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"Improving the Energy Performance of Data Centers"

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IMPROVING THE ENERGY PERFORMANCE OF DATA CENTERS

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ABSTRACT

Data centers greatly impact California's natural environment and economy. These buildings host computer equipment that provide the massive computational power, data storage, and global networking that is integral to modern information technology. The concentration of densely packed computer equipment in data centers leads to power demands that are much higher than those of a typical residence or commercial office building. Data centers typically consume 15 times more energy per square foot than a typical office building and, in some cases, may be 100 times more energy intensive (Greenberg et al. 2003). Nationally, data centers consumed 61 Terawatt hours in 2006; equivalent to the practical power generation of more than 10, 1 Gigawatt nuclear power plants (Brown et al., 2007). This is approximately equal to annual electricity consumption for the entire state of New Jersey (EIA, 2006). California has the largest data center market in the U.S., indicating that a significant portion of this energy is consumed within the State (Mitchell-Jackson, 2001).

This research project focused on identifying how data centers are currently designed and exploring potential energy saving associated with alternative building design options. The energy savings were quantified to understand when design changes resulted in significant benefits and when the benefits from alternative designs were minimal. The potential energy savings benefits were juxtaposed against changes to the environmental conditions in data centers and evaluated within the context of computer reliability concerns. The objective of this research is to provide data center designers and other decision makers with a better understanding of the benefits and concerns associated with data center energy efficiency, thereby reducing the unknown consequences that may

hinder attempts to shift away from conventional design practices.

In this UCEI project energy use simulations were performed for three different cooling systems in data centers. The first design has been identified as the conventional design common to most data centers. The second uses air-side economizers (ASE), which use large volumes of outside air during cool weather conditions to reduce the chiller load in the mechanical system. This ASE design has the potential to provide significant energy savings (Sloan, 2007), but owners and operators are often reluctant to use this cooling technique owing to concerns about the risk of equipment failure posed by introducing outdoor particulate matter into data center buildings. The increase in particulate matter associated with ASE use has been empirically evaluated in this UCEI project. The final design simulated is a water-side economizer (WSE) system, which uses outside air in combination with heat exchangers to provide reduced chiller demand without allowing outside air directly into the data center. Energy use for all three design scenarios are evaluated for multiple climate regions in California.

BACKGROUND

Rapid growth in computational demand emerging from various sectors of the economy is causing strong rates of increase in servers and IT-related hardware (IDC 2007). Server performance has doubled every two years since 1999, leading to increasingly higher densities of heat dissipation within data centers (Belady 2007). A recent EPA study estimates that US data centers accounted for 61 billion kWh or 1.5% of the nation's annual electricity consumption in 2006 (Brown et al., 2007). This is approximately double the electricity dedicated to data centers in 2000 (Koomey, 2007). The EPA study also projects that data center electricity demand could again double by 2011, though this future electricity demand could be greatly reduced as more energy efficient strategies are implemented (see Figure 1). Many of these efficiency scenarios focus on the mechanical cooling of these building, since a substantial proportion of energy consumption in data centers is dedicated to the cooling load associated with electronic power dissipation (Tschudi et al. 2003).

Figure 1: Historic and Projected Data Center Electricity Use (Brown et al., 2007)
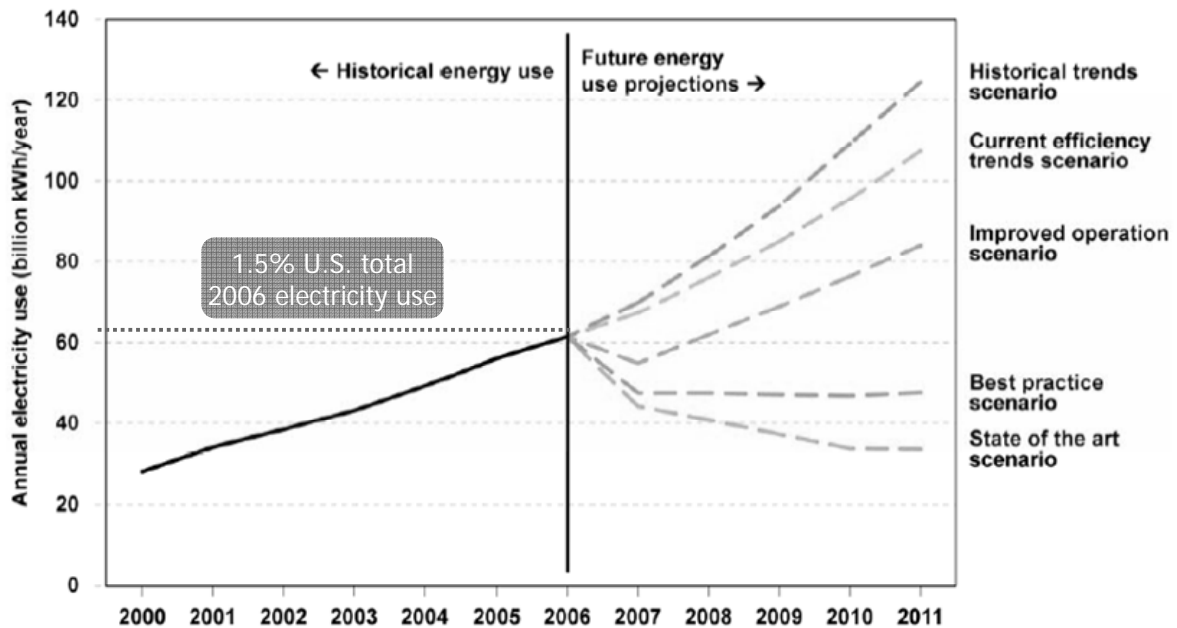

