correlation between the outdoor air (OA) damper position, chillers' power, and outdoor air temperature (OAT). In this case, the minimum supply air temperature (SAT) is about 16.7 ℃ (62℉), while the return air temperature (RAT) is set to be around 23.9℃ (75 ℉). When OAT is below 16.7 ℃ (62℉), chillers will remain off, while outdoor air provides 100% of cooling for the building. And the higher OAT is, the more outdoor air is drawn from outside. When OAT ranges from 16.7 to 23.9℃ (62 to 75℉), the largest amount of outdoor air will be drawn in, with chiller working at the same time. Meanwhile, the other outdoor air damper, which is responsible for minimum ventilation rate, is always open and stays relatively constant.

To better understand the operation mechanism, Figures 20~23 show the OAE performance on two typical days with 15-minute data. Figures 20 and 22 focus on temperature changes, including SAT setpoint, OAT, SAT, RAT, and mixed air temperature (MAT). While Figures 22 and 24 show airflow rate, indicating the on-off status of the fans. Both night purge and daytime operation can be seen in these figures.

Considering both Figure 20 and Figure 21, it can be seen that the night purge lasting from about 4 am to 5 am was a process of pre-heating to keep RAT from declining. In this case, nearly no outdoor air was taken in, and return air was heated directly without air mixing. Later in the morning, when OAT is below SAT setpoint, plenty of outdoor air was taken in to mix with RA, to reach the required supply air temperature without running the chillers. While in the afternoon, when OAT was above SAT setpoint but less than the RAT, maximum outdoor air was taken in and was cooled by the chilled water coils. All these facts indicated the outdoor air economizer was operating normally, compared with ideal performance described in [43].

On the summer day shown in Figure 22 and Figure 23, night purge was for pre-cooling. In the afternoon when OAT was above RAT, minimum outdoor air was drawn in, mixed with return air and cooled by chilled water. However, the obvious deviation of SAT and MAT from ideal conditions indicates potential failure of the outdoor air economizer or the temperature sensors.

5. Conclusions and Discussion

5.1 Conclusions

A new holistic approach, powered by measured building performance data and analytics, to inform energy retrofit of high performance buildings was presented in this study. The three analytics, energy profiling, benchmarking, and diagnostics, are based on long-term performance data monitored at short time intervals from the energy monitoring system as well as the building automation system usually installed in high performance buildings. The level of effort to conduct the three levels of analysis varies, mainly depending on the most time-consuming part of downloading, preparing and cleaning up data. The analyses, using Excel, usually take only a few days, and can be shorter once templates are setup.

The analytics were applied to a high performance building in California to demonstrate their use. Firstly, with energy profiling, energy use patterns of major end-uses were analyzed with different time scales. As the time scale shortens, more details appeared and driving factors of abnormal total energy use can be identified clearly. Secondly, energy benchmarking was conducted for some major end-uses along with total energy use, against a peer group of office buildings in the CEUS database. It is indicated that much more energy saving potential lies in the data center and air movement (mainly the AHU fans) than other end-uses. Thirdly, energy diagnostics was conducted for the HVAC system and major HVAC components with more detailed data. Though the average COP of the two chillers appeared normal, frequent cycling was harmful to the equipment. Thus, replacing one of them with a smaller chiller may not only improve the COP, but also extend their service life. As the largest electricity consumer in the HVAC system, the AHU fan system also seemed to be efficient. However, more energy may be saved if its control system can be improved, for example optimizing supply air static pressure setpoint reset and reducing night purge hours. It was also demonstrated that the outdoor air economizer in this building performed well based on detailed analysis of the correlations between key temperatures and air flows of the economizer. It is estimated that 20% (850,764 kWh per year) of the building’s electricity use can be saved, which includes about 696,000 kWh of electricity savings from the data center, 136,257 kWh from the AHU fans, and 18,507 kWh from the chillers. More energy savings related to gas heating might be achieved if hourly or sub-hourly gas use data is available for analysis.

Based on these findings and considering actual building management, the building manager of the CalSTRS building took actions to reduce energy use and improve comfort, including: (1) reducing supply air flow rate to relieve overcooling complaint by occupants, (2) raising temperature control setpoints to reduce the operation of night purge, (3) calibrating condenser level control sensor to reduce chiller cycling during low-load conditions, and (4) consolidating data center server loads to reduce the number of active servers.

In summary, this study demonstrated that: (1) there are energy saving opportunities for high performance buildings to further reduce energy use, and (2) detailed measured building performance data and analytics can help identify retrofit measures and estimate energy savings. The data and analytics presented in this study aim to shed some light on building energy performance analysis and to inform the decision making during the retrofit process.

5.2 Challenges

It is important to realize there are some challenges when the three levels of data analytics are applied to real cases. Since data is the key of all analyses, lack of data and mixed-use data points have always been two of the biggest obstacles in such work. Take the CalSTRS Building for example, the gas meter has been out of service for quite a long time, and both of the EMS and BAS have experienced data gaps to different extents. As there is only one meter responsible for the CWPs, CHWPs and HWPs in the EMS, separate energy use data for these end-uses were collected from the BAS. Thus, energy analysis of these end-uses were constrained to the fact of missing data in the BAS during 09/13/2012 ~ 12/07/2012, as well as the fact that only accumulated running hours instead of energy use data was recorded for the CWPs. Furthermore, as a mixed-use building, some end-uses like cooling tower fans and HWPs are shared by both the office tower and the podiums. Though not absolutely accurate, energy data for these end-uses were still used for analyzing the office tower, due to their relatively small contribution to the whole building's total energy use. Another challenge, not obviously, is downloading and pre-processing the monitored data from the EMS and BAS systems, which is labor intensive, not automatic, and quite often a complex process.

Adequate and good quality data at time intervals of 1 to 5 minutes for a complete year are the corner stone of detailed energy and performance analysis to pinpoint potential operation issues in buildings and identify energy retrofit measures.

Acknowledgement

This work was supported by the U.S. Department of Energy under the U.S. - China Clean Energy Research Center for Building Energy Efficiency with Contract No. DE-AC02-05CH11231.

