CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

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By

Brittni Dixon-Smith, Angela Kwok, Ryan Satterlee, Felipe Pincheira, and Will Howekamp

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If you would like to contact the authors, please write to:

c/o CIFE, Civil and Environmental Engineering Dept.,
Stanford University
The Jerry Yang & Akiko Yamazaki Environment & Energy Building
473 Via Ortega, Room 292, Mail Code: 4020
Stanford, CA 94305-4020

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Abstract

The purpose of this research is to compare measured, stored, and predicted energy data from the Jerry Yang & Akiko Yamazaki Environment and Energy (Y2E2) building to derive conclusions about its energy performance. The research team, consisting of five graduate and undergraduate students, measured energy performance data from a sample of 107 rooms, which included kitchens, conference rooms, offices, classrooms, labs, and restrooms. The data collected provide detailed information on occupancy, thermal comfort, and energy consumption during a two and a half week period. In addition, the research team extracted stored data from both the utility company's records and the Y2E2's SQL database (accessible through SEE-IT software). This research explains the sources for the differences observed in energy performance compared to the predicted model. The major finding of this study is that Y2E2's energy performance meets the expectations of its efficient design. Overall, plug loads consume a typical proportion of energy, lighting performs beyond ASHRAE standards, and the hybrid Heating, Ventilation, and Air Conditioning (HVAC) system sufficiently adheres to the thermal comfort needs of the occupants. Although Y2E2 appears to perform adequately, this study suggests that there are more opportunities for cost and energy savings. This research indicates that the largest areas for improvement are in the energy performance of labs, kitchens, and circulation spaces. Limitations of the data acquisition system and inadequate access to building information restricted the energy analysis; therefore, extensive interpolations of performance were necessary. Thus, the findings drafted by the research team only provide a rough assessment of some of the sensor energy data as compared to the collected data. Similarly, restricted access and limited expertise narrowed the research team's evaluations on the energy performance of the HVAC system to analyzing its efficiency using thermal comfort as a measure of performance.

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1 Introduction

This research analyzes energy performance in a case study of Y2E2. The 166,000 square foot building contains classrooms, laboratories, offices, and support spaces. Y2E2, completed in 2007, was the first of four buildings constructed for Stanford University's Science and Engineering Quad. One of the central design goals of the project was for the building to use 50% less energy than a building of the same characteristics following ASHRAE 90.1-2004 (See 2.0 Definitions) recommendations (Better Bricks 2007). Five main strategies were used to reduce the building's energy consumption: load reduction, passive system use, efficient system design, energy recovery, and on-site power generation. Y2E2 was designed by BOORA Architects with engineering firms ARUP and ACCO to meet the LEED and Labs21 (See 2.0 Definitions) Platinum Performance Standards, the highest LEED certificates offered.

In recent years, energy performance of buildings has become an important initiative due to forecasts of skyrocketing energy costs and environmental concerns (Honeywell 2008). Accordingly, the Energy Independence and Security Act of 2007 (EISA 2007) established energy management goals and requirements to improve the performance of buildings. Consequently, new U.S. General Services Administration (GSA, See 2.0 Definitions) buildings and major renovations were mandated to reduce fossil-fuel-generated energy consumption by 55% by 2010 and by 100% by 2030 (U.S. GSA 2011). In support of these government initiatives, The American Institute of Architects (AIA), The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), the United States Green Building Council (USGBC) and Architecture 2030 have tightened codes and standards.

To achieve these energy saving initiatives, Y2E2 was designed with advanced energy efficient technologies. However, a report published in October 2009 by researchers at Stanford's Center for Integrated Facility Engineering (CIFE, See 2.0 Definitions) called into question the level of efficiency of the building's energy reduction strategies. The research was completed by eleven graduate students who had narrow knowledge of building systems and limited access to the data necessary to evaluate Y2E2's performance. Although this led to some underdeveloped conclusions, the research was successful in identifying certain building systems that were not necessarily performing as expected. The CIFE researchers evaluated Y2E2's energy performance during the first year the building was used. Based on the original building model and with the use of energy analysis tools, they found that actual energy consumption was significantly higher than initially predicted during the building's planning stages. CIFE researchers estimated that energy consumption exceeded the initial prediction and design objective by about 65% (Kunz, Maile & Bazjanac 2009).

A subsequent study completed at CIFE addressed the discrepancies between predicted performance models and actual building performance. The research is a case study of Y2E2 and three other buildings whose energy performances rely on both the activities of occupants and the performance of HVAC systems (Maile). The results of the study showed that the discrepancies revealed in the previous study were primarily due to improper sensor calibration, insufficient data archival, lack of integration between new HVAC components, inaccurate HVAC system topologies, and a lack of measured data in simulation tools.

The purpose of this research is to provide an explanation for the observed differences in energy performance from the predicted model using measured data from Y2E2. In order to investigate energy performance, the research team conducted a field study to collect data from a sample of 107 rooms. The rooms included kitchens, conference rooms, offices, classrooms, labs, and bathrooms. The research team evaluated lighting, plug loads and thermal comfort surveys in order to derive conclusions about energy performance. This analysis reveals shortcomings of the data acquisition system and indicates which systems or elements of the building can be improved to reduce energy consumption.

2 Definitions

Active chilled beams: cooling system that uses piped cool water running through ceiling beams. Heat rising from the room is transferred by convection too cool the room.

ASHRAE 90.1-2004: professional standard set by ASHRAE to provide minimum requirements for the energy-efficient design of buildings other than low-rise residential buildings.

ASHRAE Standard 55P: proposed national standard for thermal environmental conditions for occupancy comfort.

Ballast: electrical or magnetic control device that initiates the light arc in fluorescent and high intensity discharge (HID) lights with high starting voltage.

Center for Integrated Facility Engineering (CIFE): academic research center at Stanford University for Virtual Design and Construction of Architecture - Engineering. It supports reliable engineering and management practices to plan, design, construct and operate sustainable facilities.

Clo: unit used to express the thermal insulation provided by clothing, where 1 clo = 0.155 m^2 Celsius/W (0.88 ft^2*hr*°F/Btu).

CEE 243: Stanford University course offered to undergraduate and graduate students focused on predicting and measuring building energy usage.

EveryTime Audit: Refers to the audit conducted four times per day for two weeks, recording occupancy and lighting of each of the rooms in the sample.

Fenestration: design and placement of windows and doors on the elevations of a building.

Footcandle: unit of measure for the density of light as it reaches a surface. One footcandle is equal to one lumen per square foot. Measured footcandles are sensitive to the distance from the source to the surface of measure (inverse square law) and the angle at which the light reaches the surface (cosine law).

General Services Administration (GSA): United States federal agency that provides office space, goods, and services to other federal agencies.

Hydronic radiant floors: heating system that pumps heated water from a boiler through tubing laid in a pattern underneath the floor. In some systems, the temperature in each room is controlled by regulating the flow of hot water through each tubing loop. This is done by a system of zoning valves or pumps and thermostats (radiant heating).

Illuminance: density of luminous flux on a surface. It is measured in footcandles (one lumen per square foot) or lux (one lumen per square meter).

Insolation: measure of solar radiation energy received on a given surface area in a given time. It is often expressed in W/m^2 or $kWh/m^2/day$.

Labs21: team of professionals dedicated to the pursuit of sustainable, high-performance, and low-energy laboratories that will: minimize overall environmental impacts, protect occupant safety, optimize whole building efficiency on a life-cycle basis, establish goals, track performance, and share results for continuous improvement.

LEED (Leadership in Energy and Environmental Design): internationally-recognized green building certification system developed by the U.S. Green Building Council (USGBC).

LPD (Lighting power density): maximum allowable lighting density permitted by the building code in ASHRAE 90.1-2004. It is expressed in W/ft^2 for a given building/occupancy/space type.

Lumen: unit of measure for the light energy that flows in air. The total light output from electric sources is expressed in lumens.

Luminaire (Light fixture): complete lighting unit consisting of a light or lights together with the parts designed to distribute the light, to position and protect lights and to connect the lights to their power supply. Many luminaires include one or more ballasts.

Met: unit used to describe the energy generated by the body due to metabolic activity, defined as 58.2 W/m^2 (18.4 $Btu/hr*ft^2$), which is equal to the energy produced per unit surface area of a average person seated at rest. The surface area of an average person is 1.8 m^2 (19 ft^2).

OneTime Audit: Refers to the audit conducted once over the course of the two weeks for each of the rooms in the sample. Energy consumption and illuminance were measured in this audit.

OncePerTimeSlot Audit: Refers to the audit conducted twice over the course of the two weeks for each of the rooms in the sample, once at 9 a.m. and once at 1 p.m. Occupant comfort was measured in this audit.

Precourt Energy Efficiency Center (PEEC): research center at Stanford University whose mission is to promote energy efficient technologies, systems, and practices that emphasize economically attractive deployment.

SCADA (Supervisory Control And Data Acquisition): Control system reporting data on energy consumption from the main metering of Y2E2.

Stack effect: movement of air into and out of buildings driven by relative differences in the temperature and pressure of the air inside and outside of the building at different heights.

3 Research Questions & Hypotheses

Indication of significant energy use beyond the predicted design performance of Y2E2, and the major energy end uses by plug loads, lighting, and HVAC system prompted the following research questions:

1. Why is the building consuming energy differently from the predicted model?
2. What is the division of actual energy consumption among end uses in comparison to the predicted model and design intent?
3. How does the building's energy efficient HVAC system impact occupancy comfort?

If observations and previous research indicates that the building's automated energy analysis tools lead to inaccurate estimations of Y2E2's energy consumption, then by collecting measured data the research team should be able to discern a more accurate assessment of energy consumption, and provide recommendations that will improve the data acquisition system. Assessing collected and measured data during energy audits will also help identify disparities between the actual and predicted energy performance of Y2E2.

The aim of this research is to conduct a holistic assessment of the energy consumption of Y2E2. However, basic expertise and limited access to HVAC systems inhibited the research team's ability to gather measured data. Thus, the research team was unable to fully investigate a significant portion of the building's energy use. As a result, the third question was chosen to ameliorate the shortcomings of the data collection process. The third question requires a qualitative assessment of the efficiency of Y2E2's hybrid HVAC system. Thus, instead of collecting data from the HVAC systems to perform a quantitative analysis, the research team assumed that the uniquely designed HVAC system is energy efficient and proceeded to qualitatively evaluate how well the system meets the needs of the occupants.

4 Background

Research on the energy performance of buildings has shown that actual energy consumption differs significantly from predicted energy consumption. In the green building industry, buildings are designed to reduce energy usage with the implementation of energy efficient lighting and HVAC strategies, advanced building management systems, and specialized architecture and fenestration. Although green buildings demonstrate better energy performance than conventional buildings, which meet only building codes, the actual energy consumption of green buildings often exceed that of their building models.

For LEED-NC (LEED for New Construction and Major Renovations) certified buildings, a research study of 125 buildings conducted by the U.S. Green Building Council (USGBC) and the New Buildings Institute (NBI) concluded that there was little correlation between the predicted and actual energy consumption. The measured energy consumption of the LEED buildings varied widely, with some saving more energy than predicted and others saving less (Malin 2007). In the larger context of green buildings, an assessment of 19 green buildings in Massachusetts was conducted by the Energy Engineering Program at the University of Massachusetts. The sample consisted of 6 LEED-certified buildings and 13 LEED-based Massachusetts Collaborative for High Performance Schools (CHPS). On average, the green buildings were consuming 40% more energy than predicted (Bragonier 2009; Sacari, Bhattacharjee, Martinez, & Duffy 2009).

The CIFE researchers evaluated Y2E2's energy performance in 2009, the first year the building was used. Similar to other green buildings, actual energy consumption was significantly higher than predicted. It was estimated that energy consumption exceeded the initial prediction and design objective by about 65% (Kunz, Bazjanac, & Maile 2009). Arup's report on the energy consumption of Y2E2 shows that while the actual consumption exceeded the predicted, the relative energy savings between the baseline and the design remained roughly the same for the original and calibrated designs, as shown in Figure 1 (Kunz, et al 2009).

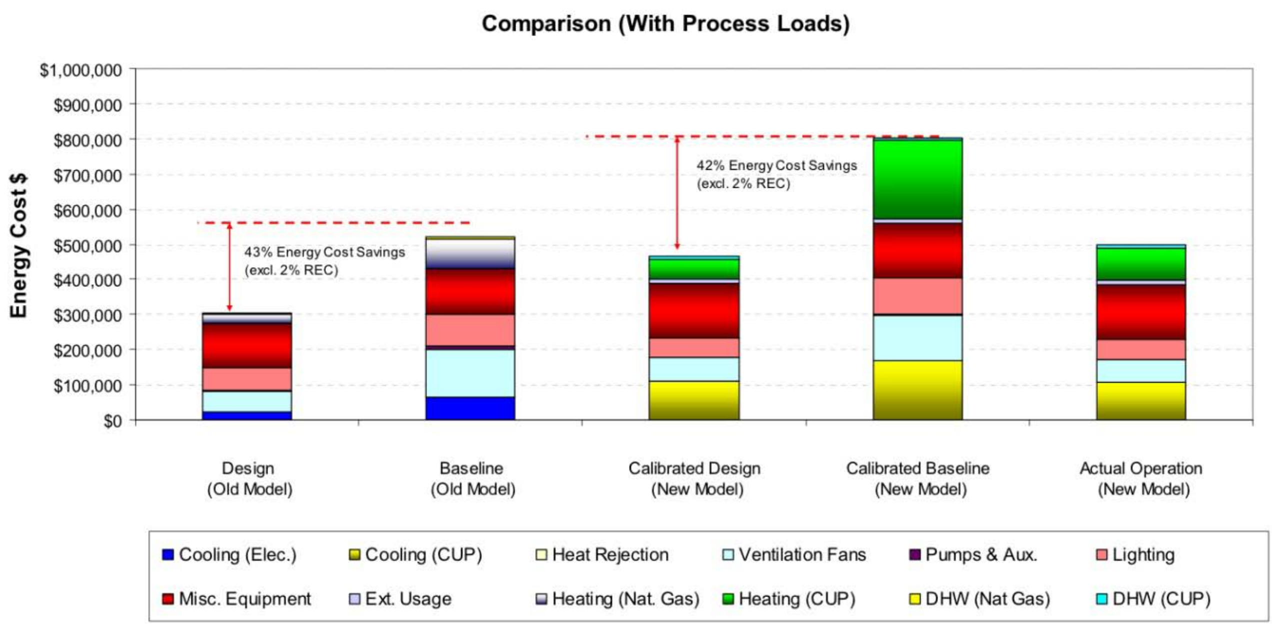


Figure 1: Comparison of models at Original Design, Calibration and Actual Operation stages. While the Actual Operation (far right) exceeds the energy consumption predicted by the Design of the Old Model (far left), the Calibrated Model (third and fourth from left) show that the Calibrated Design retains a 42% improvement over the Calibrated Baseline model. The old model was based on some assumptions that were inaccurate to the actual design of the building, causing both the Baseline and Design to be great underestimates (Kunz et al, 2009).