Figure 2 shows different potential mechanical cooling designs for data centers. Data centers consist of multiple rows of computer cabinets containing computer servers. A raised-floor plenum and computer-room air-conditioning (CRAC) units are typically used to remove the heat generated with the server operation. In this design, CRAC units are placed directly on the computer room floor. Air enters the top of a CRAC unit, passes across the cooling coils, and is then discharged to the underfloor plenum. Perforations in the floor tiles in front of the server racks allow the cool air to exit from the plenum into the data-center room. Fans within the computer servers draw the conditioned air upward and through the servers to remove equipment-generated heat. After exiting the backside of the server housing, the warm air rises and is transported to the intake of a CRAC unit. Most air circulation in the baseline scenario is internal to the data center. A small amount of air is supplied through a rooftop air handling units (AHU) to positively pressurize the room and to supply outside air for occupants. Cooling is provided by a water-cooled chiller plant. Refrigerant in the chillers is used to cool water through heat exchangers at the evaporator. The chilled water is then piped to the CRAC units on the data center floor. Waste heat from the chiller refrigerant is removed by water through heat exchangers in the condenser. Condenser water is piped from the cooling towers, which cools the water through interaction with the outside air. This conventional design is common to most mid- to large-size data centers (Tschudi et al. 2003; Rumsey 2005; Syska Hennessy 2007).

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Figure 2: Schematic of Data Center Cooling Design Scenarios
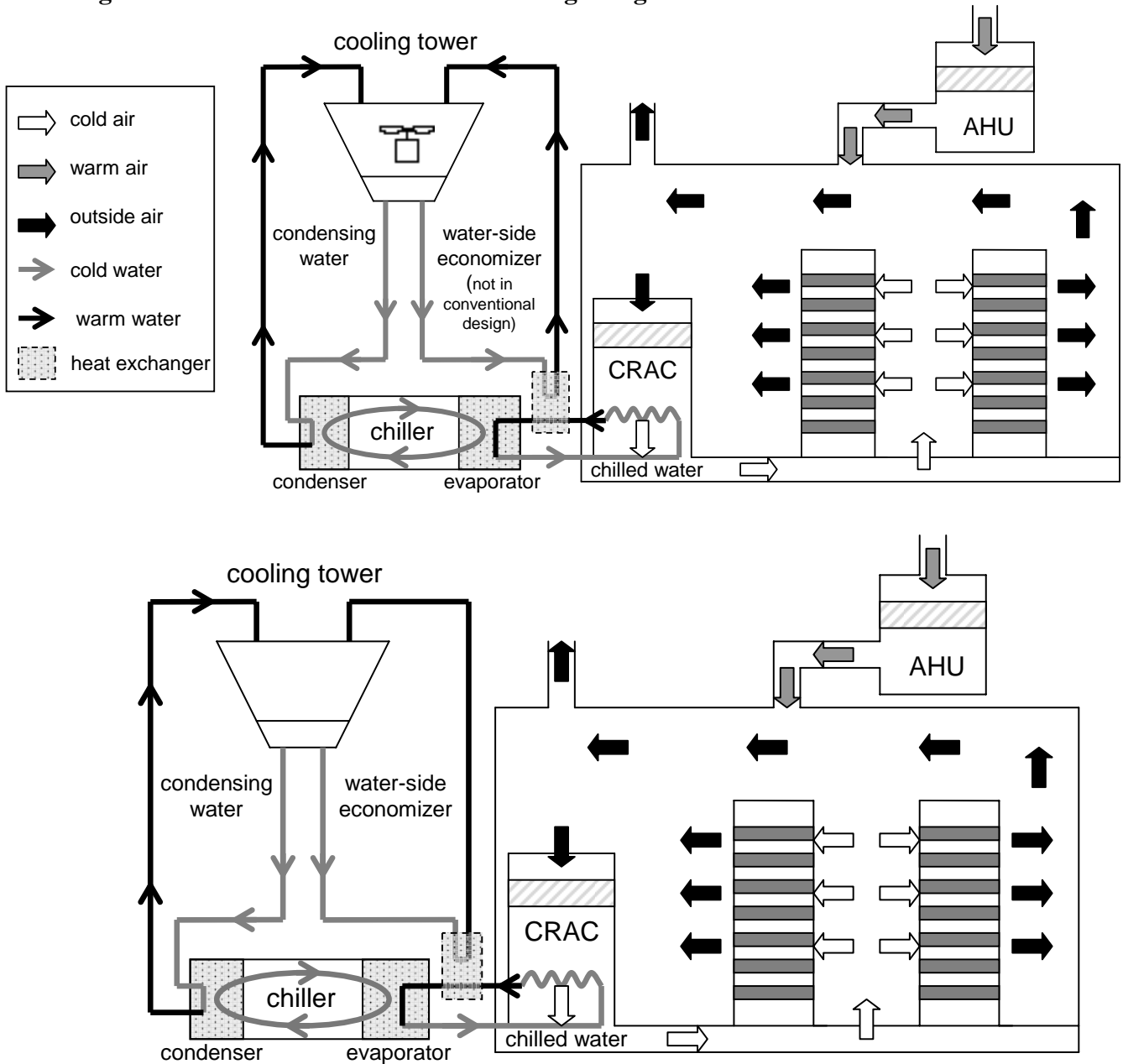
A WSE design scenario assumes a CRAC unit layout similar to that of the baseline case, except that additional heat exchangers are installed between the condenser water in the cooling towers and the chilled water supplied to the CRAC units. Under appropriate weather conditions, the cooling towers can cool the condenser water enough to cool the chilled water in the CRAC units directly, without operating the chiller plant.