Glossary

AHU	Air handling unit
ASHRAE	American Society of Heating, Refrigeration, and Air-conditioning Engineers
BAS	Building automation system
CalSTRS	California state teachers' retirement system
CBECS	Commercial Buildings Energy Consumption Survey
CEUS	California End Use Survey
CHWP	Chilled water pump
COP	Coefficient of performance
CRAC	Computer room air conditioner
CWP	Condenser water pump
DHW	Domestic hot water
DX	Direct expansion
EIA	Energy Information Administration
EMS	Energy management system
EUI	Energy use intensity
HPB	High-performance building
HWP	Hot water pump
HVAC	Heating, ventilation, and air-conditioning
ICOP	Ideal COP
IT	Information Technology
LBNL	Lawrence Berkeley National Laboratory
LEED	Leadership in energy and environmental design
MAT	Mixed air temperature
OAT	Outdoor air temperature
OAE	Outdoor air economizer
PLR	Part load ratio
PUE	Power usage effectiveness
SAT	Supply air temperature
SHGC	Solar heat gain coefficient
RAT	Return air temperature
UFAD	Under-floor air distribution
WWR	Window-wall ratio
VAV	Variable air volume
VT	Visible transmittance
WSHP	Water source heat pump

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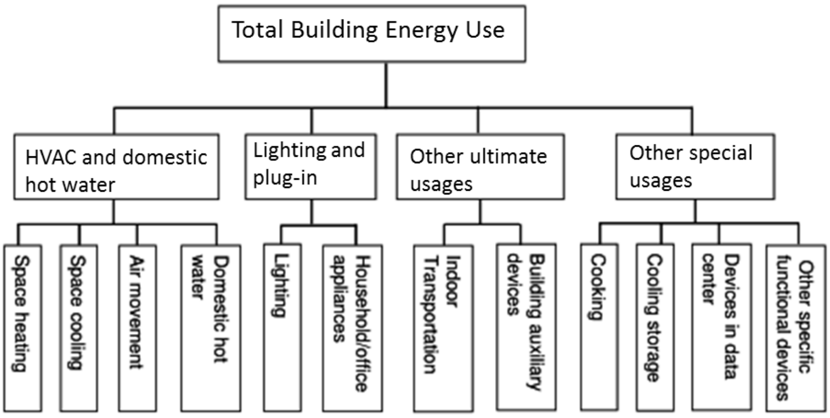
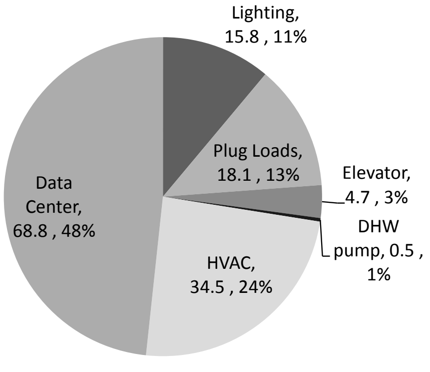


Figure 1 Building energy use data model

Figure 2 The CalSTRS Headquarters Building



(a) Total Electricity Use

(b) Data Center

(c) HVAC

Figure 3 Annual breakdowns of electricity use intensity (unit: kWh/m^{2}a)