A disconnect between predicted and post-occupancy measured energy use indicates shortcomings of energy modeling. Considering the end uses of energy in commercial buildings, there are a number of potential reasons for the invalidity of predicted energy consumption using building models. According to many studies, lighting, HVAC, and office equipment consume the most energy in a typical commercial building. Therefore, it follows that the most savings can be achieved by implementing energy efficiency measures for these building systems (Partner Energy 2006). Subsequently, these end uses may also be the largest sources of disparity between predicted and actual energy consumption. Figure 2 illustrates the proportions of energy consumption in a typical commercial building.

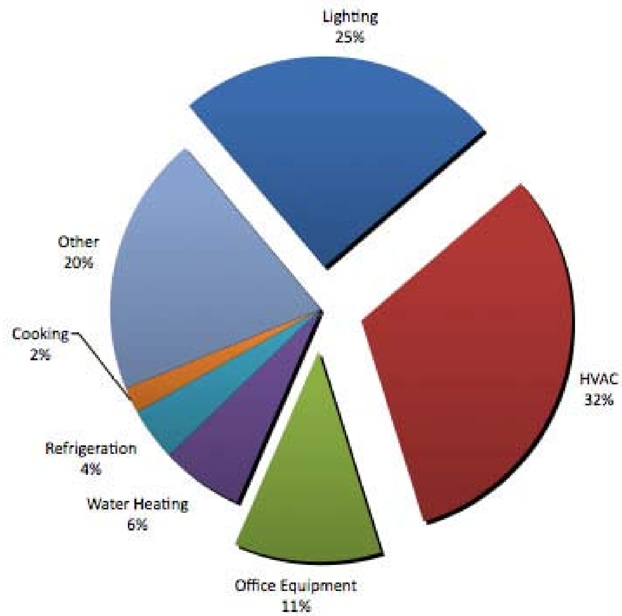


Figure 2: Typical Proportions of Energy Consumption in Commercial Buildings. HVAC systems and lighting contribute the most to power draw in a typical building. Y2E2 was designed with energy efficient systems and innovative designs to reduce these loads (Partner Energy).

4.1 Plug Loads

Plugs loads consume roughly 10-15% of commercial electricity use. In fact, 3 to 4 billion individual devices account for about 10% of total annual U.S. electricity use (Rivas 2009). Plug load reduction was addressed in Y2E2 through careful design and consideration of office sizes as well as education about building energy consumption for the occupants (Graffy et al. 2008).

Arup, the energy modeling firm that helped design Y2E2, estimated that the building would have "a 'non-regulated' end-use proportion of over 50% if no actions were taken to reduce the loads" (Graffy et al. 2008). Contrary to the end use being determined as "non-regulated" (outside the control of engineering design), plug loads were identified as a large potential for reductions, as shown in Figure 3. Offering accurate energy saving data for receptacle loads is very difficult due to their temporal nature and because information is not always available on what equipment will be used in the building. Tenants also have the ability to plug and unplug devices at their leisure or switch them out for different equipment, which adds to the difficulty of enumerating accurate reductions of energy consumption (COMNET).

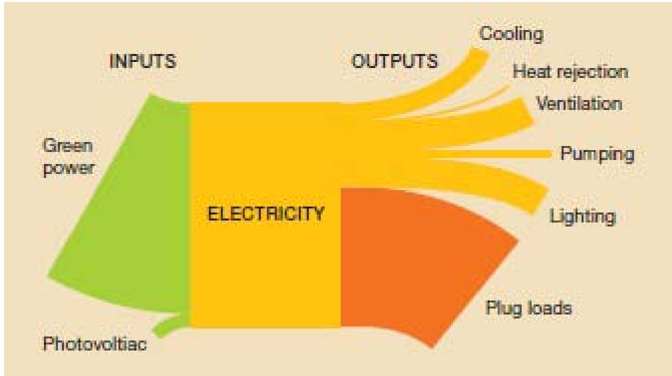


Figure 3: Energy Flow and End Uses in Y2E2. This diagram shows that Y2E2 differs from the typical building (shown in Figure 2) in that the largest end-use of electricity is plug loads, rather than HVAC or lighting. This identifies plug loads as a target for potential reduction in the energy consumption of Y2E2 (Graffy et al. 2008).

4.2 Lighting

The lighting decisions for Y2E2's design were made with load reduction and occupant productivity as primary goals. With an average direct solar insolation level of 5.4 kWh/m^2 on the Stanford campus (exceeding that of Houston and other southern U.S. cities), daylighting has great potential in Y2E2 (Graffy et al. 2008). Lighting loads were reduced through the use of varied daylighting strategies: large exterior windows, open atria, light shelves, and interior glass and polycarbonate walls (allow hallway lighting to penetrate into interior rooms). While maximizing daylighting, the design addressed occupant comfort and productivity through the use of windows with high-performance low-e glazing, fritted atria windows, and exterior sunshades to minimize glare and excessive solar heat gains (BetterBricks 2007).

With respect to artificial lighting, the design planned for the use of energy efficient building lighting and task lighting. The LED under cabinet fixtures and task lights provided in all the offices would ideally supplement daylighting to provide occupants with sufficient lighting during the daytime (BetterBricks 2007). The architectural lighting uses high performance T8 lamps and electronic ballasts, including dimming ballasts to encourage the use of only the necessary amount of light. Rooms in Y2E2 are also equipped with occupancy sensors that turn off the lights after 10-15 minutes of no movement.

4.3 Thermal Comfort & HVAC System

Because the primary objective of the Y2E2 building design was to achieve 50% less energy consumption than ASHRAE 90.1 standards, the HVAC system was not necessarily designed to accommodate the highest standards of thermal comfort. Some occupants in Y2E2 reported exercising greater tolerance of the thermal conditions because of their departmental visions (e.g., Precourt Energy Efficiency Center, See 2.0 Definitions).

Human comfort is primarily affected by the physical space and characteristics of the individual (including health, vulnerability and expectations, clothing, and physical activities) (McDowell 2007). Thermal conditions and air quality are the only elements that can be directly controlled by the HVAC components. There are six primary factors that concern thermal conditions:

metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, and humidity (ASHRAE 2004). Although there are specific factors that affect human comfort, the mechanisms used to accommodate human comfort requirements can vary. Consequently, Y2E2 uses a hybrid HVAC system to maximize energy efficiency.

There are three air handling units (AHU) within Y2E2. The function of the AHU are to draw in outside air and return air, mix them, condition the mixed air, blow the conditioned air into the building space, and exhaust excess air outside (McDowell 2007). The following AHU subcomponents help carry out these functions (See Appendix A for HVAC Subcomponent Functions):

- Exhaust Volume Control
- Constant Volume System
- Variable Air Volume System
- Exhaust Variable Air Volume Control

Y2E2's HVAC system makes extensive use of passive systems rather than mechanical systems. Passive systems create a stack effect (See 2.0 Definitions) that ventilates and cools the building. Windows are manually operated and ceiling fans are among the elements of the passive system in the north- and east-facing exterior offices. Additionally, concrete slabs and stone walls act as thermal mass to regulate temperature variance. The four atria provide primary passive heating, cooling, and ventilation for all spaces except the laboratories. Y2E2 also incorporates active systems for heating and cooling. Active chilled beams (See 2.0 Definitions), consisting of cooling coils and radiant heating and cooling, were installed throughout the building in addition to the three AHUs. Radiant flooring was installed in the entryways and the cooling coils were placed in the warmer areas of the building.

5 Methods

During the course of a ten-week period, four primary steps were taken to complete this research project. First, background research on energy audits and Y2E2; second, a training and practice session in the necessary instrumentation; third, a brief data collection followed by data entry; and finally, the analysis of data and summary of conclusions.

5.1 Energy Audit Design

The research process began with a review of energy audit practices as well as an overview of the research that had been done specifically focusing on the energy consumption of Y2E2. A major resource at this time was the set of findings from Stanford University's course CEE 243: Predicting and Measuring Building Energy Use, which for the last three years has conducted research related to the energy use of Y2E2 (see 4.0 Background for more information).

During this portion of the project, the research team decided that the focus of the project would be on the building scale, rather than on the level of individual systems, as the CEE 243 course had focused. The team also noticed a gap in knowledge. The HVAC systems in Y2E2 were designed with the intent of creating a very efficient building, but it appeared to be unknown whether these systems sufficiently satisfied occupant comfort at the same time. There was also interest in comparing energy use of the building to occupancy patterns.

In order to research answers to these questions, the research team planned a two-week audit. First, the team chose a diverse room sample of approximately one-fifth of the 519 building spaces to account for the varying HVAC subsystems. Open spaces such as hallways and staircases, while counted among the 519 total spaces, were not chosen. The research team developed a schedule for the audit (See 6.2 Data Collection), and created two surveys: one to determine occupant comfort, based on ASHRAE Standard 55P (See 2.0 Definitions), and another to estimate the energy use of each room for lighting and plug loads.

5.2 Data Collection

Over a two-week period, members of the research team visited the 107 selected rooms four times per day: at 9 a.m., 1 p.m., 5 p.m., and 9 p.m. At each of these time slots, the occupancy of each room was recorded along with the lights turned on in that room (EveryTime Audit - See 2.0 Definitions, and See Appendix C for full survey). For each room, a comfort survey was also administered twice over the course of the two weeks, once at 9 a.m. and once at 1 p.m. (the scheduled times with the highest occupancy rates), on different days (OncePerTimeSlot Audit - See 2.0 Definitions, and See Appendix C for full survey). The third part of the audit involved determining the energy consumption of each room with a full energy audit (OneTime Audit - See 2.0 Definitions, and See Appendix C for full survey).

5.3 Data Analysis: Quantitative Energy Evaluation: Plug Loads & Lighting

After collecting all of the data, the remainder of the study was spent on analyzing the information gathered in an attempt to answer the research questions posed at the start of the project. For the energy portion of the problem, this meant translating all of the collected data into a value representing energy consumption on a per day and/or per square foot basis for each room that was audited, divided between plug loads and lighting.

Plug Loads

Due to certain rooms chosen for the audit being unoccupied for the majority of, or all of, the two-week time period of the audit, 73 rooms remained to provide data on energy consumption. Plug loads were determined based on the energy audit and survey completed for each room. All equipment was either measured with a power meter or looked up in specification sheets to determine a power draw (See Appendix A for Assumptions), which was then multiplied by the occupant's estimation of the time per day each piece of equipment operates in the given power state to determine an energy draw per day. This portion of the research had a significant amount of uncertainty, especially in research labs, where many pieces of equipment could not be unplugged to be measured, and for which exact specification sheets could not be found.

To determine a measure of energy consumption for the entire building based on this sample, the data was then extrapolated based on available information. Each room was assigned a plug load in one of three ways:

1. Survey – The 73 rooms with the full energy audit were calculated as specified above. These are the most reliable data points.
2. Estimated – For the other 34 rooms that were on the audit list but unable to be audited for the reasons given above, an estimate was made. Using the data points from (1), an

average power draw was determined on a per square foot basis for each type of room (See Appendix B for room type and calculation categorization). Using the data from the EveryTime survey, an occupancy ratio was determined for each room, specifying how often that room had at least one occupant. Then, the average power per square foot was multiplied by the area of the room and scaled by the ratio of that given room's occupancy to the average for that room type. For example, a lab that was occupied twice as often as the average lab and was also twice as big would be estimated to use four times as much energy as the average lab.

3. Extrapolated – The remaining 412 building spaces had to be calculated based on the information from (1) and (2). A new power draw per square foot was determined for each room type, this time factoring in the rooms from (2), which generally were occupied less than the rooms in (1), bringing the average down and more accurately representing the building (See Appendix A for assumptions). These averages were then multiplied by each remaining room's area to approximate the plug loads for that room.

By determining a plug load for each room based on one of these three methods, the data could be grouped and compared by any metric (i.e, floor or by room type).

Lighting

The lighting energy consumption analysis was performed, starting with the audited 107 rooms. The light fixtures for each room, up to three different types, were recorded during the OneTime energy audit. For rooms that did not have recorded luminaire data (either due to locked, unoccupied rooms or lack of recordings from the OneTime energy audit), the lighting type was assumed to be the same as those in rooms in the same hallway, on the same facade, and of the same room type in terms of space use and interior/exterior location. Floor lighting plans were then used to determine or verify the number of fixture units.

To determine a lighting energy consumption value for each building space, the duration for which the lights are on in each space was determined. Each building space was assigned an hrs/day value for the lighting duration in one of four ways:

1. Survey – When available, occupant hours and lighting information from occupant responses during the OneTime energy audit was used to determine an average hrs/weekdays and an average hrs/weekend when each set of lighting fixtures in each room was turned on. The hrs/weekdays and hrs/weekend numbers for each room were divided by 5 and 2, respectively, to obtain hrs/day values for weekdays and weekends.

2. Estimated – Given no other information from the occupants during the OneTime energy audit, the EveryTime occupancy and lighting on/off audit was used to estimate the hours (See Appendix A for Assumptions). The audit lighting data points were averaged over the two-week audit period for an average hrs/weekdays and average hrs/weekend. Similarly, the determined hrs/weekdays and hrs/weekend numbers for each room were divided by 5 and 2, respectively, to obtain hrs/day values for weekdays and weekends.

3. Assumed – The assumption was made that all lighting in the circulation spaces (hallways, corridors, atria, and entryways) is on 24 hrs/day for both weekdays and weekends (See Appendix A for assumptions).

4. Extrapolated – The remaining 412 building spaces had to be calculated based on the information from (1) and (2). A lighting power draw per room and per square foot was

determined for each space type. Either the Watts per room or per square foot was used for the extrapolation, depending on the space type (See Appendix A for space type division). The averages were then multiplied by either the room count or the total floor area by space for a total value by space type.