The air-side economizer scenario (ASE) requires a different type of air delivery than typically found in a data center with conventional CRAC units. AHUs are placed outside of the data center room, commonly on the rooftop, and air is then sent to and from the computer racks through ducts. A ducted air delivery system creates greater air resistance

than a conventional CRAC unit layout, though this system better prevents cold and warm air from unintentionally mixing within the data center. During appropriate weather conditions, the AHU can directly draw outside air into the data center and exhaust all of the return air after it has passed across the computer servers. The movement of 100% outside air through the system can require more fan energy than the baseline case, as the economizer design requires more ducting, which increases air resistance through the system. However, during this 100% outside air mode the cooling is provided without operating the chiller, chilled water pumps, condenser water pumps, or the cooling tower fans.

ENERGY SIMULATION METHOD

Each design scenario described above was incorporated into the energy simulation model. The model calculations assumed a 30,000 ft^2 (2,800 m^2) data center with an internal heat density of approximately 80 W/ft^2 (0.86 kW/m^2; 2.4 MW total). This size and power density are characteristic of data centers evaluated in previous studies (Shehabi et al. 2008a; Greenberg et al. 2006; Tschudi et al. 2003). The size of data centers varies greatly; 30,000 ft^2 is within the largest industry size classification, which is responsible for most servers in the United States (IDC 2007). Power density in data centers is rapidly increasing (Uptime Institute, 2000) and a power density of 80 W/ft^2 is currently considered to be of low- to mid-range (Rumsey 2008). Basic properties of the modeled data center for all three scenarios are summarized in Table 1.

Table 1: Data Center Characteristics Common to All Design Scenarios (Shehabi et al., 2008b)

Data Center Parameters	
Floor Area	30,000 ft^2
UPS Waste Heat	326 kW
Data Center Lights	30 kW
Total Rack Load	2000 kW
Total Internal Load	2,356 kW
Average Internal Load Density	79 W/ft^2
Minimum Ventilation	4,500 ft^3/min
Supply Air Temperature	55 °F
Return Air Drybulb Setpoint	72 °F
Chiller Capacity	1750 kW
Number of Chillers	3

Energy demand is calculated as the sum of the loads generated by servers, chiller use, fan operation, transformer and uninterruptible power supply (UPS) losses, and building lighting. The chiller encompasses coolant compressor, chilled water pumps, condensing water pumps, humidification pumps, and cooling-tower fans. Energy demand for servers, UPS, and lighting are constant, unaffected by the different design scenarios, but are included to determine total building-energy use. The base case and WSE scenarios assume conventional humidity restrictions recommend by ASHRAE (ASHRAE 2005). The ASE scenario assumes no humidity restriction, which is an adjustment required to gain ASE benefits as is typical in ASE implementation (Rumsey 2008). Air-side economizers also require a different air distribution design and the fan parameters

associated with each design scenario are listed in Table 2. The properties of other pumps and fans throughout the HVAC system remain constant for all three scenarios. Values are from previous data-center energy analyses (Rumsey 2008; Rumsey 2005).

Table 2: Data Center Fan Properties (Shehabi et al., 2008b)

Fan System Parameters	Baseline and WSE			ASE	
	MUAH	Exhaust	CRACs	Supply	Relief
Total Air Flow (cfm)	4,500	4,500	495,000	437,758	437,758
Fan Motor Size, Nominal (hp)	7.5	3	10	30	50
Number of Fans	1	1	30	10	5
Fan Efficiency	53.3%	44.0%	55.6%	63.8%	67.5%
Fan Drive Efficiency	95%	95%	95%	95%	95%
Fan Motor Efficiency	89.6%	86.2%	90.1%	92.5%	93.2%
VFD Efficiency	n/a	n/a	n/a	98%	98%
Total Static Pressure Drop (in w.g.)	3.5	1	1.6	2	1

The energy modeling approach used in this study applies a previously used protocol (Rumsey 2008; Rumsery 2005) and is based on a combination of fundamental HVAC sizing equations[1] that apply equipment size and efficiencies observed through professional experience.

Both air-side and water-side economizers are designed to allow the chiller to shut down or reduce chiller energy load under appropriate weather conditions. Less overall energy is required for operation when the chiller load is reduced, but chiller efficiency is compromised. Changes in chiller efficiency are based on the DOE2.1E software model and apply coefficients specified in the Nonresidential Alternative Calculation Method (ACM) Approval Manual for the 2005 Building Energy Efficiency Standards for Residential and Nonresidential Buildings (CEC, 2005).   A water-cooled centrifugal chiller with a capacity > 300 tons and condenser water temperature of 80 °F was assumed in this analysis. A chilled water temperature of 45 °F, which is standard practice for data center operation, is used in the base case and ASE scenario. The WSE scenario uses a chilled water temperature of 52 °F, which is common when using water-side economizers. This increases needed airflow rates but allows greater use of the water-side economizers.

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[1] Building energy modeling is typically performed using energy models such as DOE-2, which simultaneously models heat sources and losses within the building and through the building envelope. However, models such as DOE-2 are not designed to incorporate some of the HVAC characteristics unique to data centers. Also, the high floor-area-weighted power densities in data centers allow accurate modeling of energy use to focus exclusively on internal heat load and the thermal properties of outdoor air entering the building. This was the approach taken in this analysis as heat generated from data center occupants and heat transfer through the building envelope are negligible relative to the heat produced by servers. The building envelope may influence the cooling load in low-density data centers housed in older buildings that have minimal insulation. Evaluating this building type is worthy of exploration, but the required analysis is more complex and outside the scope of the present paper.

Annual data center energy use is evaluated for each of the three configuration scenarios assuming that a data center building is located in each of the five cities shown in Figure 3. Weather conditions at each city are based on hourly DOE2.1E weather data for California climate zones (CEC, 2005).