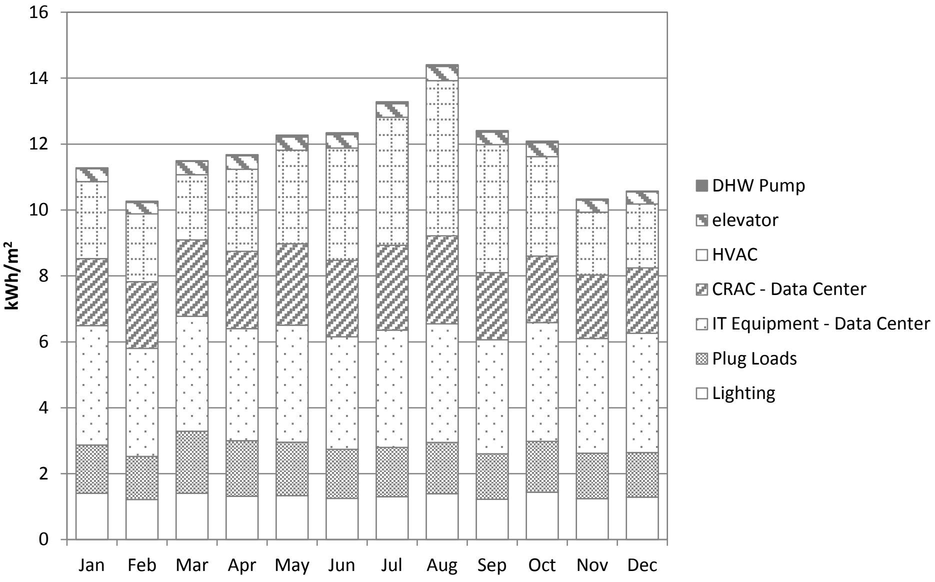


Figure 4 Monthly breakdowns of the total electricity use intensity

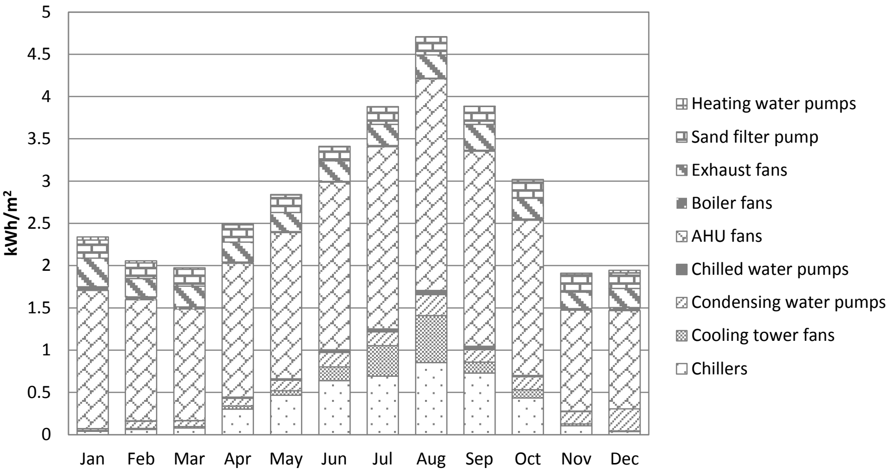


Figure 5 Monthly Breakdowns of the HVAC electricity use intensity

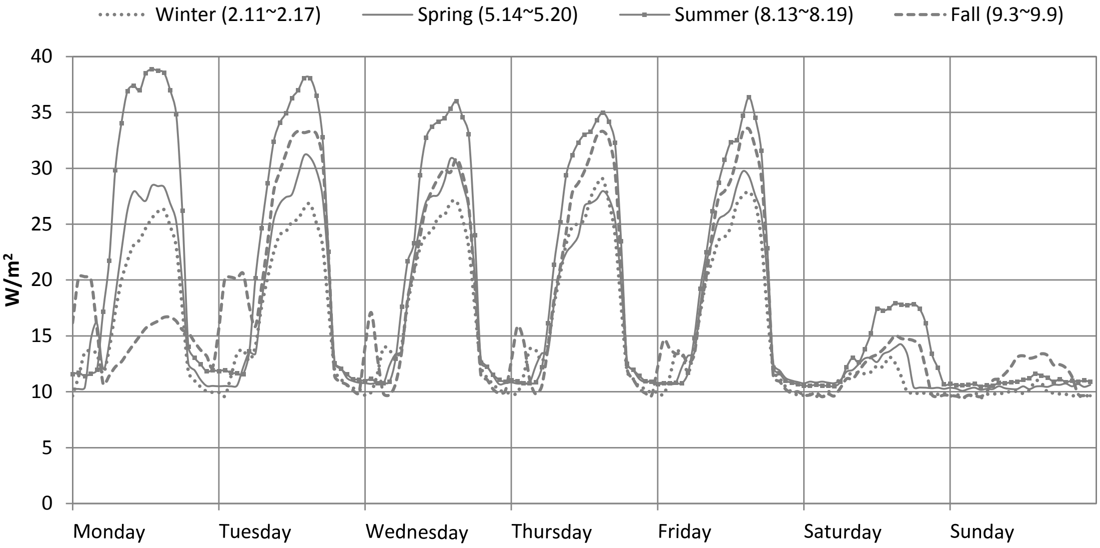


Figure 6 Hourly total electrical power in four typical weeks

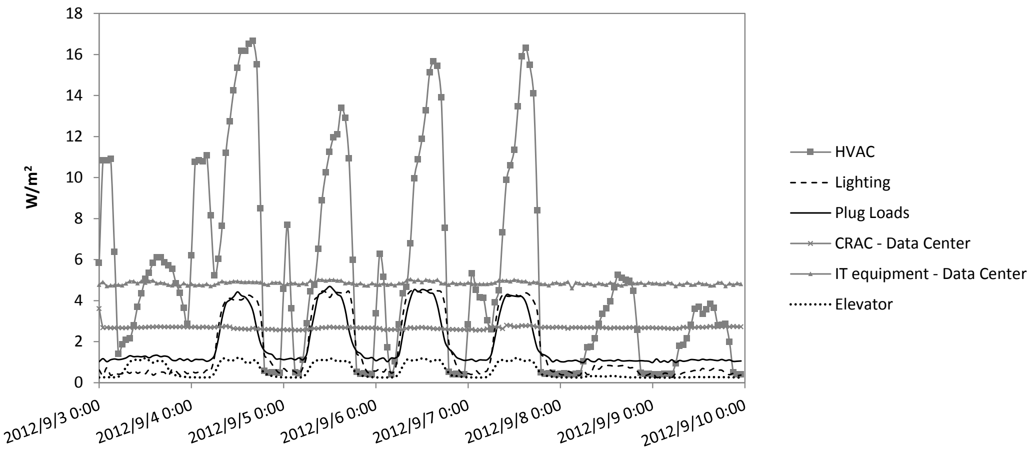


Figure 7 Hourly electrical power density of major sub-categories in a typical week

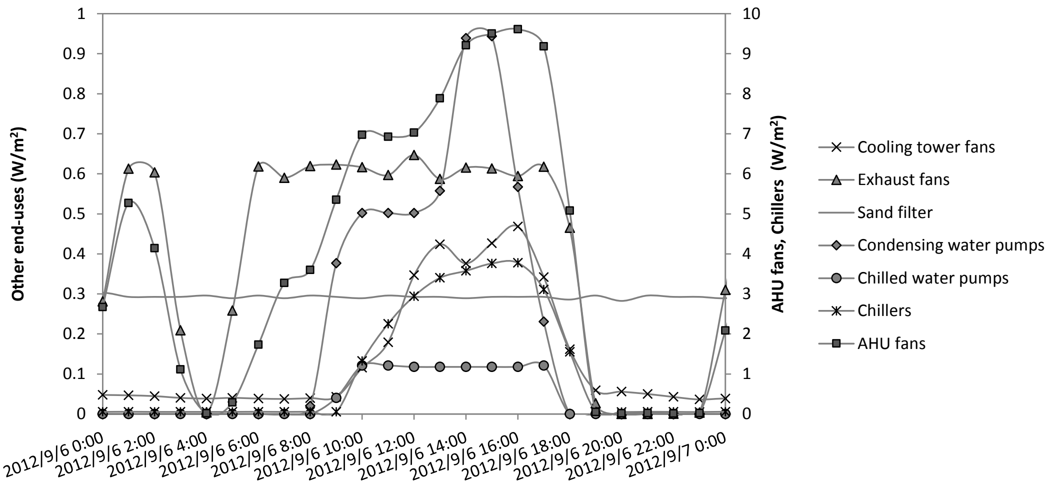


Figure 8 Hourly electrical power density of major HVAC end-uses on a typical weekday

