The Energy Dashboard: Improving the Visibility of Energy Consumption at a Campus-Wide Scale

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Abstract

Presenting a fairly controlled environment for instrumentation and implementation of energy use policies, the University of California at San Diego provides an excellent testbed to characterize and understand energy consumption of buildings at the scale of a small town with over 45,000 residents. We present data collected from four selected buildings that are archetypes of diverse buildings from residence halls to data centers. In particular, we focus on 'mixed-use' buildings where the energy consumption of IT equipment accounts for more than a quarter of the total energy use. Our detailed observations identify the primary components of the baseline energy use and the sources of peaks in energy consumption. Surprisingly, computing accounts for a large fraction of the baseline energy use, thus giving insights in how to significantly reduce power consumption by creating effectively duty-cycled buildings.

Categories and Subject Descriptors

H.4 [**Information Systems Applications**]: Miscellaneous; J.7 [**Computing in Other Systems**]: Industrial control

General Terms

Management, Experimentation, Measurement, Human Factors

Keywords

Energy, Power, Buildings

1 Introduction

The US Department of Energy (DOE) estimates that 73% of the electricity usage and 39% of the CO2 emissions in the US come from buildings [4]. Given their relatively long lifespans, buildings constitute a major opportunity for reductions in energy use. While energy use by buildings has been an important design consideration since the energy crisis of 1973, building design guidelines have not kept pace with the changing nature of buildings and their energy use. The EnergyPlus energy simulation software by the DOE, often used for LEED certification calculations, for instance, does not even account for the full scope of IT loads, often lumping these as 'miscellaneous' power loads. At the other extreme, a number of prior and ongoing efforts target compute-intensive data-centers for detailed modeling and characterization [3, 5, 10]. Buildings that have a large IT infrastructure but aren't full blown data centers however require additional research regarding their electricity usage. To address this need, this paper details results and observations from an ongoing study on the electrical energy use by a diverse array of buildings on the UCSD campus.

While the individual contributors to the total energy consumption within a building vary, the dominant consumers are often environmental control (air-conditioning and heating) including the air handling subsystems, lighting subsystems, and the IT equipment from PCs to network and server equipment. Depending on their use, the contributions of individual subsystems vary across different *types* of buildings. Increasingly, a large number of buildings can be classified as 'mixed-use', which are buildings characterized by both computing and human resources with varying balances between the two. It turns out that a good fraction of energy use in mixed-use buildings is in fact by the IT and communications/networking equipment, accounting for approximately 20% of the total energy use, second only to lighting [2].

Effective power management for buildings requires an accurate model of the various components of energy use, as well as their spatial and temporal variations, which depend on both human and environmental factors. We note that a number of past and ongoing efforts have indeed sought to build [6, 7] or use commercial hardware [13] to provide accurate measurement of power usage data on a per device or a per user basis [6, 7]. In contrast, we measure the total energy going into a building and then break it down based on individual subsystems including a selected sampling of the end points of the electrical circuits. Despite the difficulties of setting up measurement devices, we believe this is more encompassing and gives us a better picture of energy usage.

In this paper, we describe the energy measurement infrastructure and the results from our measurements. First, we describe our macro scale energy measurement setup where we look at the total energy consumed by various buildings across