ENERGY SIMULATION RESULTS

Results from each scenario modeled are presented in Table 3 as a "performance ratio" which equals the ratio of total building energy divided by the energy required to operate the computer servers. Lower value of the performance ratio implies better energy utilization of the HVAC system. The performance ratio for the base case is 1.55 and, as expected, is the same for all the cities analyzed since the operation of this design is practically independent of outdoor weather conditions. The base case performance ratio is better than the current stock of data centers in the United States (Brown et al., 2007; Koomey, 2007) because the base case represents newer data centers with water-cooled chillers, which are more efficient than the air-cooled chillers and direct expansion (DX) cooling systems found in older data centers.

The performance ratios for the ASE and WSE scenarios show that air-side economizers consistently provide savings relative to the base case, though the difference in savings between the two scenarios varies. It is important the note that even small changes in the performance ratio results in significant savings given the large amount of energy used in data centers. For example, reducing the performance ratio at the model data center in San Jose from 1.55 to 1.44 represents a savings of about 1.9 million kWh/y, which corresponds to a cost savings of more than $130,000/y (assuming $0.07/kWh).

Table 3: Ratio of Total Building Energy to Computer Server Energy (Shehabi et al., 2008b)

	San Jose	San Francisco	Sacramento	Fresno	Los Angeles
Baseline	1.55	1.55	1.55	1.55	1.55
Air-side Economizer	1.44	1.42	1.44	1.46	1.46
Water-side Economizer	1.53	1.54	1.53	1.53	1.54

Figure 3 shows the disaggregation of the cooling systems' annual energy use, normalized by floor area, for each modeled data center by location and design scenario. The annual energy use dedicated to the servers, USP, and lighting is 584, 95, and 9 kWh/ft^2, respectively. These energy values are independent of the climate and HVAC design in scenario and not included in the graphs in Figure 3. Economizers can be controlled by combination of outside air temperature, humidity, and enthalpy; however, results shown in Figure 3 are for economizer use controlled by outside air temperature only, which is the most common control design because humidity and enthalpy controls increase first cost and require great system maintenance. Results show that the ASE scenario provides the greatest savings in San Francisco while Fresno and Los Angeles provide the least ASE savings. Figure 4 shows that Los Angeles experiences many more annual hours

when the outside air temperature is low enough for economizer use. This indicates that reduced savings are not only due to the warmer climates in these two cities (especially Fresno), but savings are also limited due to the temperature only economizer controls (especially in Los Angeles). With temperature only controls, the modeling results show hours of the year when the outside air temperature is low enough for the economizer system to open and allow outside air to enter the data center, but high moisture content during these times burdened the chiller with additional latent cooling. Under this scenario the ASE system requires more operational energy that the conventional system, reducing the overall annual savings of the ASE system. Sacramento benefited the most from the WSE scenario while minimal savings were realized in Los Angeles and San Francisco. The San Francisco WSE scenario, where significant gains would be expected because of the cooler climate, highlights the importance of evaluating the temperature set point values by region. Figure 5 shows that San Francisco has a relatively narrow annual temperature distribution, and that most hours are slightly about the temperature at which the WSE system is activated. In this climate, slightly increasing the temperature within the data center, or investing in improved heat exchanging equipment can provide significantly greatly energy savings.

Figure 6 shows that removing the humidity restrictions commonly applied to data centers is necessary to gain ASE energy savings. As the relative humidity (RH) range is narrowed, energy use from the fans begins to sharply increase, surpassing the equivalent baseline energy in most of the cities. Humidity levels are often restricted in data centers to minimize potential server reliability issues. ASHRAE's guidelines released in 2005 for data centers provide a "recommended" RH range between 40-55% and an "allowable" range between 20-80% (ASHRAE, 2005). There is minimal cost in applying the more conservative ASHRAE RH restrictions in conventional data center design, such as the baseline in this study shown in Figure 6. The influence of humidity on server performance, however, is poorly documented and the need for humidity restrictions is increasingly being questioned (Fontecchio, 2007). The energy saving difference between adhering to ASHRAE's recommend RH range versus the allowable RH range is substantial, and warrants further investigation.