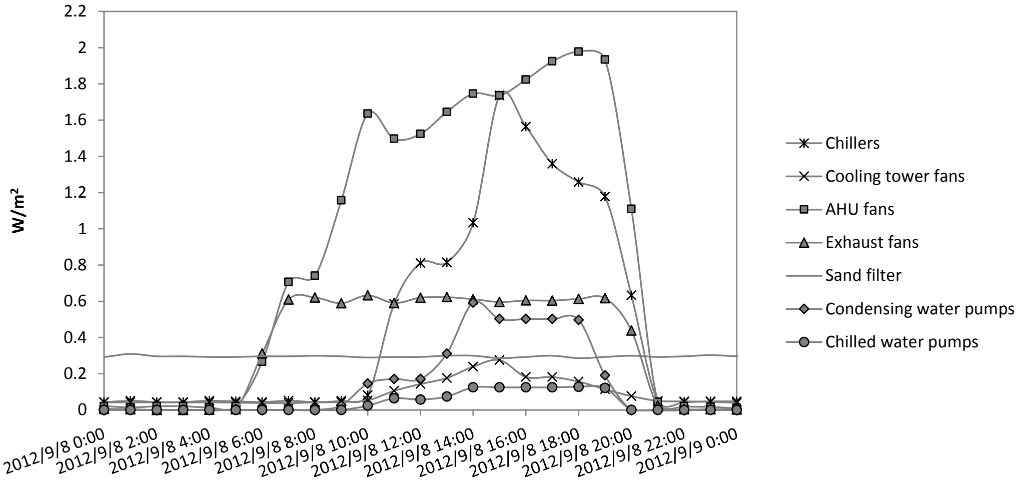


Figure 9 Hourly electrical power density of major HVAC end-uses on a typical weekend

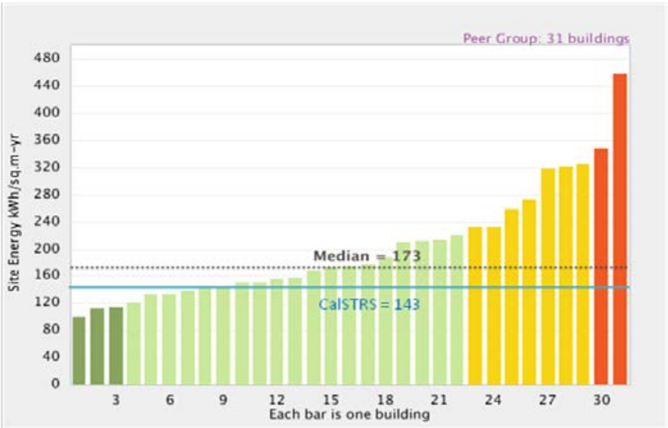
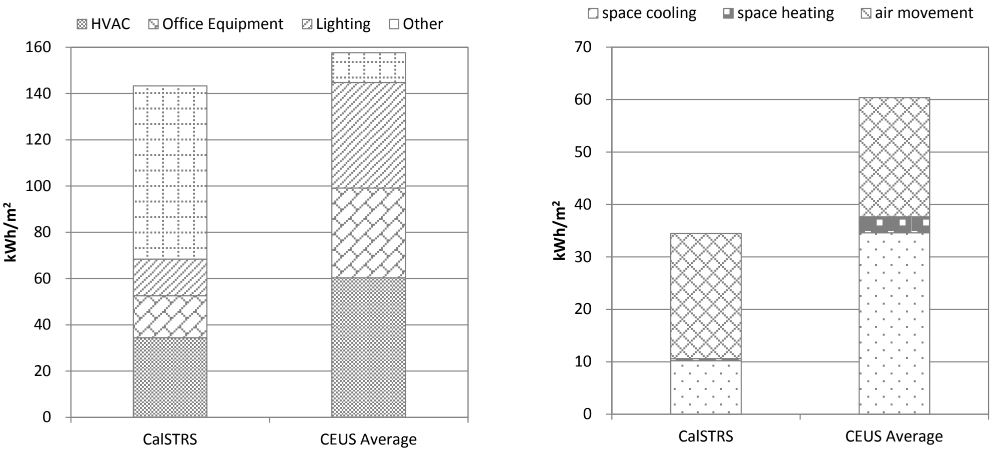