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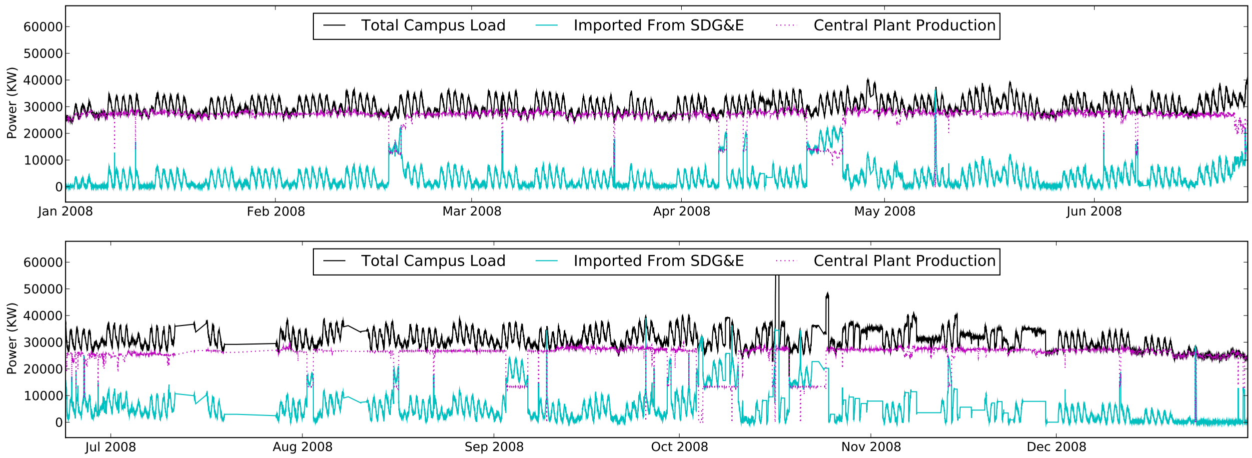

Figure 1. UC San Diego Demand Response: Tracking the real time demand, total energy imported from SDGE, and the total energy production by the Central Utilities Plant in 2008.

the campus and highlight the differences between them based on factors such as their use model and weather. Next, we consider a specific building, the CSE building, and provide a further energy breakdown based on individual floors, mechanical loads, lighting, plug loads/IT and the server cluster.

The main contribution of this paper is an accurate and detailed energy use characterization of a 'mixed-use' building, broken down into various baseline and peak-load components. Using this data we make several observations that will be crucial in devising strategies for combined energy management of climate-control systems and IT equipment.

2 UCSD Campus as a Testbed for Energy Use

In terms of scale and complexity, the UCSD San Diego campus resembles a small town. The campus is spread over an area of 1200 acres and has a daily population that exceeds 45,000 people, of which 29,000 are students. Out of these 29,000 students a significant portion (10,000) reside on campus in UCSD housing. There are over 450 buildings on the campus of which 60 of the largest buildings are currently metered to provide aggregate energy consumption data.

2.1 Centralized Energy Management System

Under a campus-wide sustainability[1] initiative, UCSD has taken on an ambitious goal to reduce energy usage and to use cost-efficient renewable energy sources with the objective of becoming energy self-sustainable[2] (or off the electrical grid) by mid-2011. To support this goal, the campus has an extensive energy generation, storage and management system in place to deliver both electricity and thermal energy in the form of high temperature and chilled water to buildings scattered across campus. The centralized Energy Management System (EMS), by Johnson Controls, is connected to sixty of the largest buildings across campus, managing their HVAC systems. The high temperature and chilled water loop is delivered from a Central Utilities Plant (CUP), which includes a 30MW co-generation system comprising two 13.5MW gas turbines, a 3MW steam turbine and a solar cell installation. The co-generation plant operates at a combined efficiency of 74% and enables UCSD to self-generate almost 80% of its electricity demand. The CUP has a capacity of 15,000 tons of chilling with a 40,000 ton-hr thermal energy storage (TES) tank. Three chillers are driven by steam turbines and five chillers are electrically driven. UCSD currently participates in San Diego Gas and Electric (SDG&E) capacity bidding program and modulates demand response (DR) manually by shifting chilled water demand from electric chillers to the TES tank, ramping the steam turbine generator by using standby conventional boilers, and changing campus-wide thermostat and static pressure set points in non-critical areas throughout campus.