Figure 3: Disaggregated Energy Use for Climate Influenced Data Center Components (Shehabi et al., 2008b)
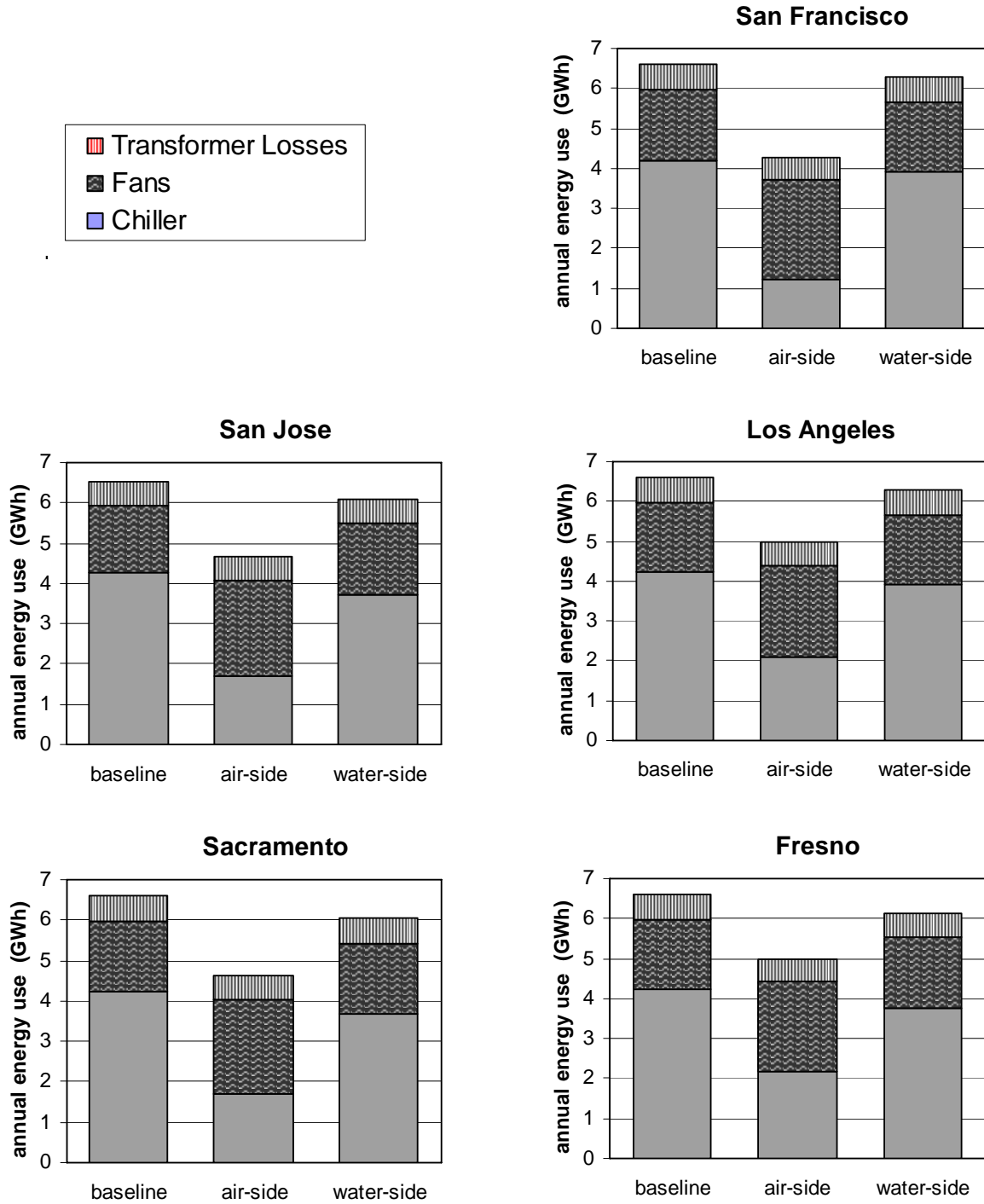
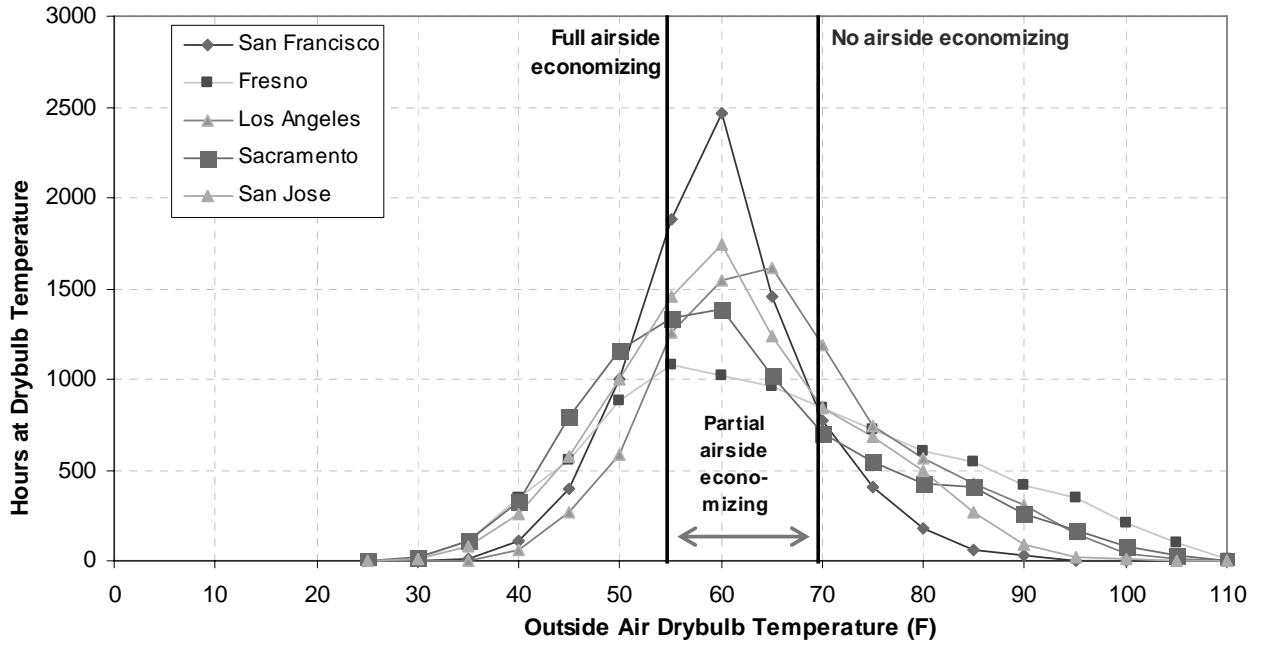**Figure 4: Annual Hourly Outside Air Dry-Bulb Temperature**