Figure 10 Benchmarking of the CalSTRS Building based on whole-building EUI



(a) Breakdowns of the whole building EUI

(b) Breakdowns of the HVAC EUI

Figure 11 Benchmarking of major sub-categories

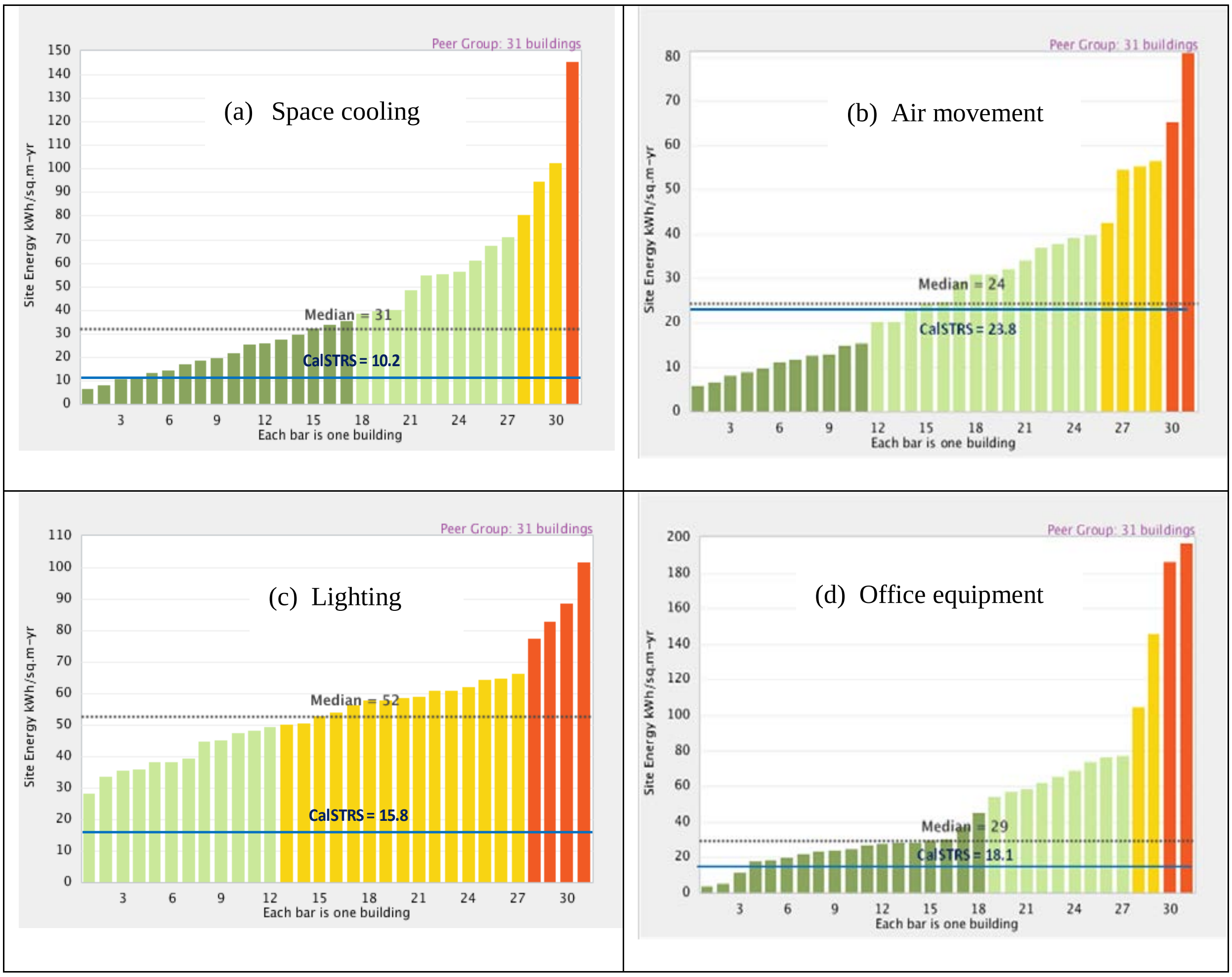


Figure 12 Rankings of buildings’ EUI for major sub-categories

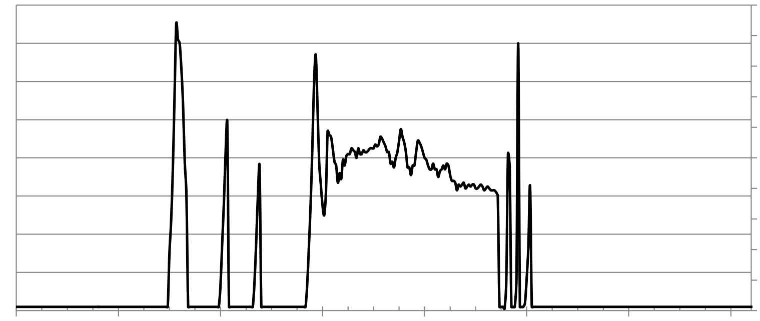


Figure 13 Chiller performance on a typical weekday in transition season

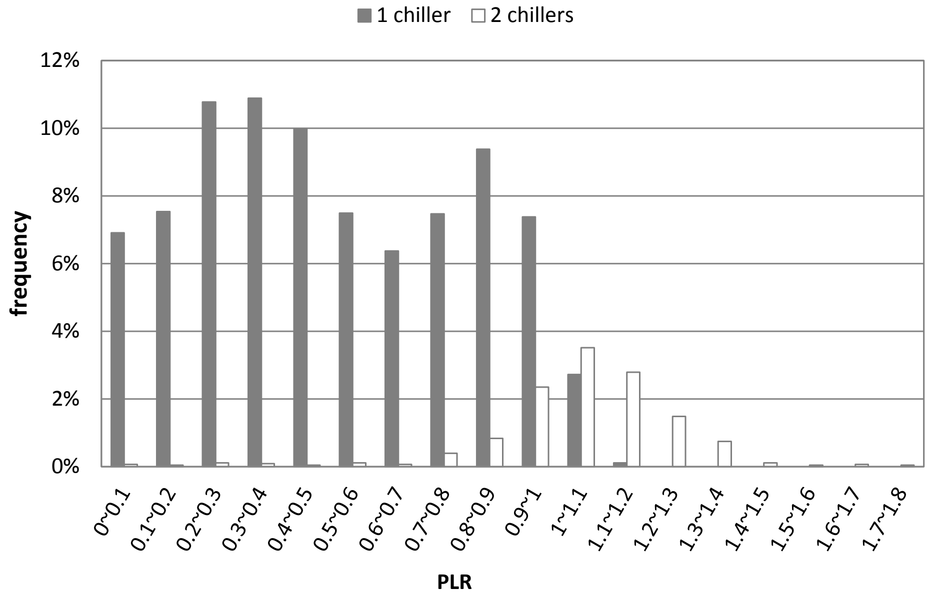


Figure 14 PLR frequency distribution in the cooling season

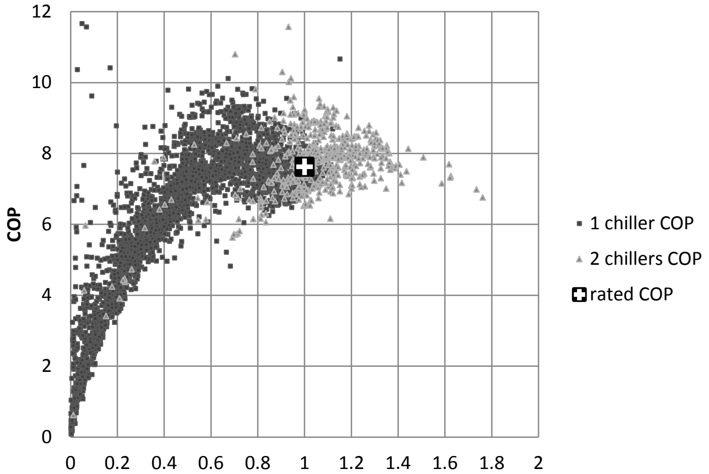


Figure 15 COP ~ PLR scatter plot in the cooling season

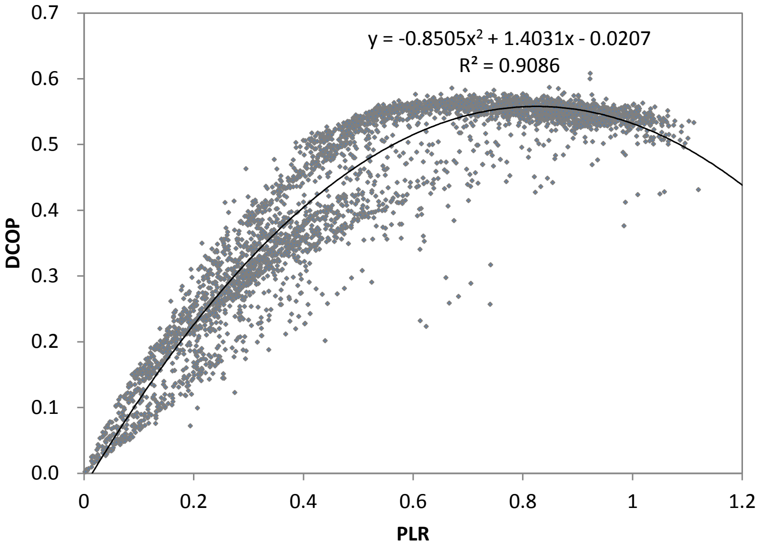


Figure 16 Single chiller's DCOP ~ PLR scatter plot in the cooling season

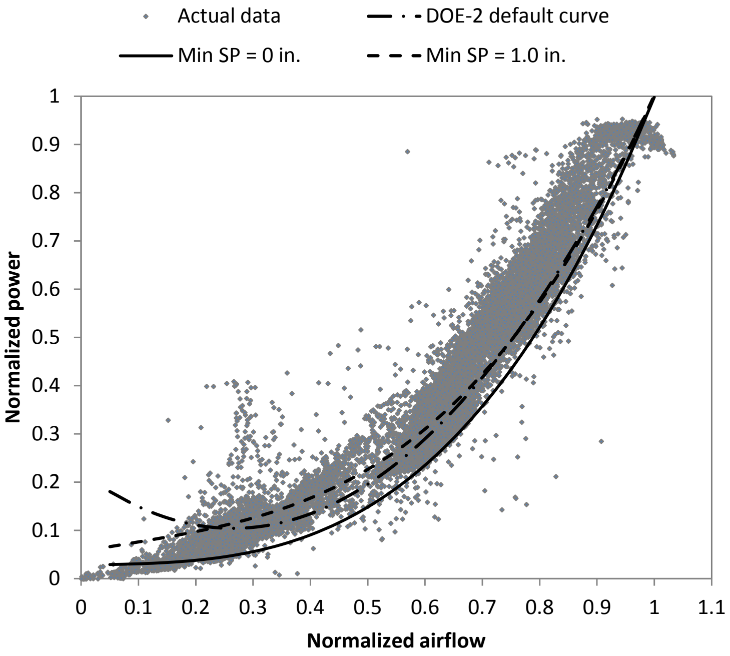


Figure 17 Performance of the AHU fan system

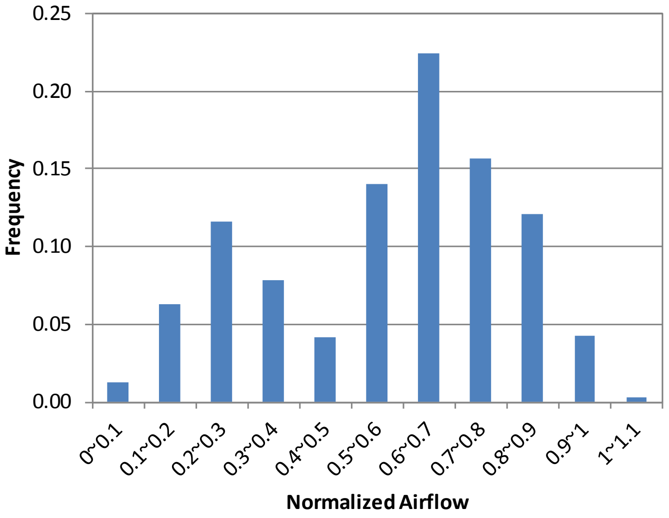


Figure 18 Histogram of supply air flow

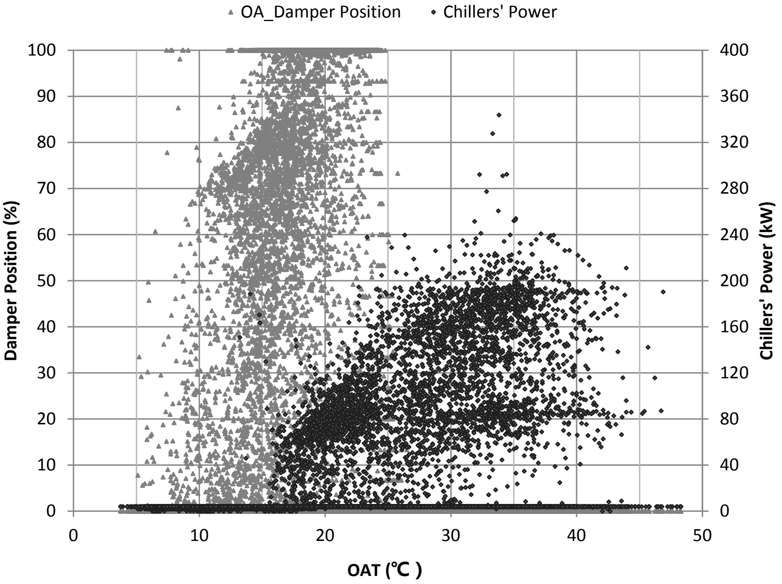


Figure 19 Correlations between OAT and OA damper position, chillers’ power

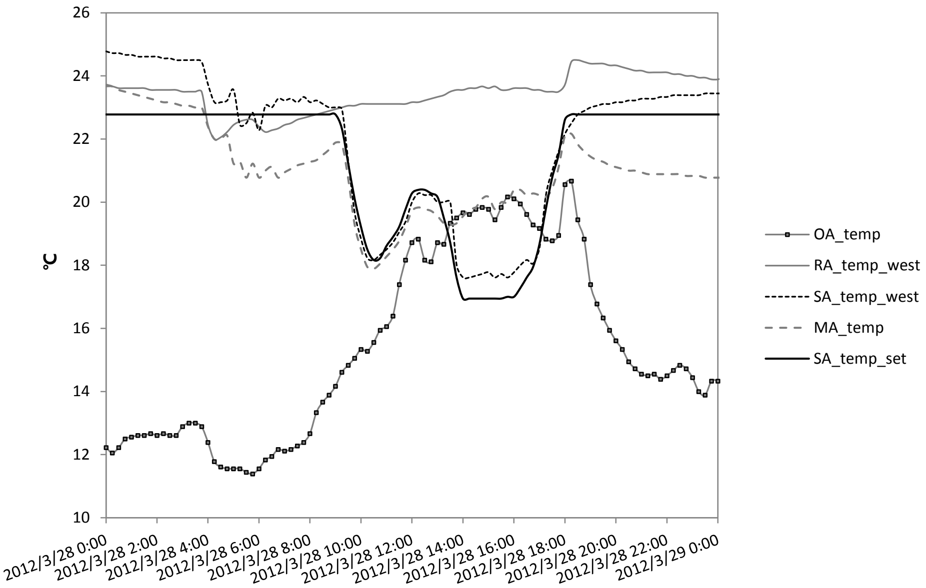


Figure 20 Air economizer performance on a typical Spring day - temperature

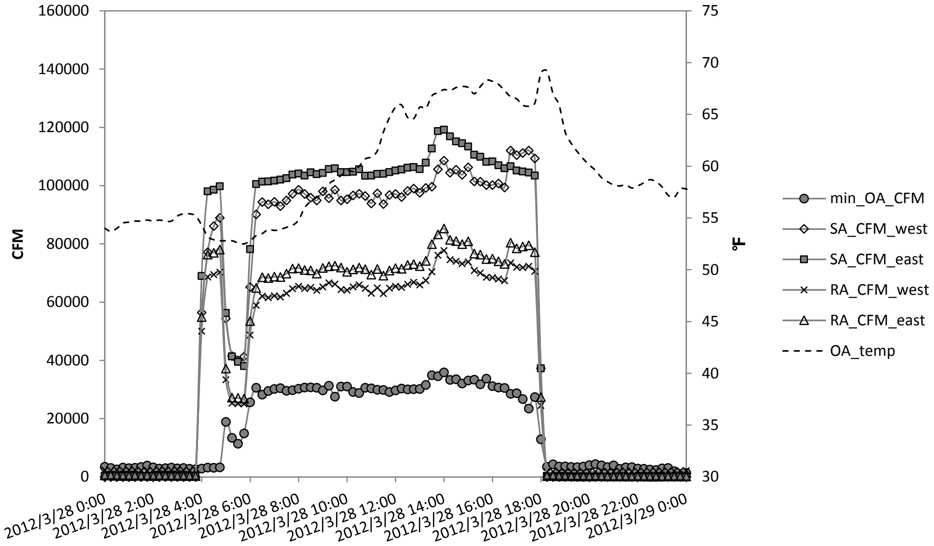


Figure 21 Air economizer performance on a typical Spring day - airflow

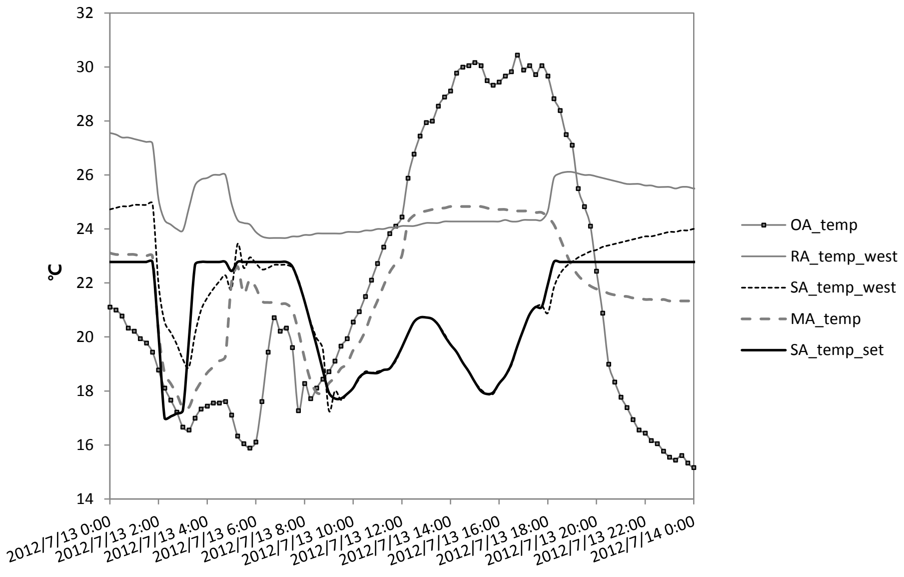