The technical specifications of the different fixtures were determined from the "Stanford University SEQ 2 Environment and Energy Building Project" Lighting O&M Manual (Binder 10) for Project No. 7224-00, compiled by Hathaway Dinwiddie, and specification sheets from the respective websites of the lamp, ballast, and luminaire manufacturers. An average W/room and an average W/sqft were determined for each room. These figures were then averaged among rooms of the same room type. Based on the room type, the averages were calculated based on either the room count or the square footage (See Appendix B for room type and calculation categorization). The values in Watts were then used to extrapolate to the full 519 building spaces for a lighting energy usage value in kW per room.

Installed lighting power densities were also calculated for the entire building and by space type to compare with ASHRAE 90.1-2004 commercial lighting power standards (IESNA 2005). The installed W/sqft was determined by calculating the power consumption, assuming 24 hrs/day usage of all installed lighting (See Appendix A for assumptions). Light fixtures and their corresponding power usage for each space type were likewise extrapolated to all the spaces in the building for the calculations.

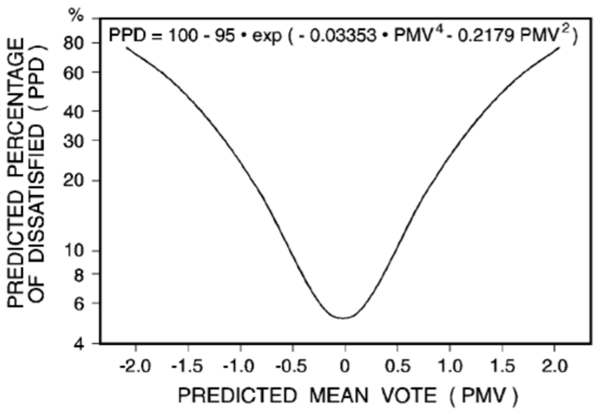
5.4 Data Analysis: Qualitative Energy Assessment: Illuminance

Analysis with illuminance data collected in the audited rooms was performed through visual representations on floor plans. The data for only the 1st through 3rd floors was processed, considering that neither the basement nor the mezzanine floors receive daylight. The illuminance values in footcandles (fc), measured with all lighting off in the rooms, were plotted according to an illuminance color scale on the floor plans. Information from the EveryTime lighting on/off audit was used to determine whether daylighting or lighting from the hallways or atria were sufficient in the rooms, such that room lighting was not used by the occupant(s) consistently during at least one of the four audit times per day. This information was illustrated on the floor plans in addition to the illuminance values, represented by differentiation between the room outlines (See 7.3 Illuminance Results).

5.5 Data Analysis: Qualitative Energy Assessment: Thermal Comfort & HVAC

The research team used the computer model method (PMV-PPD) provided by ASHRAE Standard 55P to evaluate the occupant's comfort zone. Predicted Mean Vote (PMV) is an index that expresses the quality of the thermal environment as a mean value of the votes of a large group on the ASHRAE seven-point thermal sensation scale (+3 hot, +2 warm, +1 slightly warm, 0 neutral, -1 slightly cool, -2 cool, -3 cold). Predicted Percentage Dissatisfied (PPD) is an index that reflects the thermal comfort level as a percentage of thermally dissatisfied people. The scale assumes that people voting ±2 or ±3 on the thermal sensation scale are dissatisfied and people voting 0 are neutral (Olesen et al. 2004). This method is used when occupant activity levels reflect metabolic rates between 1.0 met and 2.0 met (See 2.0 Definitions) and the clothing worn provides no more than 1.5 clo thermal insulation (See 2.0 Definitions, See Appendix C, Audit Survey Guide, See Appendix A for assumptions).

Using occupants' responses to survey questions (OncePerTimeSlot Audit) on the six primary factors (i.e., metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, and humidity) contributing to thermal comfort, the team was able to determine the comfort zone of the occupants by inputting this data into a PMV calculator. ASHRAE recognizes three main zones of comfort: Class A, Class B, and Class C. The figure below illustrates the necessary ranges of PMV for occupants to be designated to any given class. Class B is a typical application and is used for most environments. However, Class A requires a building design to have a higher than normal comfort standard and Class C uses relaxed or less than normal comfort standards.



Comfort Class	PPD	PMV Range
A	< 6	-0.2 < PMV < + 0.2
B	< 10	-0.5 < PMV < + 0.5
C	< 15	0.7 < PMV < + 0.7

Figure 4: Predicted Percentage of Dissatisfied (PPD) as a Function of Predicted Mean Vote (PMV) & Three Classes of Acceptable Thermal Comfort for General Comfort. The research team's comfort survey allowed us to calculate PMV, which can be plotted as a point along this curve, giving a PPD value. The standard Class B aims to keep at least 90% of the building occupants satisfied with their thermal comfort. (ASHRAE Standard 2003)

After categorizing the occupants by comfort class, the results were plotted using the PMV-PPD graph in Figure 4. The research team analyzed the spaces by their indicated HVAC subcomponents (i.e., passive and/or active) and by floor. Further analyses of spaces that were particularly hot or cold helped to understand why some occupant votes indicated thermal extremes in comparison to other rooms using the same HVAC subcomponent. Factors considered were surrounding rooms, the clo value of the respondent, and energy consumption of the space (i.e., lighting and plug loads as indicators). Lastly, in addition to graphing the results, the research team also mapped the thermal comfort results (See Appendix B for floor plans). The floor plans include only rooms that had complete thermal comfort surveys.

Note that the PMV-PPD graphing method only applies to spaces that use mechanically controlled or passive HVAC systems. However, the PMV calculator was still able to calculate Indoor Operative Temperatures for the secondary graphing method. The secondary graphing method is used when occupants have control over operable windows and other passive systems have subjective comfort standards, which results in shifting expectations for comfort (ASHRAE 2003). According to ASHRAE Standard 55P, in addition to having operable windows as a primary means of regulating thermal conditions, there must not be any mechanical cooling system for the system (e.g., refrigerated air conditioning, radiant cooling, or desiccant cooling) to be considered naturally conditioned. The metabolic rates for these spaces must also fall between 1.0 met to 1.3 met and occupants need to be able to freely adapt their clothing to indoor and outdoor conditions. Spaces that are naturally conditioned were graphed used the template in Figure 5.

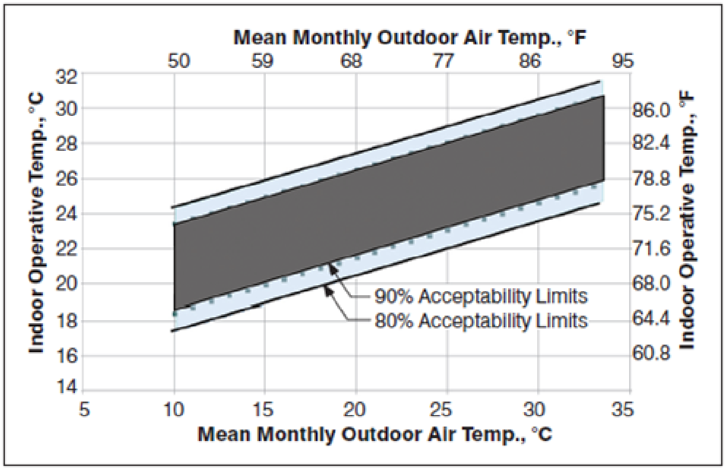


Figure 5: Acceptable Operative Temperature Ranges for Naturally Conditioned Spaces. This representation is a new optional method for determining acceptable thermal conditions in naturally conditioned spaces. The model is derived from a global database of 21,000 measurements taken from four different continents. This shows that the acceptable range for indoor temperatures centers around a value related to the outdoor temperature (Olesen et al. 2004).

6 Observations

6.1 Energy Performance

The observations gathered during the audit led to a set of plausible explanations for the variation between the predicted and actual energy performance of Y2E2. These observations can be categorized into faults of occupant behavior, the building design, building system/operation, incorrect model assumptions, and equipment provided or departmental organization.

Occupant Behavior

- In multiple spaces, occupants do not take full advantage of the common areas on every floor, an integral component of the building design. A number of occupants do not utilize appliances in the kitchens, but instead keep personal microwaves, fridges, electric water kettles, and coffee machines in their offices. Other occupants keep personal electric staplers and shredders, which are available in the copy rooms.
- Kitchens, conference rooms, and computer labs seem to waste a disproportionate amount of energy when unoccupied. One potential explanation is that no one takes responsibility for these common spaces. Another one is that lights in conference rooms and kitchens take several minutes to reach full brightness. Computers in the labs are also slow to turn on, prompting people to leave them on for the next user.
- The cleaning staff often does not turn off lights after they finish cleaning a room. The lights stay on until turned off by occupancy sensor control.

Building Design

- In the original design, a building management system (BMS) would inform occupants when to open or close their windows in their offices. The assumption that occupants would continuously refer to the BMS user interface and adhere to the recommended instruction was a fault in the design.
- Full use of daylighting is limited due to the intense solar radiation received by the exterior offices. Under such circumstances, occupants lower the blinds, but still receive excessive solar heat gains.
- Lack of airflow and ventilation are common comfort complaints, especially in enclosed, interior rooms.
- The openings in the translucent polycarbonate walls were uniquely designed to allow daylighting and air flow into the interior rooms, but became a security issue and had to be modified such that the openings do not provide the same benefits.
- The specialized energy-efficient HVAC design may have resulted in occupant discomfort; the rooms with chilled beams and fans are too cool in the winter and rooms with heaters are too warm in the summer -- observed from occupant comments. Due to the discomfort, personal heaters and fans are used, necessitating additional plug loads.

Building System/Operation

- Flaws in the advanced sensor-controlled systems in the building detected by the CEE 243 2009 class included incorrect programming of the atria window system control for night purge (Maile, Bazjanac, & Kunz 2009). Atria windows on the 1st and 2nd floors were on a time schedule rather than being dependent on indoor and outdoor temperatures. Atria windows on the 3rd floor appeared not to follow any control strategy. It is still uncertain whether the flaws in the sensor controlled systems have been repaired.
- Other system-controlled windows, including the 2nd floor Red Atria East windows, open during inappropriate times and weather conditions.
- Occupancy sensors installed in certain rooms are overly sensitive to people walking past the rooms. Among rooms within the sample, the following such rooms were observed: 128, 164, 266, 300, 307, and 334.
- The lighting in circulation spaces appears to lack a standard operation scheme for the building. The percentage of lights turned on in each hallway varies significantly, from all off to all on. There are circulation spaces that have every other light on and others have around every third light on. There is also no consistency between floors or atria.

Energy Modeling

- The assumptions on the allocation of building spaces may have caused a large discrepancy between actual and predicted energy consumption. Lab spaces are extremely dense users of energy (high W/sqft) and an underestimation of lab spaces could result in underestimation of total building electricity consumption.
- Other assumptions made in the original energy model that needed to be adjusted according to the occupied usage of the building, are detailed in “Stanford University Y2E2 Energy Model Calibration” by Arup in July 2009.

Equipment Provided/Departmental Organization

- The LED task lights provided in the offices use only a maximum of 8 W of power and were coupled with a motion sensor system installed underneath the desk spaces, for an intended energy efficient system. Occupant feedback during data collection revealed that the lamps break easily and do not provide sufficient illuminance.

- Computer and copy machine settings can be altered to reduce energy loads (e.g., Power Save mode). Observations showed that a significant number of computers, especially those in computer labs, do not go into sleep or standby modes. Copy machines also remain on for extended periods of time.

6.2 Thermal Comfort

A general set of comfort complaints was gathered during data collection. The feedback regarding discomfort and measurements relevant to occupant comfort can be categorized into several larger building observations: temperature and humidity variation due to location, circumstantial use of space, solar radiation, natural ventilation system, and specialized HVAC system based on the facade.

Temperature and Humidity Variation due to Location (Based on measurements)

- The upper two floors are generally warmer and more humid than the lower two floors.
- Exterior and atria offices are generally warmer than interior offices.

Circumstantial Use of Space

- Spaces such as research labs, computer labs, and server rooms have constraints that conflict with occupancy comfort. According to reports by occupants:
  - Research labs are typically “slightly cool” to “cool”, due to the temperature, humidity, and ventilation conditions that must be maintained for lab experiments.
  - Computer labs and server rooms are typically “slightly warm” to “warm”, due to the heat generated by the computing devices.

Natural Daylighting/Ventilation

- Solar heat gains as well as glare cause discomfort to certain occupants with exterior offices. Other occupants with atria offices wish for more daylighting.
- Several occupants receive overly cool drafts from the automated windows, during night purge and the winter season. This may or may not be a consequence of incorrect logic in the control system of the windows.
- Insufficient ventilation and airflow -- especially at the start of the occupant hours -- was a common complaint among interior offices, and is usually resolved by keeping the doors to the hallways open in the morning.

Occupant Temperature Control

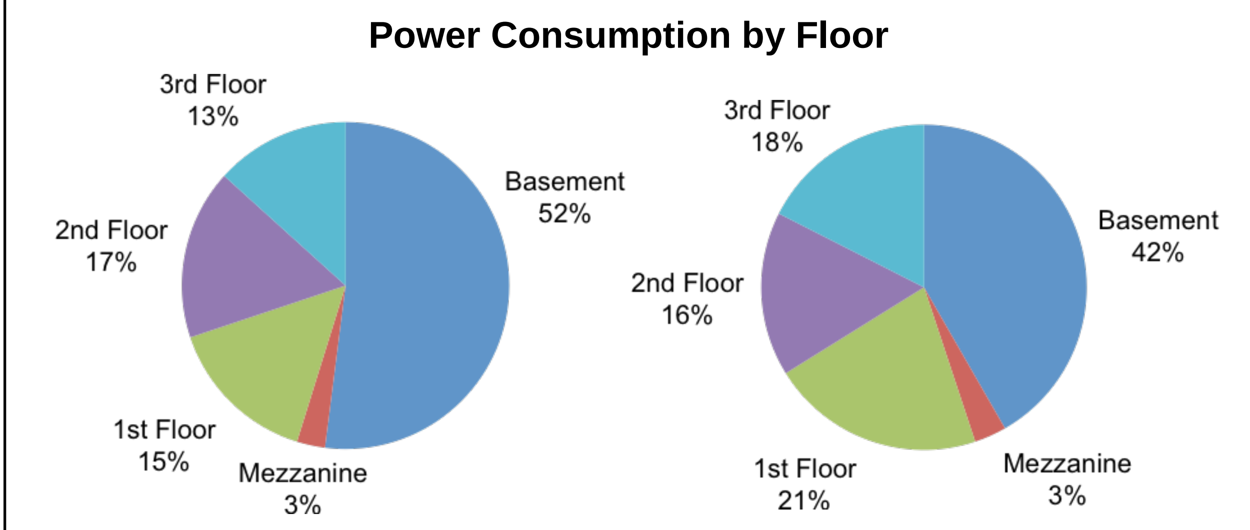
- The temperature dials in the rooms claim to allow the occupants to control the temperature by +/- 2^{o}F. A large portion of the occupants surveyed was aware that the dial had no effect on their room space temperature. Many expressed frustration that Stanford would attempt to placate their thermal discomfort with a placebo device.
- While many HVAC engineers have successfully used this strategy to increase occupant comfort without actually giving them control of the HVAC systems (Checket-Hanks), it appears that this does not hold true when the occupants are aware of the strategy. It may have negative effects on their perception of the building instead.
- Professor Jeffrey Koseff confirmed that at the time of installment, the temperature dials could be used to adjust the room temperature, but they were later disabled due to the increased strain they placed on the HVAC systems.