Figure 1 plots the UCSD demand response for 2008. As can be seen from the figure, the yearly energy demand of the entire UCSD campus ranges from 26MW to 36MW. Most of this energy demand is serviced by the co-generation plant with the shortfall imported from SDG&E. The energy imported from SDG&E ranges from 0MW to 10MW, with larger amounts imported during the summer months. During the middle of several months, central plant production goes down significantly. This corresponds to times when the plants are brought down for maintenance.

2.2 Energy Measurement Infrastructure

At the campus scale, the energy measurement infrastructure includes instrumentation of various buildings with energy meters for collection of real-time energy usage data. The buildings under measurement have varying degrees of human occupants and IT equipment. In most buildings the meters provide data about the total electricity demand as well as the total thermal demand. The thermal energy demand for individual buildings is calculated using several measured parameters including the rate of chilled water passing though the building and the temperature of the water when it enters and exits the building. The electric meters installed at the building level are three-phase commercial grade high-accuracy PowerLogic meters (from Schneider Electric) that

[1] http://sustain.ucsd.edu/

[2] http://greencampus.ucsd.edu/

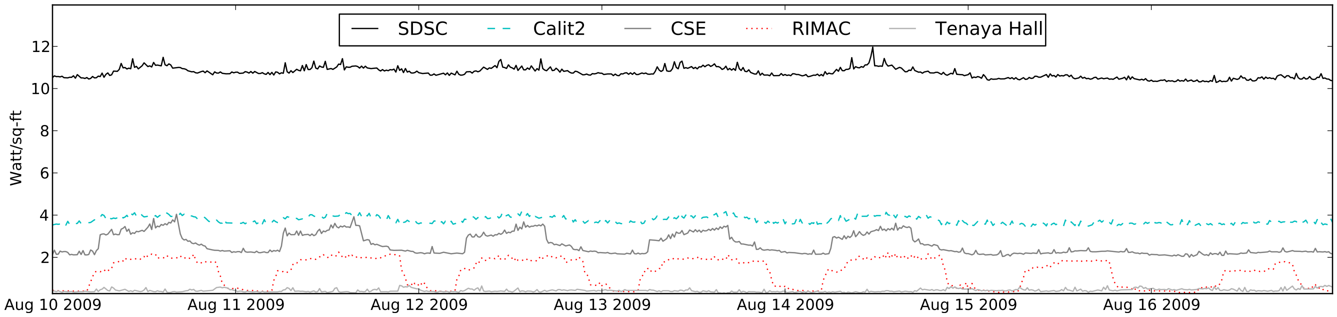

Figure 2. Comparing various buildings depending on their usage modalities. The data presented is for a week in August.

send data back to central campus servers over a wired communication network. These meters measure various electrical parameters such as power factor, voltage levels, real and reactive power, minimum and maximum demand, etc.

For a much finer grained measurement of energy use data, we selected the Computer Science and Engineering building as a test bed. The CSE building is unique in several aspects that make it an ideal testing ground for conducting research in energy efficiency in a mixed-use building. The CSE building has a closed loop system that provides zonal and floor-by-floor control of air flow, temperature, and lighting conditions. It also provides dynamic control of window shading, is coupled to the central campus chilled water loop, and also has local refrigeration capabilities. With around 600 occupants, it has approximately 750 desktop PC machines, one machine room for computer servers and six instructional computer labs. Combined, the computer resources account for over 25% of total building energy consumption, even during nights and weekends. The machine room holds a large number of computer servers and nodes. Cooling for the machine room is provided by the campus chilled water loop in addition to additional HVAC units that run on electricity. For these finer grained energy measurements, we have instrumented the CSE building with submetering on 15 separate circuits that report energy use broken down by plug loads, lighting, and the machine room on individual floors.

2.3 Data Storage and Visualization

All UCSD meters currently report data back to a central campus data acquisition server. Managing the data is challenging since each meter is configured to report data several times a second, and each record contains multiple measured parameters (power, KVA, power-factor, demand etc) including minimum, maximum and average values for each parameter. A separate storage and visualization server collects the individual meter readings and stores aggregate time-stamped data at 15 minute intervals in a database.