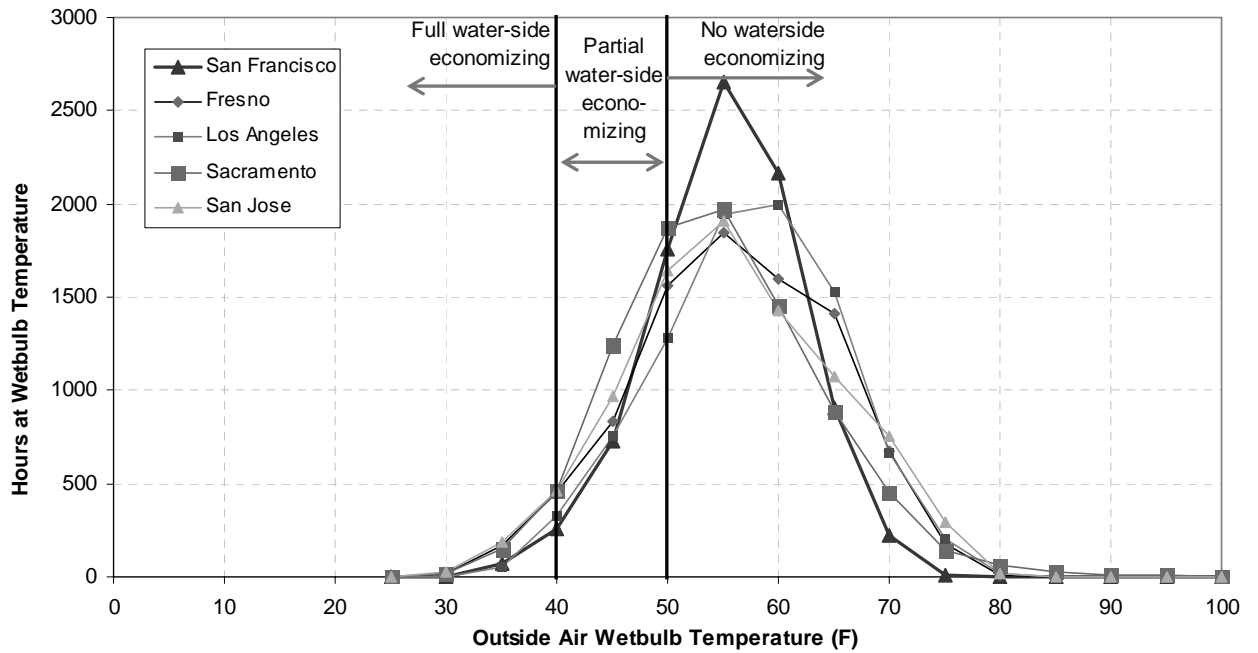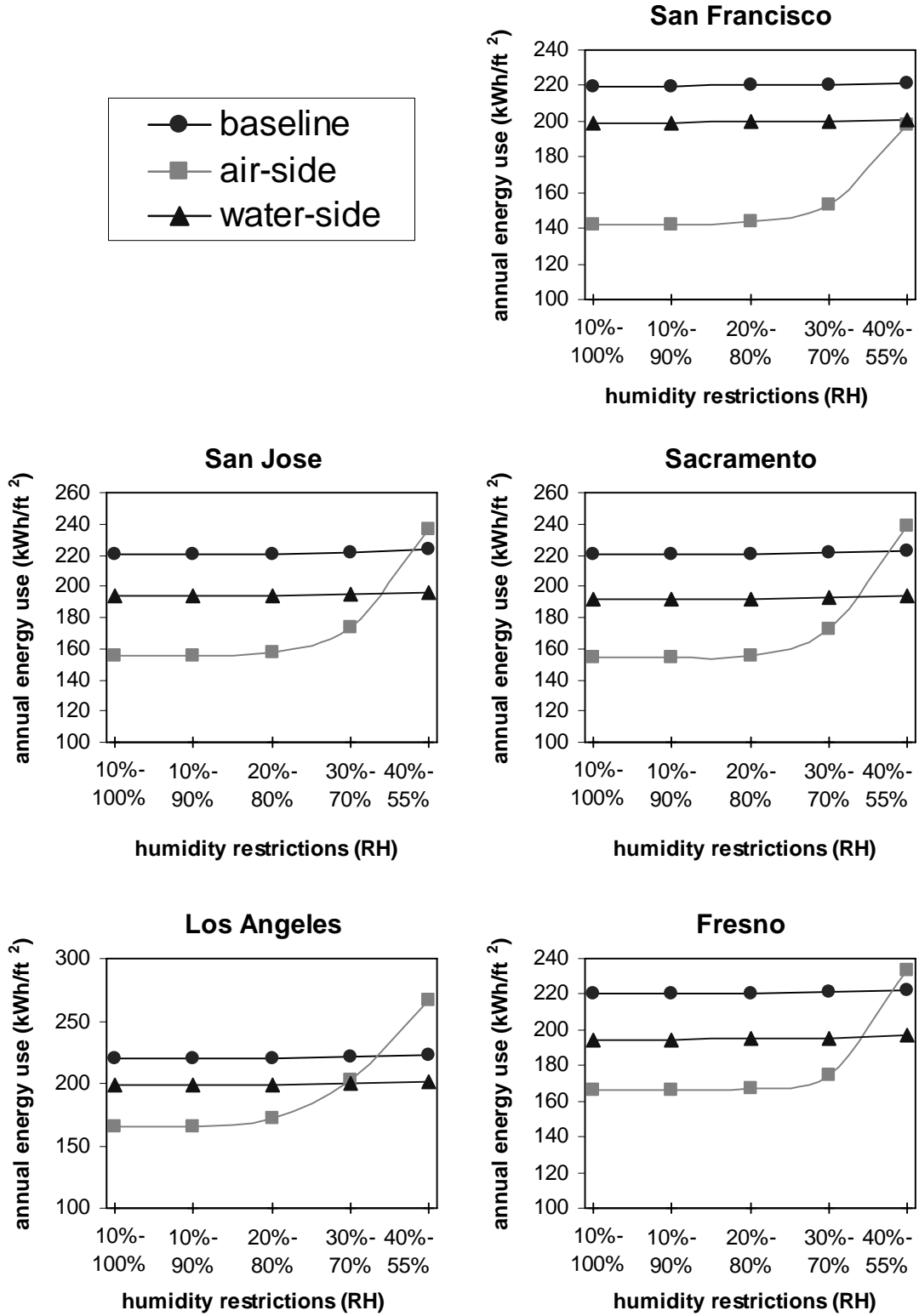**Figure 5: Annual Hourly Outside Air Wet-Bulb Temperature**