7 Results & Discussion

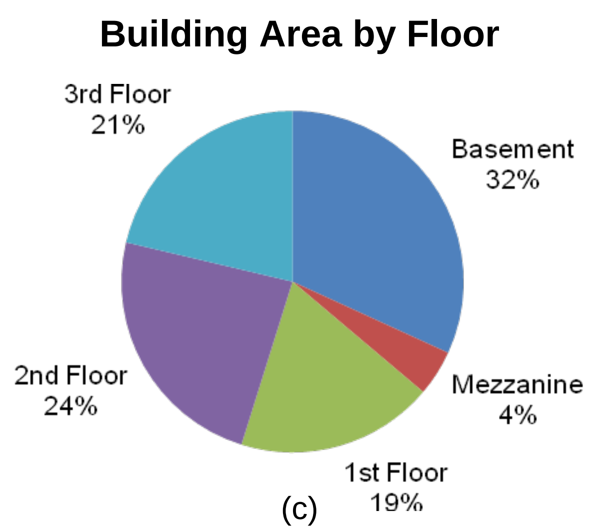
7.1 Energy Results

The determined plug load and lighting electricity consumption values were analyzed by floor and by space type for comparison between the two end uses. These measured and calculated values were also compared with sensor data (both through SCADA and SEE-IT) and predicted data (modeled by previous researchers with eQUEST).

7.1.1 Plug Loads & Lighting



(a) Plug Loads (b) Lighting



(c)

Figure 6: (a) and (b) Comparison of Plug Load and Lighting Power Consumption by Floor and (c) Building Square Footage by Floor. While the basement is only slightly larger by area than the other three main floors, as shown in (c), it uses a disproportionately large amount of both the lighting and plug load power draws of the building.

Result: Both the plug load and lighting power consumption by floor percentages matched expectations. As shown in Figure 6 (a) and (b), the basement consumed the largest percentage, at least 42%, of the electricity in both end uses. The basement consumes a disproportionate amount of power, exceeding its 32% of total building floor area by at least a 10% margin. The mezzanine consumes a percentage comparable to its 4.3% of building floor area. The remaining upper three floors consume roughly equal portions, as expected considering their similar space types and floor areas.

Discussion: The basement consists primarily of research labs, on a floor area basis. Research labs are major electricity users, due to the nature of the lab work being performed in the spaces. The lights are on for hours beyond the regular business hours since lab researchers are not on a business day schedule and certain experiments require attention during other hours of the day, during weekdays and weekends. In addition, lab researchers commented that they do not always check the lab for remaining colleagues before leaving the lab and instead leave the lights on, which may remain on until the next day. As for plug loads, research labs have a high density of equipment and instruments that operate for long duration of hours. Equipment that remains on for extended hours includes commercial-sized lab refrigerators, ovens, and air pumps.

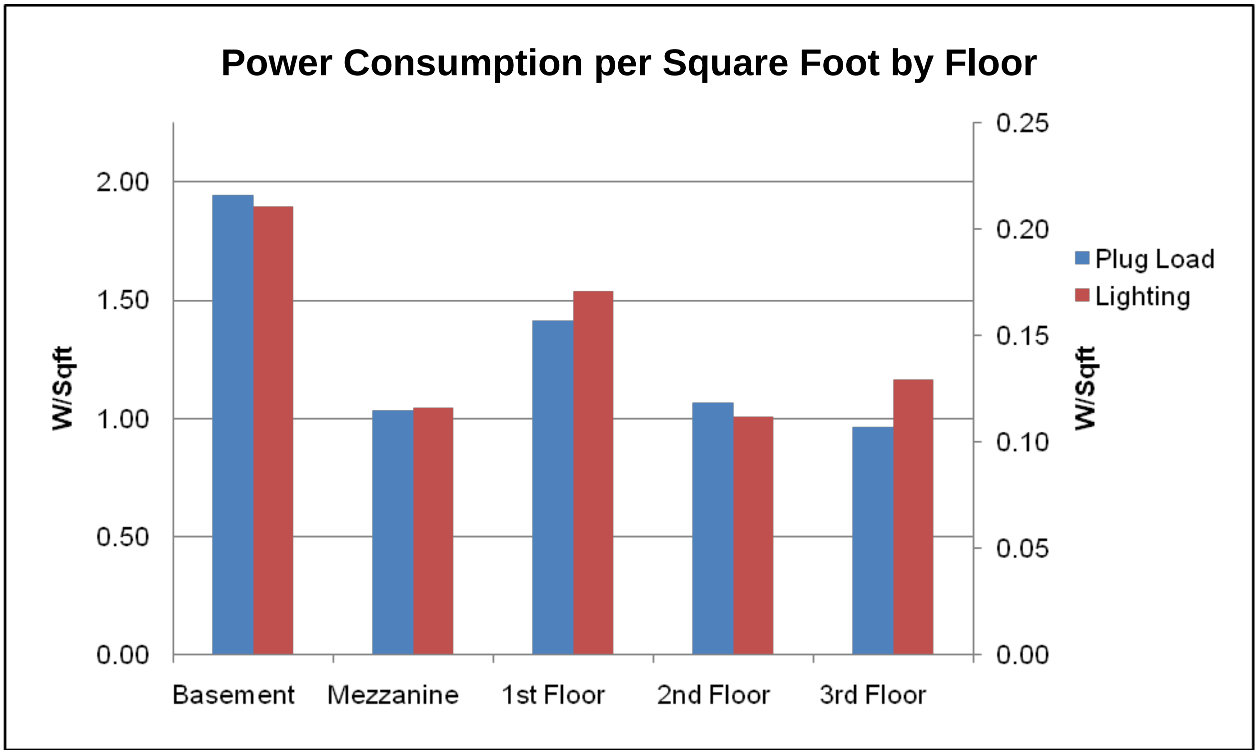
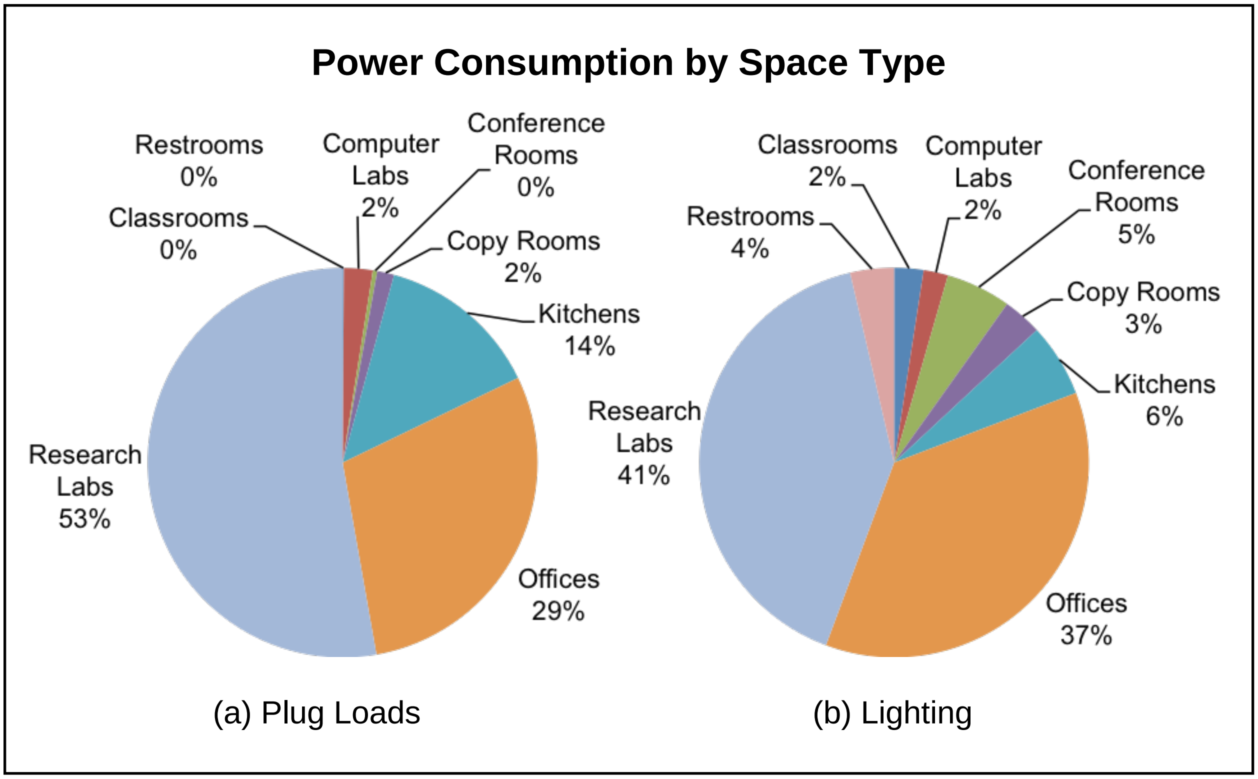


Figure 7: Comparison of Plug Load and Lighting Power Consumption per Square Foot by Floor. Both Plug Loads and Lighting follow the same trends over the five floors, suggesting that these end-uses are closely tied, likely by the space types and occupancy on each floor.

Result: The comparison of plug load and lighting power usage per square foot by floor suggests that the two end uses are closely related. As shown in Figure 7, the relative power usages between the five floors are comparable for both plug loads and lighting. The greatest W/sqft electricity consumption for both end uses is the basement, followed by the 1st floor. The W/sqft consumptions by the mezzanine, 2nd, and 3rd floors were relatively close in value for both plug loads and lighting.

Discussion: This indicates that on an absolute and on a per square foot basis, the basement is the floor that has the greatest opportunity for electricity load reduction. It is important to investigate how each of these floors is being used to explore the reasoning behind these trends.



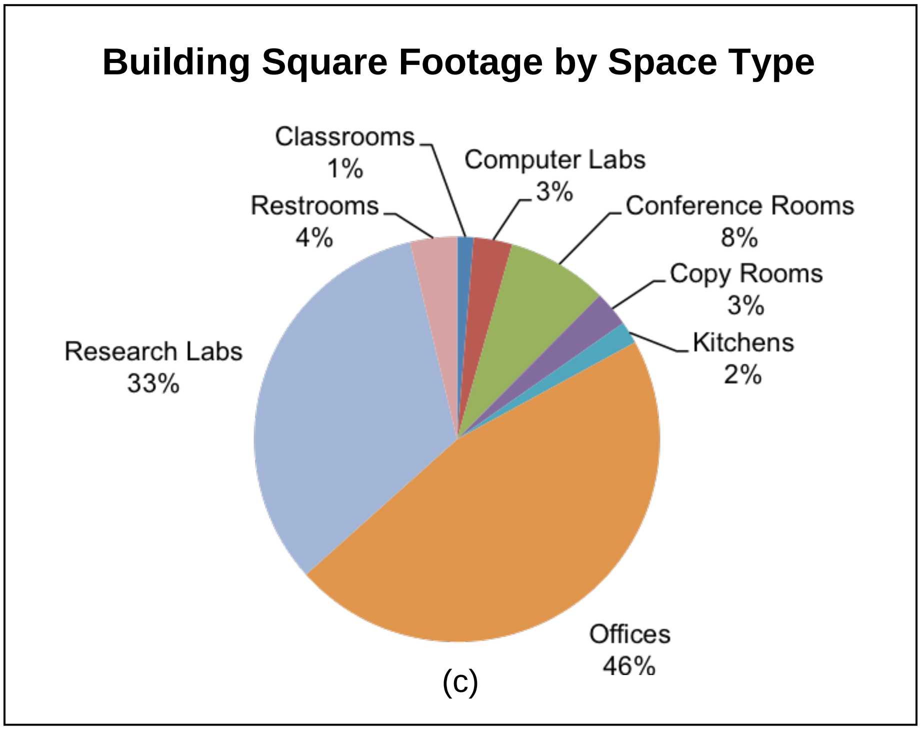


Figure 8: (a) Plug Load and (b) Lighting Power Consumption and (c) Building Square Footage by Space Type. While power consumption is generally related to the square footage of each type of room, research labs use a disproportionately high portion of both plug loads and lighting.

Result: The relative power usages by space types shown in Figure 8 are mostly as expected, with research labs being the greatest consumer, followed by offices. Research labs use a percentage of the power greater than its percentage of the building area, due to plug load for the large number of equipment and lighting for long occupied hours. Comparing the power consumption to the building area by space type, offices are the next most significant user, as expected, because the building area is 46% office space. The major difference between plug loads and lighting is kitchen power consumption. Kitchens have high power draw by plug loads, especially in comparison to its percentage of total building area.

Discussion: The power consumption by space type confirms that research labs are a significant user of energy, both plug loads and lighting, and should be a focus for energy load reduction.

The disproportionately high power consumption by kitchens can be explained by the large number of appliances, including fridges, coffee makers, microwaves, and hot water boilers, in the relatively small square footage of kitchens. The full-size fridges in the kitchens are particularly a large end use, since they remain on during all hours of the day. The kitchen percentage of power consumption exceeds its 2% of building area by 4 percentage points for lighting and 12 for plug loads. The kitchens appear to be another space type with opportunity for improvement in terms of energy usage reduction.