3 Initial Results and Observations

We now present initial energy consumption data gathered from our measurement infrastructure. We present aggregate data across various buildings that are being monitored to show how usage modality affects their energy use and take a detailed look into the energy breakdown. We present data spanning a year to highlight the effect of seasonal changes, as well as detailed plots to highlight changes during a week. Finally we present a breakdown of the various energy consumers in the CSE department. The weekly data for all these plots is taken from one week in August 2009, from August 10th (Monday) through August 16th (Sunday) to cover a normal work week (with summer classes) and weekend.

3.1 Effect of Usage Modality

Figure 2 presents energy data for a week in August 2009 for several types of buildings. We use Watts/sq-ft as the metric of comparison since the buildings are of different sizes. ‘Tenaya Hall’ is a residential dorm for undergraduate students while ‘RIMAC’ is the campus gymnasium. ‘CSE’ is the Computer Science and Engineering building and ‘Calit2’ is a research building that houses a nanoscale fabrication facility and a machine room on-site; we consider both of these as mixed-use buildings. Finally, ‘SDSC’ is the San Diego Super Computer Center with a large number of computer servers. As can be seen from the figure, CSE and Calit2 consume significantly more power per sq-ft than RIMAC and Tenaya Hall. The primary cause for this is power consumed by the additional IT infrastructure in the CSE and Calit2 buildings. SDSC has a significantly higher power/sq-ft value than all the other buildings, attributed to the power consumed by the computer nodes. The daily variation of the CSE and RIMAC buildings are caused by the rise in power consumption during work hours because of the way these buildings are used. To maintain climate control the air handlers and the chilled water pumps are operational from 6AM - 5PM, which causes power to increase during the week for both buildings.

3.2 CSE as a Mixed-use Building

We now look at the CSE building in further detail to identify both long term and short term variations in its energy consumption. Figure 3 illustrates the total electrical load of the entire department. This includes all plug-loads, all the lighting circuits, and power consumed by the machine/server room. It also includes the mechanical loads in the building such as power consumed by the motors of the air handler units that are responsible for circulating the air throughout the building, the air compressors, and the pumps that drive chilled and hot water loops throughout the building. The thermal energy demand of the building is not included because the data was not available at this time. Since San Diego is a coastal city, with a moderately cool climate year round, the main thermal energy cost is due to cooling.

As seen from Figure 3, the total electrical load in the CSE building has a similar profile throughout the year, despite