Figure 6: Annual Hourly Outside Air Drybulb Temperature (Shehabi et al., 2008b)

DATA CENTER INDOOR AIR QUALITY

Results from the energy simulations above indicate substantially less energy use with the ASE design relative to both the conventional design and the WSE design for all five California climates evaluated. ASE implementation has been minimal, however, due to concerns about equipment damage from outdoor pollutants. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recently published the "Design Considerations for Data and Communications Equipment Centers," which lists possible airborne contaminants and how each could adversely affect electronic data equipment (ASHRAE, 2005). Fine particulate matter is identified as the pollutant of primary concern when introducing outside air into the data center environment. Empirical results show that particulate matter composed of deliquescent salts can cause electronic equipment failure. Previous experiments used sulfate salts to demonstrate current leakage from particle deposition under conditions of high humidity (Litvak et al., 2000). Water soluble components of particles that deposit on equipment circuits can dissociate at high relative humidity and become electrically conductive (Weschler and Shields, 1991). While particle accumulation by deposition between conductors occurs on a timescale of years, the deliquescence of deposited particles can be a rapid event, on the timescale of minutes or seconds. Sudden spikes in relative humidity have the potential to induce equipment failure.

Airborne particle concentrations previously measured in various data center (Shehabi and Tschudi, 2006) were evaluated in this research. Table 4 presents time-averaged, size-resolved, measured indoor particle concentrations for particles of diameter 0.3-5 µm in the eight data centers monitored. The experimental monitoring protocol of these particle measurements is described in Shehabi et al. (2008a).

Table 4: Average measured indoor particle concentrations at eight northern California data centers (µg/m^3) (Shehabi et al., 2008a)

data center location	particle size range (µm)					
	0.3-0.5	0.5-0.7	0.7-1.0	1.0-2.0	2.0-5.0	Total
Sunnyvale	n/a	1.07	0.84	1.44	1.28	4.64
Walnut Creek	0.06	0.02	0.03	0.07	0.05	0.22
Rocklin	0.13	0.02	0.03	0.07	0.08	0.33
Redwood City	0.20	0.07	0.05	0.12	0.40	0.84
Dublin	0.14	0.03	0.03	0.07	0.03	0.30
Oakland	0.08	0.02	0.01	0.02	0.03	0.15
San Francisco	0.33	0.12	0.07	0.13	0.30	0.95
Berkeley	0.08	0.04	0.03	0.05	0.11	0.31

The first data center in Table 4 (Sunnyvale) is a data center with an ASE mechanical design while the remaining seven data centers all represent the conventional design shown in Figure 2. Average indoor concentrations for particles of diameter 0.3-5 µm average less than 1 µg/m^3 in all conventional data centers monitored. Indoor particle

concentrations were measured to be low and steady at Rocklin site (Figure 7), which was representative of measurements for the other data centers with conventional design. The average measured indoor concentrations at the Rocklin site was 0.3 $\mu g/m^3$, with the indoor proportion of outdoor particle (IPOP) being approximately 1% of the corresponding outdoor values.

Figure 7: Time Average Particle Concentration at a Conventional Data Center in Rocklin, CA, October 2006 (Shehabi et al., 2008a
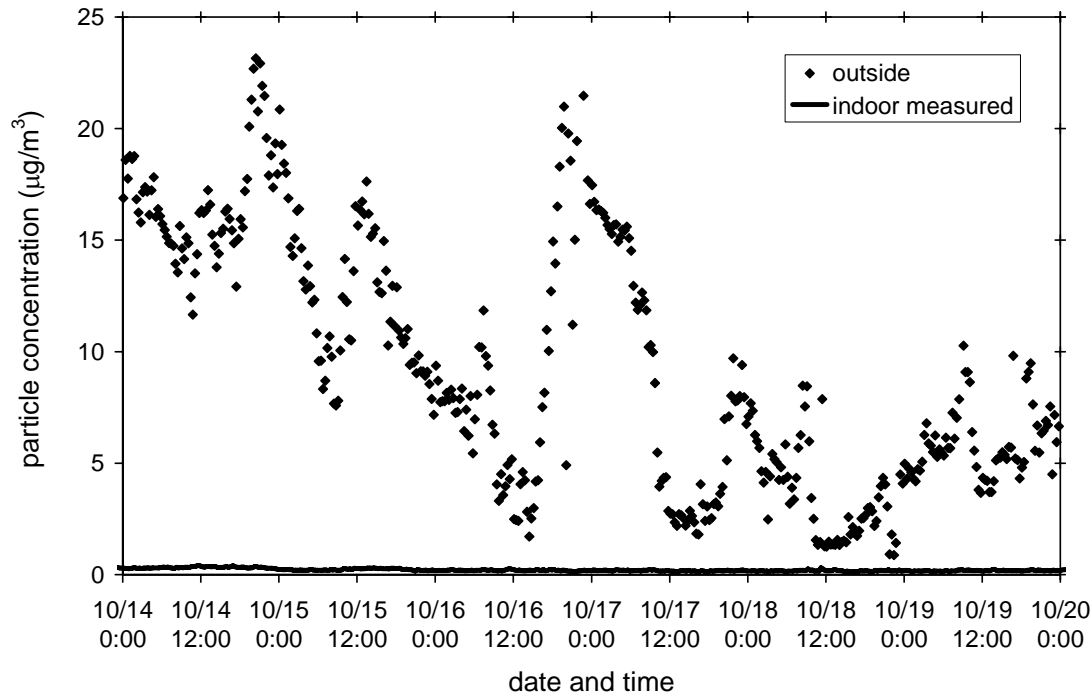
As expected, indoor particle concentrations are strongly related to the rates at which outdoor air enters the building. Time-averaged indoor concentrations are approximately an order of magnitude higher at the Sunnyvale site, where a high percentage of outside air was used during a portion of the monitoring period due to the ASE mechanical design at this location. At this data center the average measured indoor concentration was 4.6 $\mu g/m^3$ and the IPOP was about 20%. This concentration remains lower than the indoor concentration limit for data centers suggested by ASHRAE for fine PM (15 $\mu g/m^3$). Particle guidelines for data centers vary widely among industry documents and some server manufacturers recommend maximum concentrations that are orders of magnitude higher (ASHRAE, 2005). The measured particle concentration at Sunnyvale is similar to previous measurements made in an office building across the same particle size range (Fisk et al., 2000). However, outdoor concentrations around the office building in the Fisk et al. study were much lower than the levels measured in Sunnyvale. High variability in indoor concentration is observed at the Sunnyvale site and is clearly associated with the proportion of outside air being toggled between 1% and 85% of the supply airflow. The indoor concentration between these two HVAC modes differs by an order of magnitude.