Plug load power draw is largely influenced by the density of equipment and the circumstantial use of the space type. Lighting, on the contrary, largely corresponds with the square footage of the space type. In Figure 8, the lighting power consumption pie (b), as opposed to the plug load power consumption pie (c), resembles the building area by space type pie (c) more closely.

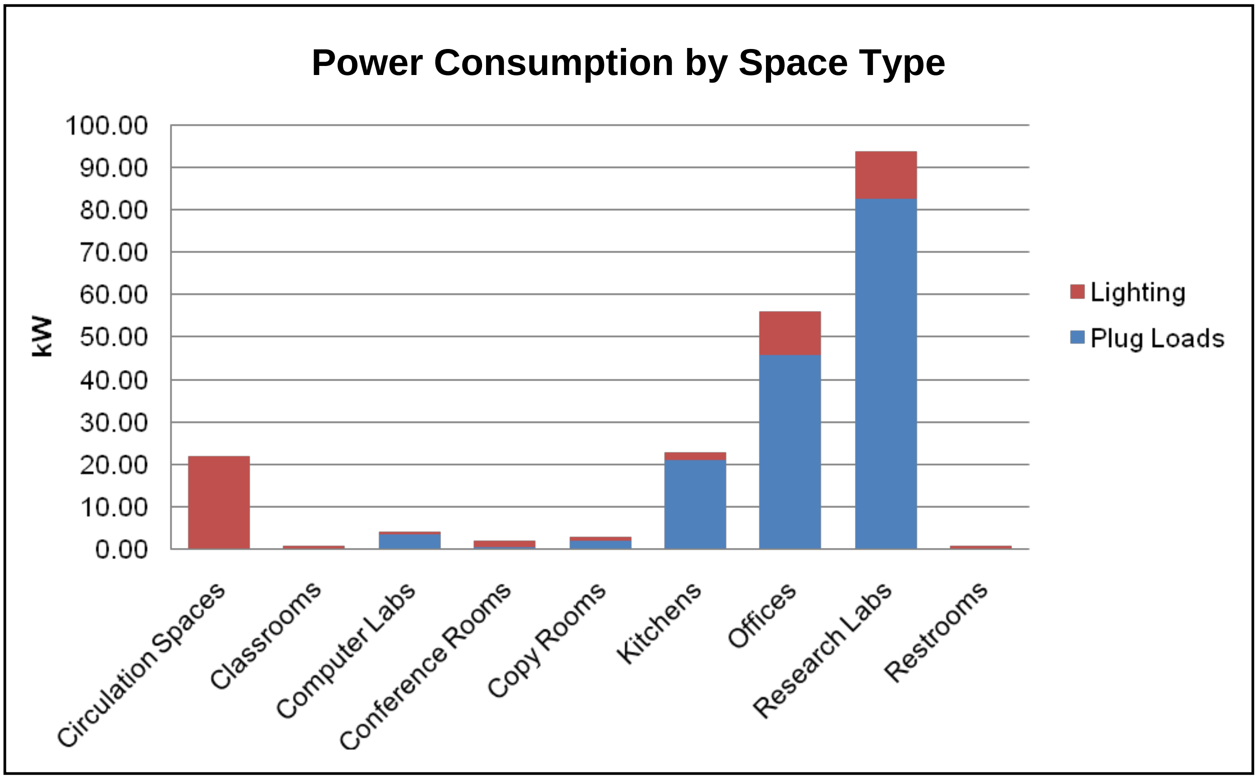


Figure 9: Plug Load and Lighting Power Consumption by Space Type. This representation conveys the difference in scale between plug loads and lighting. While lighting is a huge factor in circulation spaces (See 7.1.3 Lighting for more discussion), plug loads far outweigh lighting for the majority of the building.

Result: The power consumption by space type in Figure 9 better illustrates the contribution of plug load and lighting power draw to the total. Across the space types that utilize plug loads, the portion of plug load power consumption is several times that of lighting power consumption. As detailed in the Arup document (Graffy et al. 2008), plug loads have a large opportunity for power load reduction.

Discussion: Plug load power consumption may be so much higher than lighting power consumption because there is more control over lighting power usage through design and building operation. Figure 9 indicates that lighting, particularly in circulation spaces, should be an area of focus when addressing small energy reduction targets. However, if larger energy reduction targets need to be met, plug loads likely need be tackled, despite their classification as non-regulated end use.

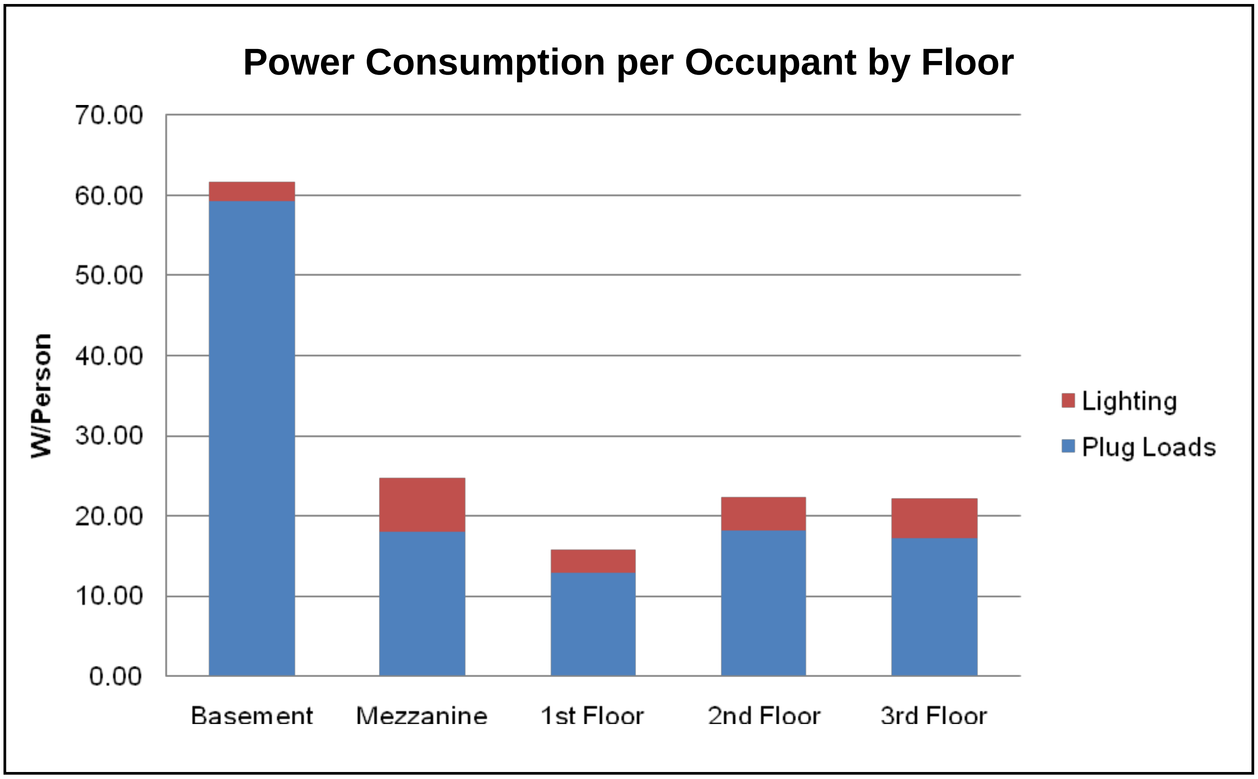


Figure 10: Power Consumption per Occupant by Floor. Per occupant, the basement uses nearly three times the combined plug load and lighting power of each of the other floors.

Result: While previous graphs showed that the basement draws more than its share of power per square foot, the results are even more exaggerated when looking at a value-based metric such as per occupant.

Discussion: Across all metrics and comparisons, the basement uses a disproportionate amount of power. Based on these results, the research team concludes that this additional power is not used to serve more occupants, but rather to serve a smaller number of occupants that are each using a large amount of power. Again, this is due to the high density of research labs in the basement.

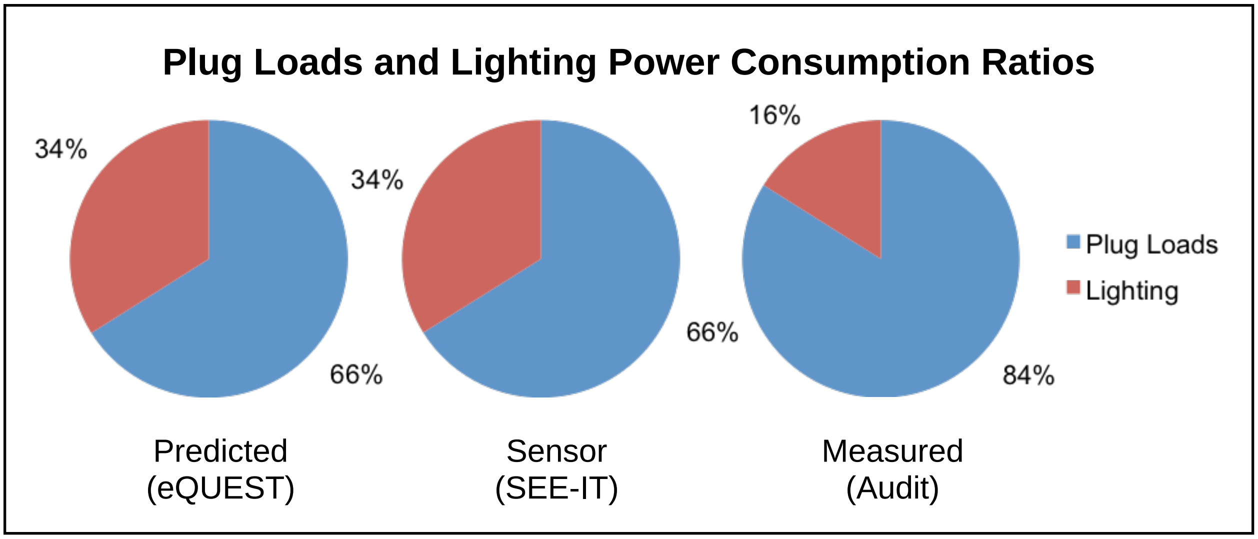


Figure 11: Predicted, Sensor, and Measured Power Consumption Ratios. The Predicted data matches the Sensor data very well, but this Audit suggests that plug loads contribute much more than lighting.

Result: In relating the measured values back to the research question regarding disparities between predicted and actual values, the measured data was compared with predicted data from eQUEST modeling and sensor data retrieved from SEE-IT.

The power consumption breakdown between plug loads and lighting is shown in Figure 10 for predicted, sensor, and measured data. The two charts for Predicted (eQUEST) and Sensor (SEE-IT) data show equal ratios between plug loads and lighting. This result was obtained despite the inclusion of different sets of data (See Discussion, below). The Measured (Audit) data differs by 18 percentage points in comparison to those of the Predicted and Sensor data.

Discussion: The disparity between the sensor (SEE-IT) data and the measured (Audit) data can likely be explained by the level of accuracy of each measure. While both measured plug load and lighting data relied to some extent on responses from occupants as to their usage, the plug load analysis required a larger amount of estimation and extrapolation. There are only several different lighting fixtures to check for power consumption, but there are thousands of unique pieces of equipment throughout the building, all of which have their own power usage characteristics. This likely led to a greater overestimation of the measured plug load than the measured lighting.

The varied plug load and lighting power consumption ratios can also be explained by the availability of predicted (eQUEST) and sensor (SEE-IT) data. The predicted data was limited to two predicted values: the total "Miscellaneous Equipment" and total "Area Lights" energy demands for July. This source lacked breakdown of power draw by floor. The sensor data did not provide aligned real-time power draw information for the 3rd floor west plug loads, 2nd floor lighting, and emergency lighting, due to flaws in the submetering system (See 7.2 Electric Metering Results). The measured (Audit) pie was adjusted such that it reflects the same set of data as the sensor (SEE-IT) pie.

7.1.2 Plug Loads

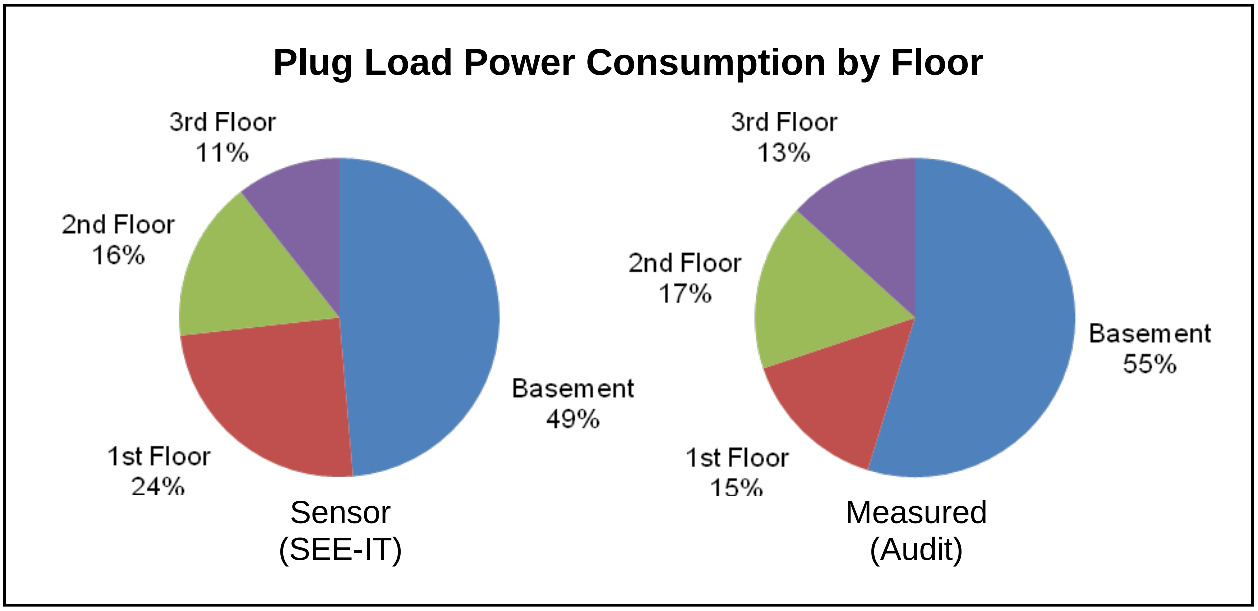


Figure 12: Comparison of Sensor and Measured Plug Loads by Floor. The audited data matches up closely with the ratios by floor recorded by SEE-IT.