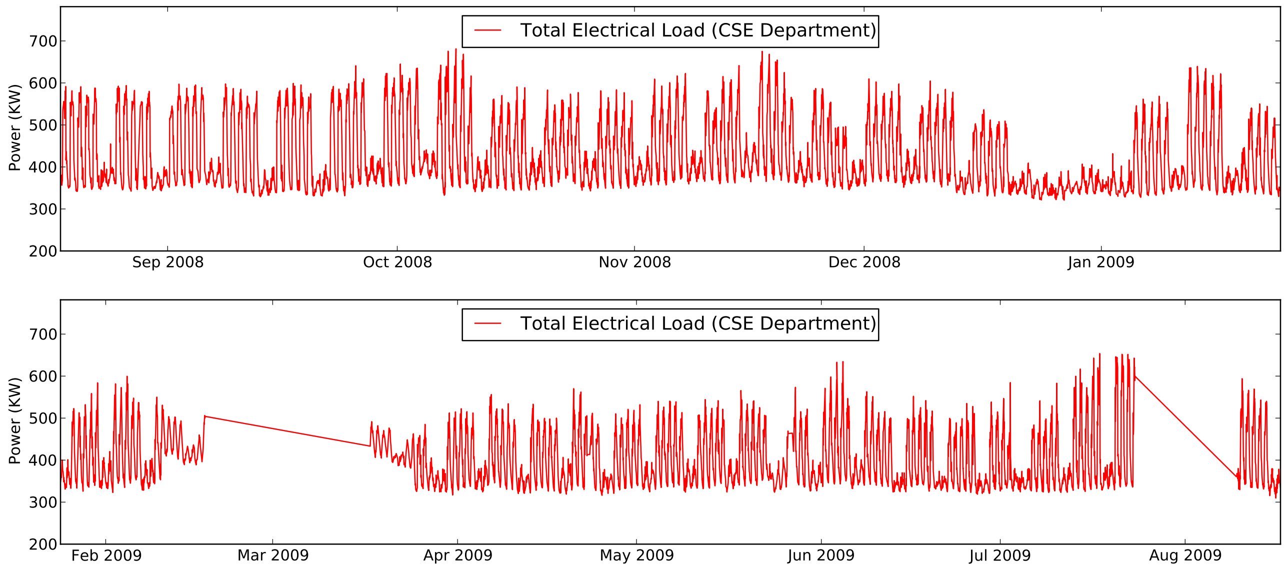

Figure 3. CSE Mixed-use Building: Total electrical load for a year (August 18th, 2008 through August 16th, 2009). While the daily load varies by as much as 250KW, it never goes below 325KW. This is the base load of the CSE building. Due to data collection issues some data around March 2009 and August 2009 is unavailable.

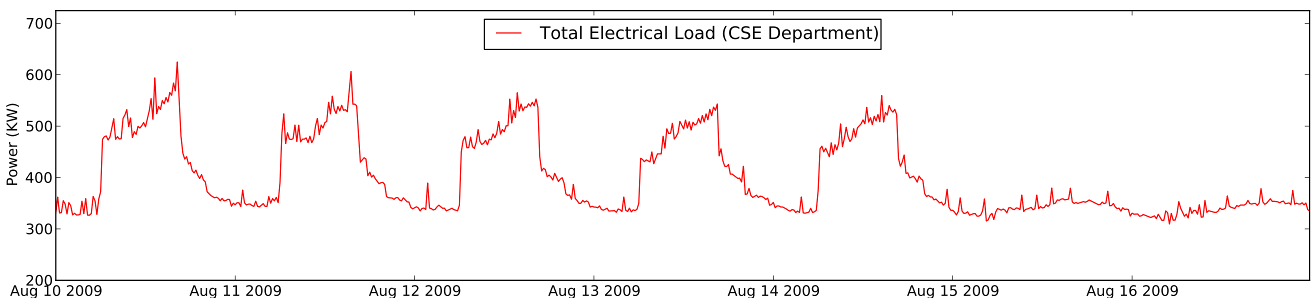

Figure 4. Variation of the electrical load in the CSE building at UCSD during a week in August.

spanning multiple seasons. The peak loads in the summer months (July - August) are higher than in Winter (November - February), due to the additional cooling required. Importantly, the 'base-load' of the building, i.e. the minimum power consumption, remains similar throughout the year and never falls below 325KW. This can be seen clearly in Figure 3 from December 18th, 2008 to Jan 5th, 2009 when the university was closed for winter break. During this time period the building occupancy was expectedly very low and as a result the climate control units were configured not to turn on during the day by default and could only be manually activated in individual offices. Despite that, the base load of the building in this period was still over 325KW.

3.3 Energy use Breakdown and Observations

Figure 4 shows the total electrical load on CSE, for one week in August this year. During weekdays, the demand rises dramatically around 6AM due to climate control systems starting up air handler units and chilled water pumps, with demand peaking around 3pm - 4pm. This is as expected since temperatures gradually rise during the day. Other causes that lead to higher demand relate to building use during the day, which includes classroom activity, labs, as well as the increase in the number of occupants. Around 5pm during weekdays there is a sharp drop in the total load since by default the energy savings settings of the climate control system kick in and as a result some of the air-conditioning units and air handling units shut down. Users in individual labs and offices are able to manually alter this after 5pm. As temperatures drop and building occupancy reduces during the evenings the total load decreases gradually. Since CSE also houses graduate student offices and labs, building occupancy remains high until late in the evenings (around 8PM). The lowest electricity demand occurs between 8PM and 6AM. Importantly, during the weekend when building occupancy is low, the climate control systems are preset to activate on manual activations only.