Figure 22 Air economizer performance on a typical Summer day - temperature

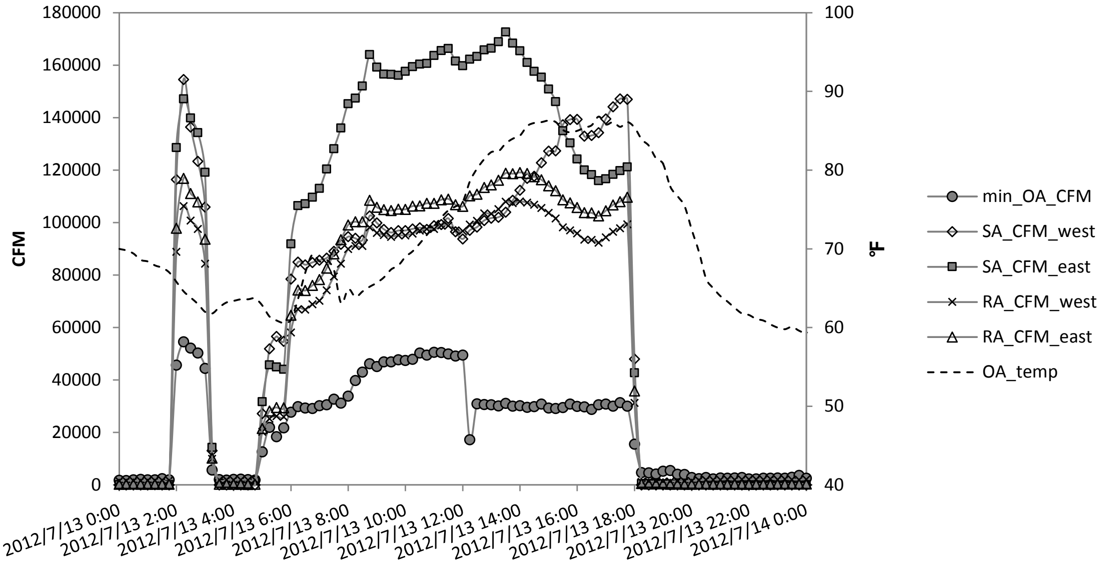


Figure 23 Air economizer performance on a typical Summer day - airflow

List of tables

Table 1 Summary of the CalSTRS Headquarters Building

Category	**Item name**	**Descriptions**
General Information	**Name**	CalSTRS Headquarters
	Location	West Sacramento, California
	Year of construction	2009
	Climate zone	ASHRAE Climate Zone 3B
	Type	Office (13 floors), Podiums (5 floors)
	Number of floors	18 Floors
	Floor area for office tower	29,728 m^2 (320,000 ft^2)
	Operation hours	Generally M-F 6:00am - 6:00pm
	Max. Occupancy	1200 people
Building Envelope	**Exterior wall assembly**	Façade
	Roof assembly	cast concrete
	WWR	100% curtain walls
	Window	Low-e with low SHGC and high VT
	Shading devices	Interior blinds
Lighting System	**Interior general lighting**	T-5
	Interior task lighting	Occupant-specific
	Exterior lighting	High intensity discharge
	Control system	Manually on, schedule off, dimmable control (Lutron), some areas with occupancy sensors.
	Operation hours	Interior lighting off at 6 pm
HVAC	**Cooling system**	2 York water-cooled chillers with variable speed compressors for the office tower; WSHPs for the podiums
	Heating system	3 gas boilers for the office tower; WSHPs for the podiums