Result: The comparison of sensed and measured plug loads show similar ratios of the distribution by floor, even if the magnitudes are different (See Figure 13, below). In each case, the basement accounts for roughly half of the plug loads, with each of the remaining three floors using relatively similar amounts of power. Note: Due to shortcomings of the SEE-IT system, the portion of the plug loads coming from the West of the 3rd floor had to be estimated based on the other data (See 7.2 Electric Metering Results for further discussion, See Appendix A for Assumptions).

Discussion: This graph shows that the assumptions and extrapolations that went into the research team's calculations based on occupancy and room type resulted in a depiction of the building power consumption that is relatively accurate.

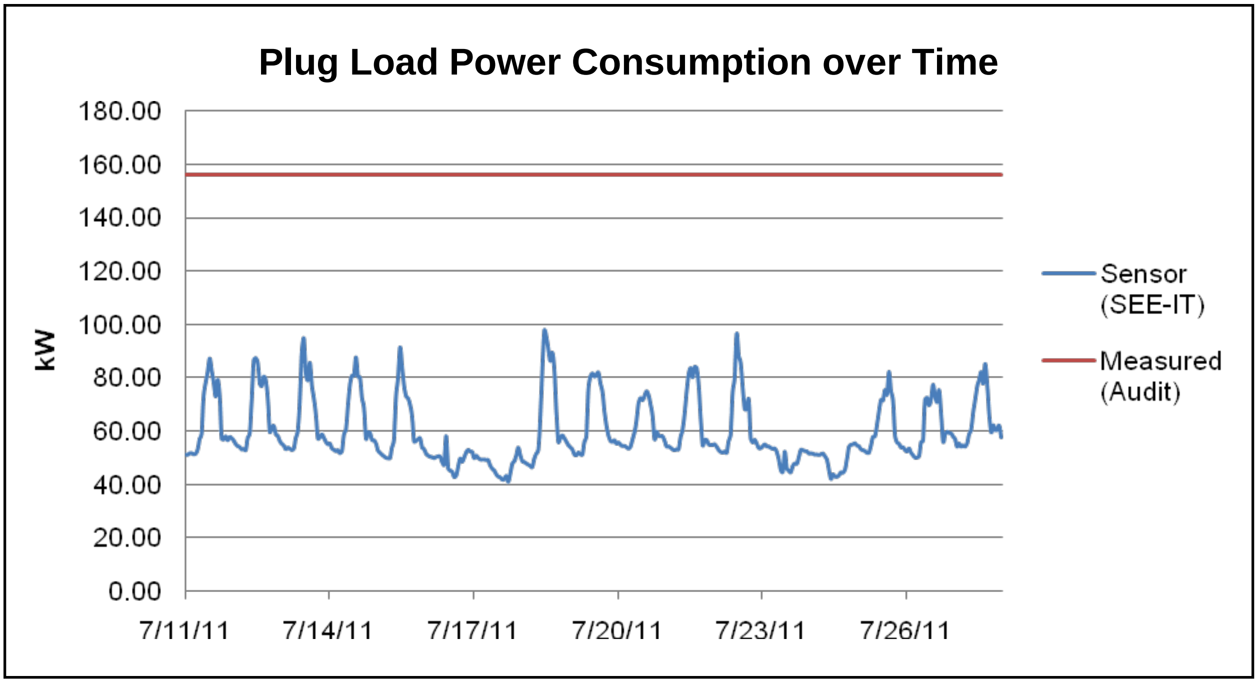


Figure 13: Comparison of Sensor and Measured Plug Loads over Time. The audit resulted in an estimated power draw much higher than that reported by SEE-IT. It also does not capture the changes over time recorded by SEE-IT.

Result: The time-scale comparison of the sensor data to the measured data reveals a large disparity, with the measured plug loads accounting for approximately 2.5 times the value recorded by the building sensors.

Discussion: This graph highlights the shortcomings of an audit performed by hand. First, the measured data attempts to represent in one horizontal line what the sensors can report in thousands of data points, each specific to a moment in time. The audit also drastically overestimates the plug loads of the building. This is likely due to a combination of overestimating the number of hours each piece of equipment is on as well as using nameplate power consumptions in calculations, which are often overestimates. It is also likely that the sensed data is a slight underestimate, as some of the 3rd floor demand is offset by the rooftop solar panels (See 7.2 Electric Metering Results).

7.1.3 Lighting

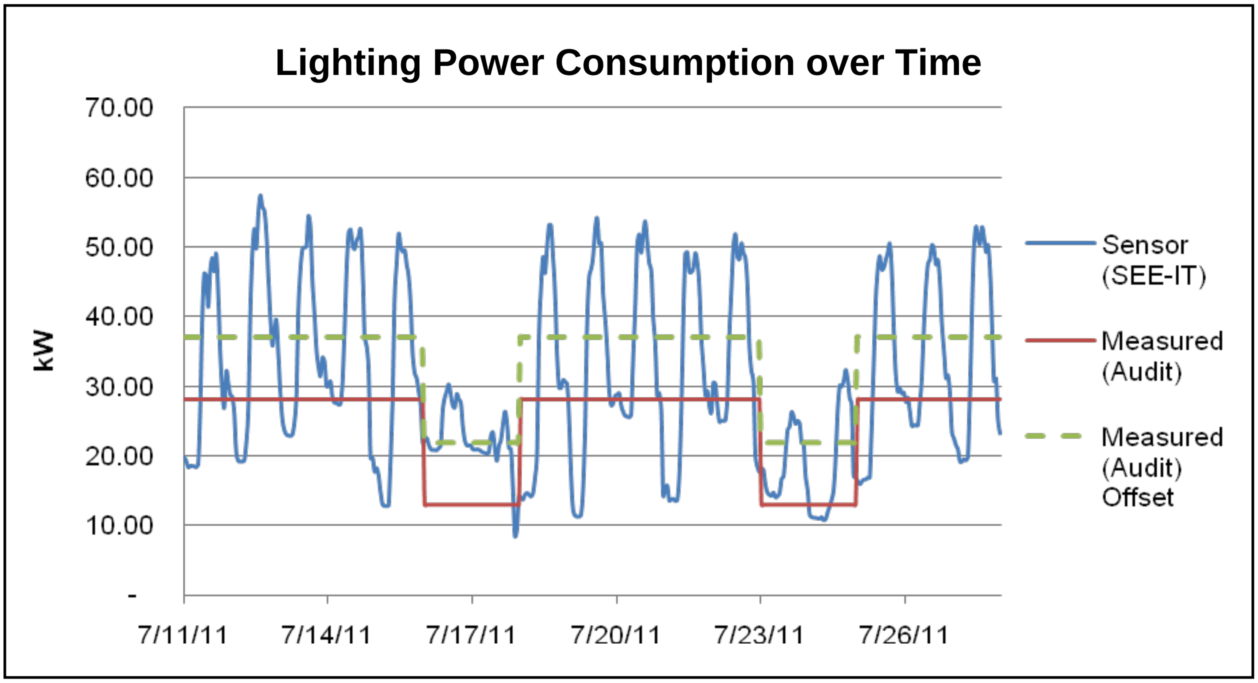


Figure 14: Comparison of Sensed (SEE-IT) and Measured (Audited) Lighting over Time. The audit data resulted in a power draw lower than that of the sensed data reported by SEE-IT, by roughly 9 kW. The captured ratio between weekday and weekend consumption matches that reported by SEE-IT, as shown by the green, dotted offset trend line.

Result: The time-scale comparison of the sensor data to the measured data in Figure 14 shows that the lighting power consumption based on the audit data may be an underestimation of the actual lighting power usage. Both the Measured (Audit) weekday and weekend power draw values are low, but appear to be offset from the Sensor (SEE-IT) power draw by the same 9 kW margin as shown in Figure 14.

Discussion: There are a number of possible explanations for the underestimation of lighting power consumption as evaluated by the energy audit. The lighting duration in hrs/weekday and hrs/weekend for a large portion of the 107 rooms were estimated based on audits at 4 hour intervals. The Sensor (SEE-IT) data tracks real-time lighting power draw, allowing for more accurate lighting information particularly at hours outside of the energy audit. Other reasons may be related to the power draw of the lamp and ballast combinations used in the light fixtures. These values were based on specifications rather than measured power draw.

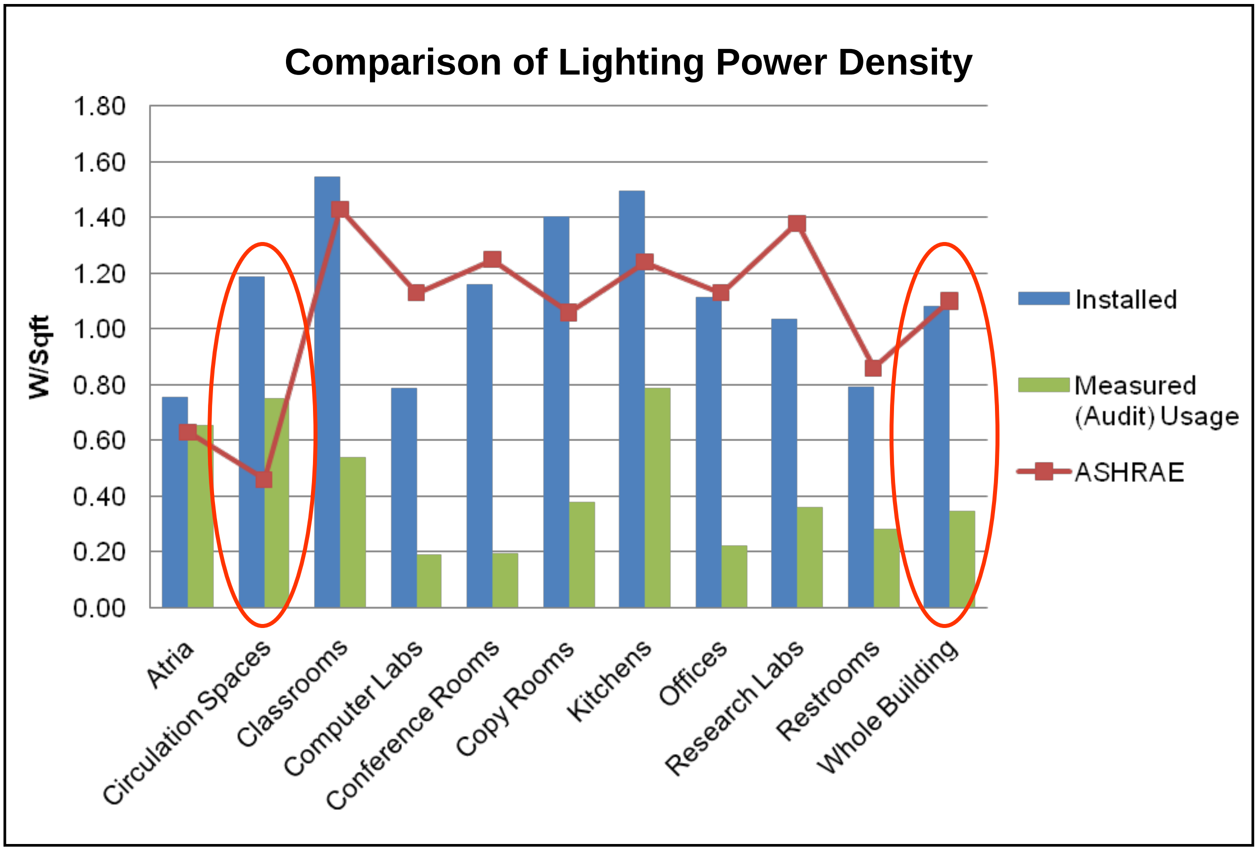


Figure 15: Comparison of Lighting Power Density. While the overall building meets the standards for LPD set by ASHRAE (far right), not all space types do. Circulation spaces particularly stand out for their over-installation and overuse of artificial lighting (second from left).

Result: As shown in Figure 15, the installed lighting power density (LPD, See 2.0 Definitions) in Y2E2 exceeds the standards in ASHRAE 90.1-2004 for the following space types: atria, circulation spaces, classrooms, copy rooms, and kitchens. However, the average LPD for the whole building is roughly equal to the ASHRAE standard for a combined office and school/university building. The measured (audit) lighting power consumption is below the ASHRAE standard for all space types except circulation spaces.

Discussion: The installed LPD for the circulation spaces significantly exceeds the ASHRAE standard value. The measured average power usage is also greater than the standard, highlighting lighting in circulation spaces as an area for energy reduction. The comparison of the installed LPD to the average usage in circulation spaces reveals that approximately a third of the installed lighting in circulation spaces is not being used. This can be interpreted from the graph because light fixtures in these spaces remain on 24 hrs/day. From both energy and cost standpoints, lighting design in circulation spaces calls for improvement.

The LPD for copy rooms and kitchens also exceed the standards, which suggests that common spaces with small floor areas may not be the best design for efficient lighting. Despite the significant lighting power consumption by research labs (Figure 2), the installed LPD for research labs is already below the corresponding standard value as shown in Figure 15. The nearly matching values for the installed and standard LPD for the whole building may be an indication that only the building LPD standard was taken into account in the lighting design.