There are three important observations that we can make from the data presented in Figure 3 and Figure 4. First, the dynamic variation of electrical load during the day is as expected and fairly predictable. Second, the 'base-load' of this mixed use building is almost as high as the dynamic variations during the weekdays. Finally, and most importantly,

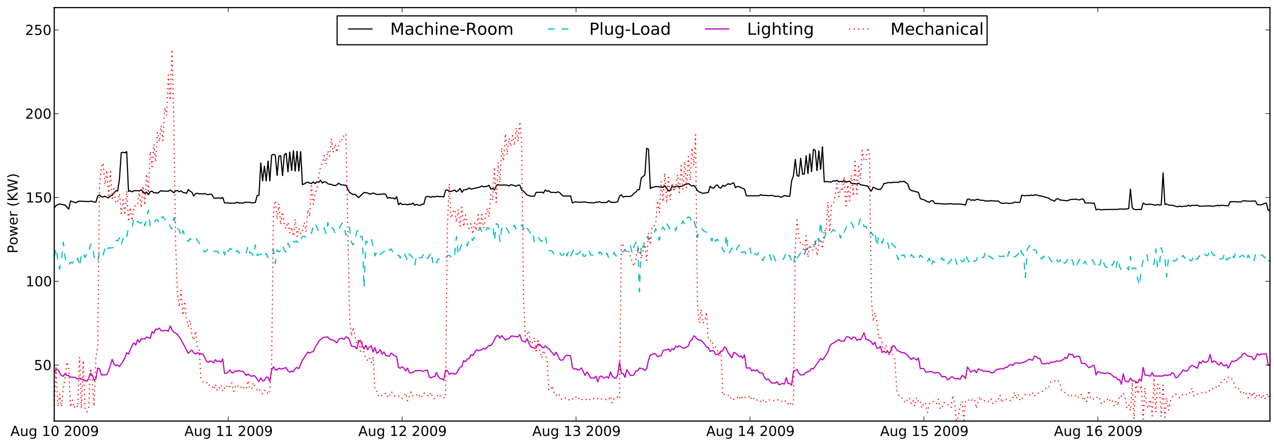

Figure 5. Detailed breakdown of the energy consumption of the CSE mixed-use building. The data presented is for a week in August.

this base load is consumed regardless of actual occupancy (even during weekends or holidays).

To determine a further breakdown of the total electrical load presented in the previous section we have instrumented the CSE building with submeters placed on major subsystems of the building. The additional metering was added to isolate the energy consumed by various circuits feeding the machine room, multiple lighting circuits feeding individual floors, and mechanical load imposed by the climate control system such as air handler systems. The submetering on the 15 main electrical circuits has given us a good deal of visibility on where the electricity is actually going.

We have categorized the electrical loads in the building into four categories: power consumed by all the IT and cooling equipment including the compute servers in the machine room (*Machine-Room*), power consumed by lighting equipment on all floors (*Lighting*), power consumed by all the plug loads including desktops and laptop PCs (*Plug-Loads*) and power consumed by the mechanical subsystems in the building including the air handlers and climate control units (*Mechanical*). Figure 5 shows the power contributions of each of these categories for a week. Although not shown in the figure, the power measurements in each of these categories add up to the total electrical load of the CSE building, as measured by a separate meter.