	Air system	UFAD + VSD fans at AHU for the office tower
	Room set-point	21.7 – 24.4 °C (71 - 76 °F)
	Operation hours	M-F 6:00am - 6:00pm (two floors are operated from 5:00am in workdays)
Internal Equipment & others	**Transportation systems**	7 passenger & 1 freight OH hoist (office tower); 3 passenger OH hoist & 2 hydraulic freight elevators (podiums)
	DHW	Natural gas boiler (café kitchen), electrical heaters for domestic hot water (gym showers, restrooms, break rooms)
Control & Monitoring	**BAS (Building Automation System)**	Niagara / Tridium system with Staefa controllers
	EMS (Energy Monitoring System)	Eaton system - PowerXpert

Table 2 List of major data points

Data type	**Point description**	**Number of points**	**Data source**
Energy use data	Outdoor lighting	1	EMS
	Indoor lighting	15	EMS
	Plug loads	14	EMS
	Computer room air conditioners (CRAC), data center	10	EMS
	IT equipment, data center	14	EMS
	Supply fans, HVAC	4	EMS
	Return fans, HVAC	2	EMS
	Chillers, HVAC	2	EMS
	Cooling tower fans, HVAC	4	EMS
	Chilled water pumps, HVAC	2	BAS
	Hot water pumps, HVAC	3	BAS
	Condensing water pumps run time, HVAC	2	BAS
	Boiler fans, HVAC	3	EMS
	Sand filter pump, HVAC	1	EMS
	Exhaust fans, HVAC	5	EMS
	Domestic hot water pumps	1	EMS
	Elevators	1	EMS