7.1.4 Occupancy

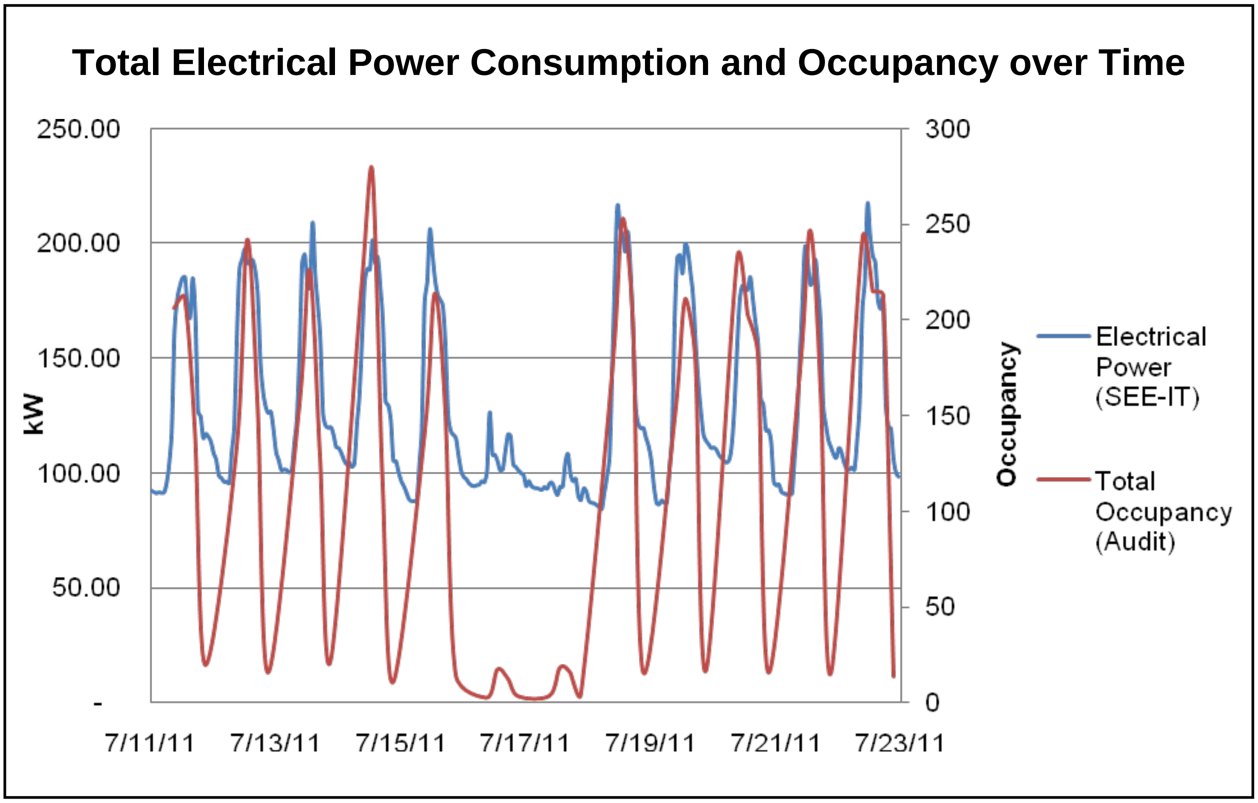


Figure 16: Comparison of Electrical Power and Occupancy. While the peaks of the Electrical Power match up with the peaks in Occupancy, the valleys are not nearly as low, suggesting a relatively high "base load" power draw from plug loads and lighting that remain on even with little or no occupancy of the building.

Result: A comparison of the power draw of plug loads and lighting over time to occupancy shows that the total power draw is closely related to occupancy, as measured by this audit. There is, however, a larger disparity at night and on weekends, when occupancy drops to nearly zero, yet plug loads hover around 100 kW.

Discussion: This graph suggests that there is a relatively high (nearly 100 kW) "base load" power draw of plug loads and lighting that is insensitive to the occupancy of the building. This is likely due to large appliances that stay on 24/7, such as refrigerators, freezers, and other lab equipment. Our audit indicated that other equipment, such as computers and monitors, also stayed on for long hours. A future study aimed at reducing the energy demand of Y2E2 could research whether all the equipment drawing this 100 kW really needs to be on 24/7 or if some portion is drawing power unnecessarily.

Result: Another portion of this analysis focused on identifying specific rooms from this audit that may be using more than their fair share of power through plug loads and/or lighting. To make this evaluation, rooms were compared on a value basis, using the number of occupants of the room as the value. By comparing each room by power draw per occupant and narrowing down to just those that use more than double the average across the building, the expected results are obtained: mostly copy rooms and kitchens, which have high process loads and very few occupants, are left on this list, along with some research labs and offices.

Additionally, the research team identified the rooms of each type that have a relatively high power draw for their usage, including some very low users that just happen to be more than the other rooms of their type, by filtering the list to those rooms that use more than double the average power draw per person for that specific type of room.

The intersection of these two sets points out the rooms that use more than their share of power per person. This suggests that the following rooms, of the 73 for which energy audits were performed, are potential areas for improvement: B26, 202, 242, 266, 279, 280, 297. Kitchens have been excluded from this list, as the methods used in the occupancy audit likely underestimate the number of people that actually utilize the kitchens. Performing the same analysis on lighting loads reveals the following rooms: B26, 101, 105, 266, 326. It is notable that room B26, a Research Lab in the basement, shows up on both of these lists. This is likely due to the fact that it is a relatively large lab with many pieces of equipment but often had only a few lab researchers working at one time. For the full listing of rooms with this analysis, please see Appendix B.

7.2 Electric Metering Results

Concerning electric metering in buildings, the normal practice is to keep track of the electricity consumed by the entire building only. This practice does not consider end uses and it provides minimal information about energy demand. In contrast, Y2E2 implemented a sub-metering system in addition to its two main meters. This sub-metering system provides detailed information about electricity demand by end use, such as plug loads, lighting, HVAC system, emergency and standby equipment. Electricity demand is further broken down into east and west and/or floor subsections. This level of detail allows a comprehensive understanding of how electricity is being consumed in Y2E2 and makes it easier to isolate and determine potential problems or areas for improvement throughout the building.

Taking advantage of the large amount of historical energy data available for Y2E2, the original intent was to compare results from this energy audit with data exported from the utility database and SEE-IT. Although both sources presented certain advantages and disadvantages, they complemented each other and served as valuable references for comparison after making some adjustments. The utility data was reliable but it only gave general information about the electricity demand of the entire building. On the other hand, SEE-IT data was sometimes questionable but it provided detailed information about the end uses of electricity. After analyzing the historical data, certain values from SEE-IT were found suspicious. The plug load data for the third floor west was significantly higher than any other section, surpassing the plug load demand of any other floor. Also, lighting data for the entire second floor was given as zero at all times. Due to these issues, further analysis was completed for Y2E2's metering system and the mapping of data to the SQL database. As a result of this process, the origins of these problems were identified. However, these problems were not resolved due to time constraints and because they go beyond the scope of this research. Nevertheless, after tracing the design of Y2E2's metering system and the mapping of data points, a list of observations and recommendations for future work was developed by the research group.

The data from the sub-metering system in Y2E2 travels through a couple of gateways before it is stored as SQL data. First, the data from the meters, in modbus language, is converted into

LON language. Then, the LON data, accessed by iLON servers, is converted to SQL language. SEE-IT accesses the SQL database to obtain the historical energy data of Y2E2. This chain of communication leaves room for potential errors as energy data is transferred between gateways. For this reason, it is very important to make sure that the mapping of data points is correct. Furthermore, it is critical to understand how the metering system is designed and what is being measured by each meter to avoid double counting of data.

Three issues concerning values for the third and second floor were found when reviewing SEE-IT data:

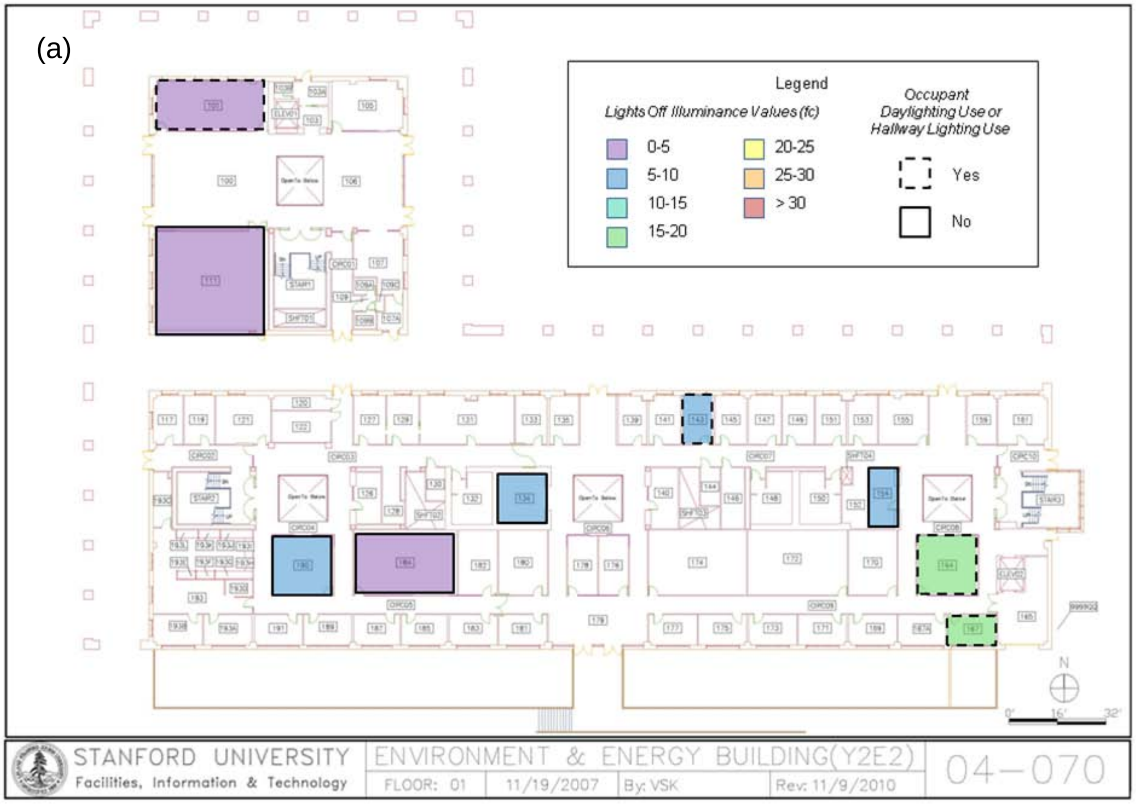
- The plug load electricity demand given for the 3rd floor west was much higher than any other section of the building, accounting for 39% of the total plug load demand of Y2E2. Real time data from the EATON meters was compared to SEE-IT data to check for correlation. As expected, the data points did not match at all. The values from SEE-IT were about 20 times greater than the values from the sub-meter. Up to the LON servers, the data is not distorted. Therefore, the root of this problem is most likely in the conversion to SQL language. Careful attention should be given to the mapping of data points in the SQL to identify the problem and fix it. Until then, the plug load data for the third floor west should be considered unreliable.

- Determining the true plug load demand on the 3rd floor is problematic because of the way that the photovoltaic (PV) panels are set up, as identified by the researchers of CEE 243 (CEE 243 Wiki). The three PV panels are connected to the meters used for monitoring the plug load demand. The thin film and mono-crystalline panels are connected to the east meter T3NE, while the poly-crystalline panel is connected to the west meter T3NW. As the power generated by the PV panels is fed into the panel boards, the demand for utility power is reduced. Consequently, the plug load data for the third floor is not the true demand. Unfortunately, the power generated by the PV panels cannot be accessed directly. This power could be calculated to determine the PV panels' contribution. However, matching timestamps with the meter data would create another issue. Regardless, it is essential to determine the contribution of the PV panels in order to have true accountability of the plug load demand.

- The lighting demand corresponding to the second floor was given as zero on SEE-IT. Real time data from the EATON website for the lighting load on the second floor, meter 2NHE (IP 171.67.88.121), did not show any zero values during an observation time of about an hour. On the contrary, real time data pulled out from the Altitude Management website (IP 171.67.80.21) did show zero values for the meter 2NHE during an observation time of about an hour. Consequently, the root of this problem is in the conversion between modbus and LON language. Similarly to the first problem, the second floor's lighting demand data exported from SEE-IT or the Altitude Management website should be considered unreliable until the problem is fixed.

7.3 Illuminance Results

(a)



(b)

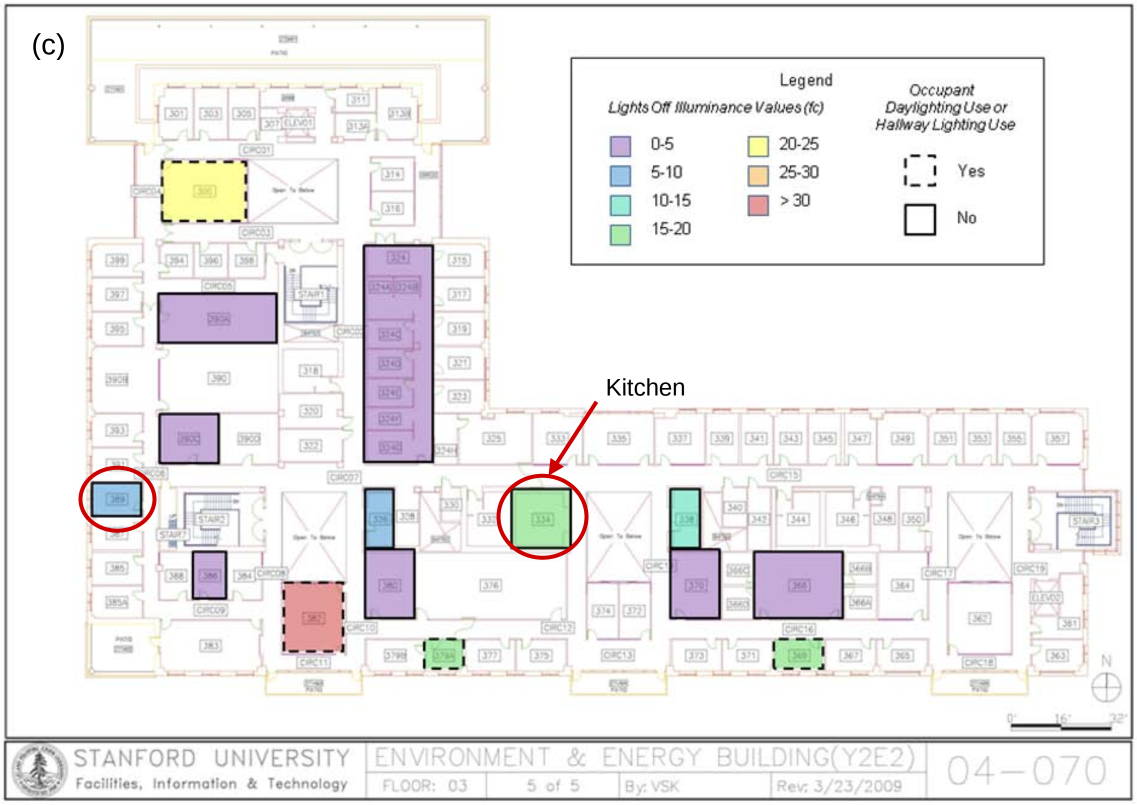


Figure 17: (a) 1st floor, (b) 2nd floor, and (c) 3rd floor illuminance values from daylighting and/or hallway lighting plotted on floor plan using a color scale, along with occupant use of daylighting and/or hallway lighting. The rooms with sufficient daylighting, exclusively exterior rooms, utilize daylighting. The threshold is shown to be around 10 fc. Kitchens do not take advantage of the daylighting received, indicating an area for improvement.