From Figure 5 it can be seen that the largest contributor to the total CSE electrical load is the equipment in the machine room, denoted by *Machine-Room* in the graph, which remains fairly constant during the entire week and does not exhibit much variation. Occasional slight increases in load occur when large compute jobs or backups have been scheduled (August 11th and August 14th in the graph), causing the load to increase by 25KW. Even during the weekend (August 15th and August 16th) the load remains constant at around 150KW, essentially showing that most of the compute nodes (servers) are not powered off or put into lower power modes. The next major contributors are the *plug-loads* which vary between 120-140KW during the week and remain close to 120KW during the weekend. Most of these plug-loads are in fact IT related loads, such as desktop PCs and monitors. In total, IT equipment accounts for more than 70% of the baseline electricity load for the building!

As part of another experiment [1] we accounted for at least 700+ desktop PCs not including about 250 or so in the undergraduate labs in the basement. At around 100W each [1], including the monitor, these desktop PCs account for approximately 100KW of the total plug load in the building. Although the power contributed by plug loads reduces over the weekend, it is still over 120KW suggesting that most PCs are actually not powered off or put into low power modes when not in use [1, 9, 11, 12]. The contribution of lighting to the total load on the CSE building is less significant and hovers around 50KW, increasing to 75KW during work hours and reducing to about 40KW during the weekends. The largest variation is observed by the *Mechanical* loads, which range from 25KW during off-peak hours to about 225KW during peak hours. The major portion of the mechanical loads are the climate control systems and the air-handler units which start up automatically at 6AM as denoted by the sharp increase. The mechanical load continues to increase gradually and load peaks around 3-4pm when the occupancy of the building is at maximum and the temperature is higher. At around 5pm the climate control system switches to energy saving mode shutting down most air-handling units, as denoted by the sharp decrease seen in Figure 5.

There are several important observations from Figure 5. First, IT load in this mixed-use building is significant when considering both plug-loads and the machine room, accounting for more than 50% of the total electrical load during peak hours and reaching almost 80% during off-peak hours. Second, the mechanical load is the next biggest contributor to the total load on the building, although most of it goes towards maintaining climate control. Finally, the base-load on the building is largely from the IT equipment, both servers and desktop PCs, and it does not lower during weekends.

4 Discussion and Future Outlook

In general, there are two ways to reduce the energy consumption in buildings. The first is to use advances in energy efficient designs of components and replace existing subsystems with these alternatives. Examples include replacing incandescent lights and CFL with LEDs and installing more efficient HVAC units. The second way is to improve the efficiency of existing systems, primarily by reducing the amount of wasted work. Examples include powering off the climate control subsystems during non-work hours and keeping only the essential lighting powered on during nights. To achieve energy efficient operation, both these mechanisms – replacing existing systems with lower power alternatives and managing existing systems better – need to be employed.

Our results show that much of the energy consumption, especially the base-load of buildings, is due to the IT infrastructure. In fact, buildings with a large IT footprint, such as CSE, have a higher power consumption per unit area than residential buildings. Clearly, a potential for reduction in IT power use exists, especially to drive down the base load of the buildings during low use times, e.g. at nights and over weekends. One of the most important observations from our data is that IT power consumption remains high even when computers are not in use. This is typically due to users not wanting to lose connectivity to their systems (such as when they want to use remote desktop), and thus leaving their computers on despite being away.

IT power saving schemes such as Wake-on-LAN [8] and Somniloquy [1] can reduce power by expanding the use of power saving states while maintaining the responsiveness and availability of IT equipment. For example, had Somniloquy [1] been in use in the CSE building and using the data for the week of August presented in Figure 5, we can estimate the potential energy savings. Assuming all desktop PCs in the building were powered on for 45 hours during the week (8 hours a day, for 5 days per week + additional 5 hours) and were using Somniloquy at other times (during the evenings and the weekends), the direct energy savings from the reduction in plug loads alone over the entire week would have been around 20%. Additionally, if servers in the machine room were also using Somniloquy, using the same 45 hour work week, another 28% energy savings would be possible. Since this equipment will no longer be generating heat, second order effects such as reduced load on the air-conditioning and climate control system would lead to even more energy savings. Combined, the total energy savings would potentially be close to 50% of the current levels. One line of research we are currently doing is incorporating technology such as Somniloquy into users' machines and measuring the power savings that are being achieved in reality.