HVAC operating data	AHU supply air temperature setpoint	1	BAS
	AHU supply air temperature	2	BAS
	AHU return air temperature	2	BAS
	AHU mixed air temperature	1	BAS
	AHU supply air flow rate	2	BAS
	AHU return air flow rate	2	BAS
	outdoor air damper position	2	BAS
	minimum outdoor air flow rate	1	BAS
	Chilled water supply/return temperature	2	BAS
	Chilled water flow rate	1	BAS
	Evaporating temperature	2	BAS
	Condensing temperature	2	BAS
Environmental data	Outdoor air temperature	1	BAS

Table 3 Load ratios in four different seasons

Load Ratios	Winter	Spring	Summer	Fall	Annual Average
working day to non-working day	3.5	3.5	3.4	2.4	3.2
day to night	3.8	5.0	6.3	4.3	4.9

Table 4 Comparison of average load ratios between the CalSTRS Building and the reference buildings

Average Load Ratios	CalSTRS	RB 1	RB 2	RB 3
working day to non-working day	3.2	3.0	1.3	1.8
day to night	4.9	4.1	1.7	2.1

Table 5 Benchmarking of PUE for data centers

Benchmarks of PUE			**CalSTRS**
Standard	**Good**	**Better**	
2.0	1.4	1.1	1.66

Table 6 Benchmarking of the AHU fan system efficiency

Benchmarks (W/CFM)			CalSTRS (W/CFM)
Standard	Good	Better	
0.9	0.6	0.3	0.65

Table 7 Efficiency benchmarking of supply fans and return fans

W/CFM	Supply fans	Return fans
Actual	0.53	0.16
Rated	0.70	0.32
Average of CEUS	0.87	0.33