Figure 8 shows indoor concentrations responding rapidly to changes in the HVAC system between "low" outside-air mode (ASE turned off) and "high" outside-air mode (ASE turned on). When in the "low" mode, results were similar to those at the conventional data centers. During this mode of operation, the measured indoor concentrations were approximately 1 to 2 µg/m^3 for nearly all times, regardless of outdoor concentrations. During the "low" outside-air period, the IPOP was about 3%, which is comparable in magnitude to values at the other two sites (~ 1%). A sudden increase in particle concentration is apparent in Figure 8 whenever the HVAC system switches to the "high" outside-air mode. The increase in indoor particle concentration begins toward the end of the day, around midnight, and then typically ends late in the morning. During the "high" outside air mode, the indoor concentration increases by nearly an order of magnitude (as compared with the "low" outside air mode) and varies more directly in response to changing outdoor concentrations. The indoor concentration shifts from approximately 3% to 36% of the outdoor concentration. The higher indoor concentration is sustained until the HVAC returns to the "low" outside-air mode.

Figure 8: Time Average Particle Concentrations at an ASE Data Center in Sunnyvale, CA, August 2006 (Shehabi et al., 2008a)
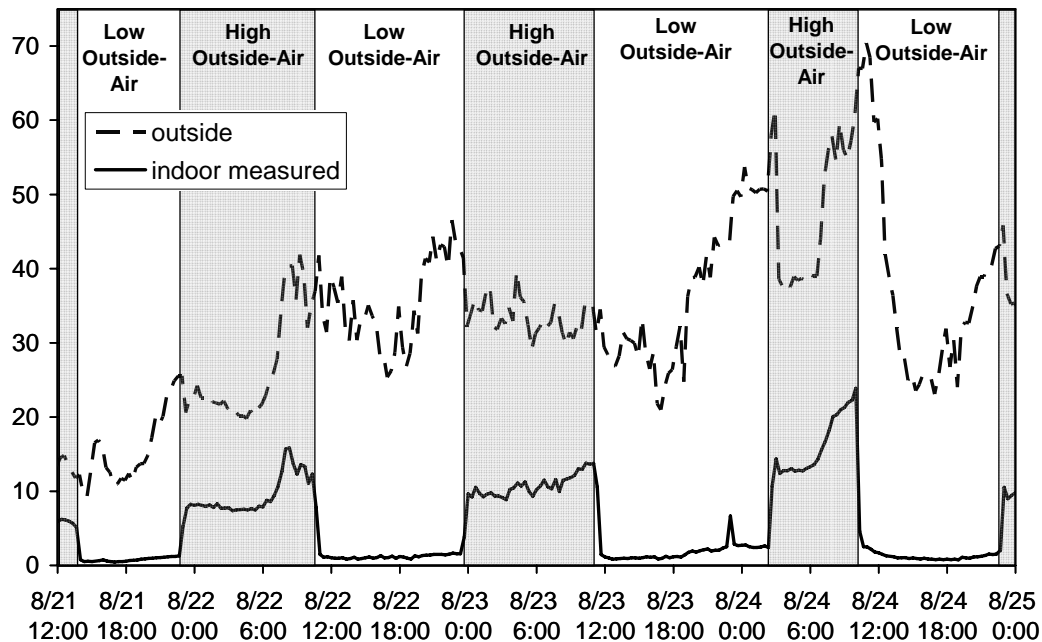
While particle data evaluated in this research confirm and quantify the increase in particle concentrations caused by using more outside air, the equipment risk associated with this concentration increase remains unknown. The indoor particle concentrations at Sunnyvale were still well below particle limits recommended by some server manufacturers and were less than the limit suggested by the ASHRAE. The results from this research project provide data center designers and other decision makers with quantified energy saving potential; highlighting the value of ASE implementation and identifying when conventional parameters, such as humidity restriction, economizer

sensors, and temperature setpoint can be adjusted to maximize savings. These potential benefits emphasize the value for a more thorough understanding of the equipment reliability risks associated with the indoor particle concentration identified and evaluated in this research project.

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