Further work on finer grained energy measurements is however needed to obtain more precise real time energy use data. Although we have achieved visibility at a macro level of the CSE building power consumption, we propose to combine our current measuring efforts with a more detailed measurement of the individual plug loads in the building. In order to do this, we have started instrumenting the building using smaller energy meters, and provide that same data in real time on our Energy Dashboard website. These meters give us visibility not just at an macro-level, but at the level of individual user machines and systems. We hope to use this data to find even more interesting energy use trends at a micro-level, and combine it with our macro-level data to identify further energy savings opportunities.

We believe that while the CSE building is IT heavy, it is representative of a typical office building. We seek to apply this level of data measurement to other buildings around the UCSD campus to verify that our conclusions are still valid. This will allow us to characterize and compare different buildings and validate that considerable energy savings are still achievable even when IT load is less.

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6 References

[1] Y. Agarwal, S. Hodges, R. Chandra, J. Scott, P. Bahl, and R. Gupta. Somniloquy: Augmenting Network Interfaces to Reduce PC Energy Usage. In *Proceedings of USENIX Symposium on Networked Systems Design and Implementation (NSDI '09)*. USENIX Association Berkeley, CA, USA, 2009.

[2] California Energy Commission. CEC End-Use Survey, CEC-400-2006-005, March 2006. `http://buildingsdatabook.eren.doe.gov/`.

[3] J. Chase, D. C. Anderson, P. Thakkar, A. Vahdat, and R. P. Doyle. Managing Eenergy and Server Resources in Hosting Centers. In *Proceedings of SOSP '01*, 2001.

[4] DOE. Buildings Energy Data Book, Department of Energy, March 2009. `http://buildingsdatabook.eren.doe.gov/`.

[5] X. Fan, W.-D. Weber, and L. A. Barrosso. Power provisioning for a warehouse-sized computer. In *Proceedings of ISCA '07*, 2007.

[6] X. Jiang, S. Dawson-Haggerty, P. Dutta, and D. Culler. Design and Implementation of a High-Fidelity AC Metering Network. In *Proceedings of IPSN/SPOTS '09*, 2009.

[7] M. A. Kazandjieva, B. Heller, P. Levis, and C. Kozyrakis. Energy Dumpster Diving. In *Proceedings of HotPower '09*, 2009.

[8] P. Lieberman. Wake-on-LAN technology. `http://www.liebsoft.com/index.cfm/whitepapers/Wake_On_LAN`.

[9] S. Nedevschi, J. Chandrashekar, B. Nordman, S. Ratnasamy, and N. Taft. Skilled in the art of being idle: reducing energy waste in networked systems. In *Proceedings of the 6th USENIX Symposium on Networked Systems Design and Implementation (NSDI)*, 2009.

[10] R. Raghavendra, P. Ranganathan, V. Talwar, Z. Wang, and X. Zhu. No "Power Struggles": Coordinated Multi-Level Power Management for the Data Center. In *Proceedings of ASPLOS '08*, 2008.

[11] J. Roberson, C. Webber, M. McWhinney, R. Brown, M. Pinckard, and J. Busch. After-hours Power Status of Office Equipment and Energy use of Miscellaneous Plug-load Equipment. *Lawrence Berkeley National Laboratory, Berkeley, California. Report# LBNL-53729-Revised*, 2004.

[12] K. Roth and K. McKenney. Energy Consumption by Consumer Electronics in US Residences. *Final Report to the Consumer Electronics Association (CEA)*, 2007.

[13] WattsUP. WattsUP Energy Meters. `http://wattsupmeters.com`.