Result: The 1st, 2nd, and 3rd floor illuminance values with lights off for 43 rooms are displayed in Figure 17. Trends observed from the floor plans include daylighting use exclusively by the exterior offices, except for room 202, whose occupant utilized hallway lighting. There was also a wide range of illuminance values from nearly 0 fc to greater than 30 fc.

Discussion: The offices and conference rooms with illuminance values of at least 10 fc used daylighting, which confirms the daylighting strategy employed by/integrated in Y2E2's design. Exterior rooms that had relatively low illuminance values, such as room 389 are likely an indication that the blinds were down in those rooms. This may be due to excessive heat gain or glare from the daylighting, preventing use of the daylighting received. Two of the three building spaces that had greater than 10 fc but still used artificial lighting were kitchens: 210 and 334. Combined with the observation that kitchen lights often remain on even when unoccupied, this shows that lighting energy efficiency can be improved in kitchen spaces.

7.4 Thermal Comfort Results

Temperature differences of up to 3^{o}F from room to room are not uncommon, but often one or several rooms are uncomfortably warm or cold. This condition could be caused by several factors, including inadequate insulation, air leakage, poor duct system design, duct leakage, unwanted heating by the sun in warmer months, or a failure in part of the heating and cooling system. Due to limited access to HVAC subcomponent systems and limited expertise, the research team was unable to do a proper assessment of the factors listed above. However, the team used lighting and plug loads as indicators for temperature variance in a room. The following graphs and illustrations are a summary of the Thermal Comfort results. Note that analysis was only done by comparing rooms and/or zones that have the same subcomponents. Entire building comparisons would be misleading because each zone is subjected to different ASHRAE criteria for thermal comfort.

Figure 18 is a template of the graph used by the research team to analyze the obtained results. The ASHRAE Thermal Comfort Standards are based on 80% overall acceptability, while specific dissatisfaction limits vary for different sources of local discomfort. Occupants that are not satisfied usually have individual differences in preference and sensitivity (Olesen et al., 2004). The Thermal Sensation Scale is a reflection of the actual mean vote provided by the occupant in the survey and the Predicted Mean Vote in the PPD-PMV graph displays the calculated results.

PPD-PMV

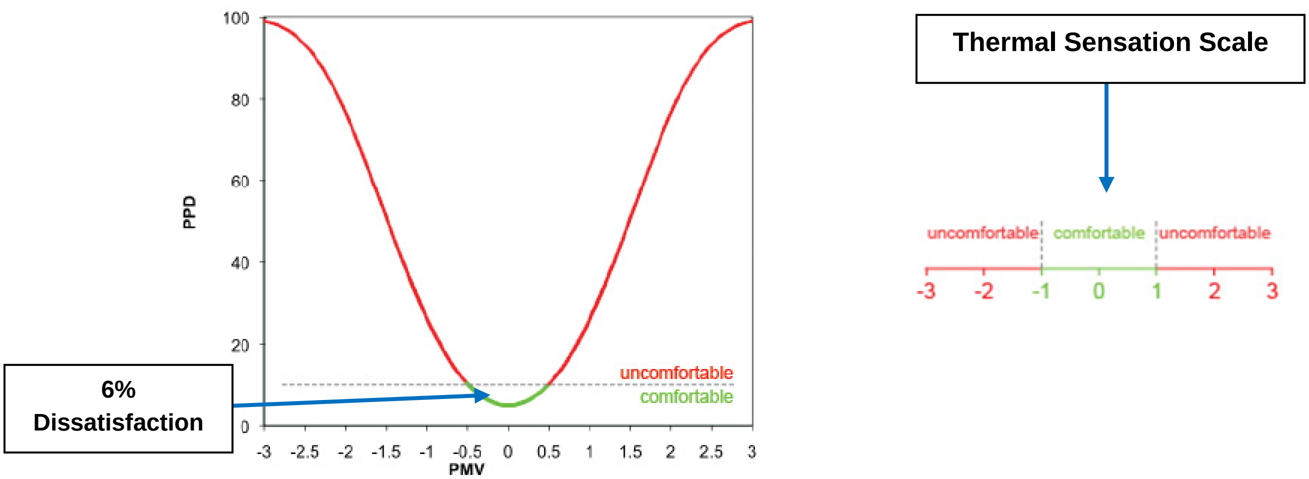


Figure 18: The PPD-PMV graph is the template provided by ASHRAE that the research team used to graph and analyze the results. If the PMV data points were graphed in the green portion of the curve, then less than 6% of occupants are estimated to be dissatisfied with their thermal comfort. If only 6% of the occupants are dissatisfied, this reflects the maximum percentage of occupants that can be dissatisfied for the building or zone to be considered as having ideal thermal conditions. Thus the research team has labeled the portions of the graph with less than or equal to 6% of occupants dissatisfied as "Comfortable." Any data points graphed on the red portions of the curve indicate a higher percentage of occupants dissatisfied and generally signify ineffective HVAC systems or relaxed standards for thermal comfort.

7.4.1 Comparison of HVAC Zones

Comparison of All Zones with Constant Volume Subcomponents

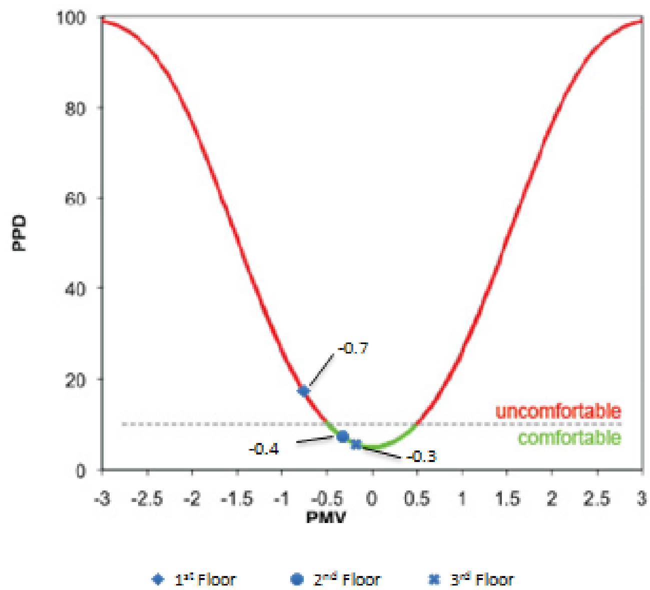


Figure 19: This figure illustrates differences in thermal comfort for the 1st, 2nd, and 3rd floors in Y2E2. All the rooms compared in this figure only use Constant Volume Subcomponents to regulate the temperature.

Result: Overall, all the zones with Constant Volume subcomponents seem to have relatively cold temperatures, based on ASHRAE thermal comfort standards. The 2nd and 3rd floors appear to be in a normal or acceptable thermal comfort range. However, more occupants on the 1st floor appear to be dissatisfied with their thermal comfort. The occupants on the 2nd and 3rd floors fall into Comfort Class B, whereas, the 1st floor occupants fall into Comfort Class C. Thus, ASHRAE predicts that 10% or less of the occupants on the 2nd and 3rd floors are dissatisfied compared to 15% or less on the 1st floor. The predicted results indicate that occupants on these floors are slightly cold, which corresponds to the actual mean votes provided by the occupants that reflect their thermal sensation (See Appendix B for PMV Calculations).

Discussion: Reasons that the occupants on the 1st, 2nd, and 3rd floors could be experiencing colder temperatures could be due to mechanical problems with the HVAC system or could be related to the set points for each room. Our results showed that the 1st floor experienced the coldest temperatures; this may be due to the fact that heat rises, which results in the lower floors being cooler. Additionally, the average clo value for the 1st floor occupants was higher than the average clo for the 2nd and 3rd floor (See Appendix B for PMV Calculations), which may indicate that the occupants have tried to adapt to the colder temperatures.

Comparison of All Zones with Exhaust Constant Volume & Constant Volume Subcomponents Using PMV

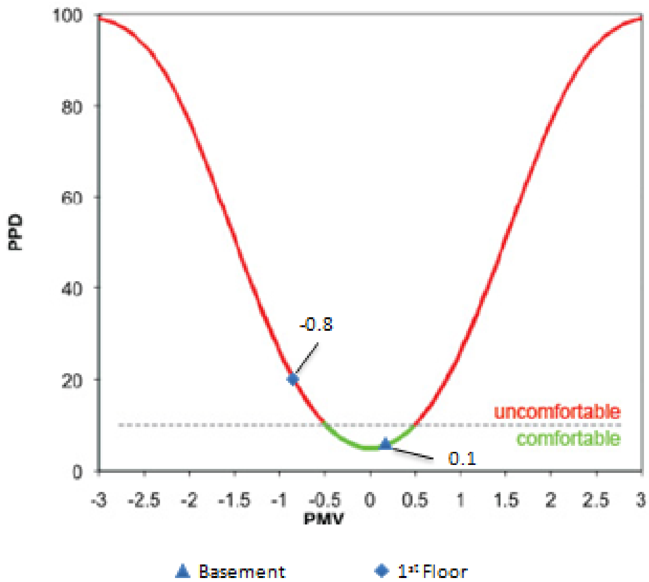


Figure 20: This figure illustrates differences in thermal comfort for the basement and 1st floor in Y2E2. All the rooms compared in this figure use only Constant Volume and Exhaust Constant Volume Subcomponents to regulate the temperature.

Result: According to ASHRAE calculations, the basement has less people dissatisfied with their comfort than the occupants on the 1st floor. The surveyed occupants from the basement fall into Comfort Class A, while the occupants surveyed on the 1st floor fall into Comfort Class C. Additionally, the Predicted Mean Vote of the surveyed occupants on the 1st floor perceived the temperatures as being colder and the occupants in the basement perceived the temperatures as being warmer. However, the average occupant Actual Vote for thermal comfort for both the basement and the 1st floor is -0.5, suggesting that they feel the same (See Appendix B for PMV Calculations).

Discussion: Surprisingly, the occupants on the 1st floor appear to be experiencing colder temperatures than the occupants in the basement. This finding is surprising because the basement accommodates all the wet labs in the building and these spaces often require cooler temperatures. This finding may be due to the adaptive nature of the occupants in the basement. Occupants in the basement most likely expect the temperature to be cooler; therefore, they may be more likely to wear more clothing. This assumption is supported by the clo value of the occupants, which was higher for occupants of the basement than those of the 1st floor (See Appendix C PMV Calculations). Other plausible reasons for these results are that the PMV Calculator may be inaccurate or the results are biased due to the small sample size.

7.4.2 Comparison of Thermal Comfort by Floor

Comparing PMV to Actual Mean Vote for Surveyed 1st Floor Occupants

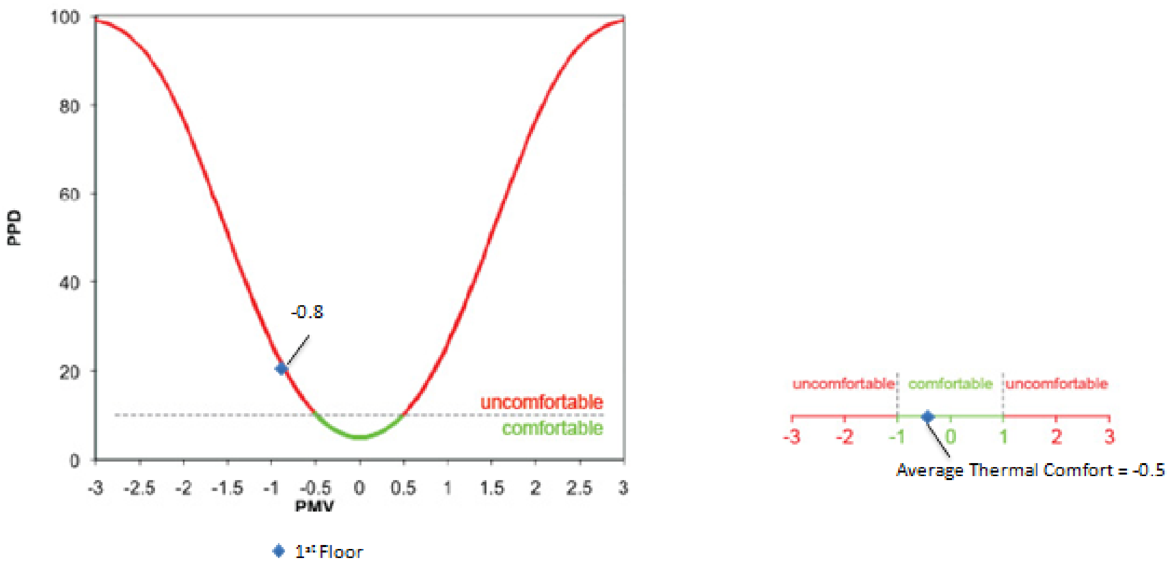


Figure 21: This figure illustrates thermal comfort for the 1st floor of Y2E2. The scale on the right provides a visual comparison of the actual average thermal comfort reported by occupants to the Predicted Mean Vote derived by the PMV calculator.

Result: Occupants on the 1st floor are in Comfort Class C, according to the Predicted Mean Vote. However, the Actual Vote suggests that the occupants consider themselves more neutral. Both results indicate that the occupants on the first floor are experiencing colder temperatures.

Discussion: Differences in the Predicted Mean Vote and the actual Average Thermal Comfort of the occupants may be attributed to discrepancies with the PMV calculator. Additionally, occupant perceptions can be biased. In an interview with Stanford University Civil Engineering Professor, Jeffrey Koseff, he shared that he observed that when occupants feel a draft they equate this feeling with cooler temperatures even when there is no difference in the measured temperature.

Comparing PMV to Actual Mean Vote for Surveyed 2nd Floor Occupants

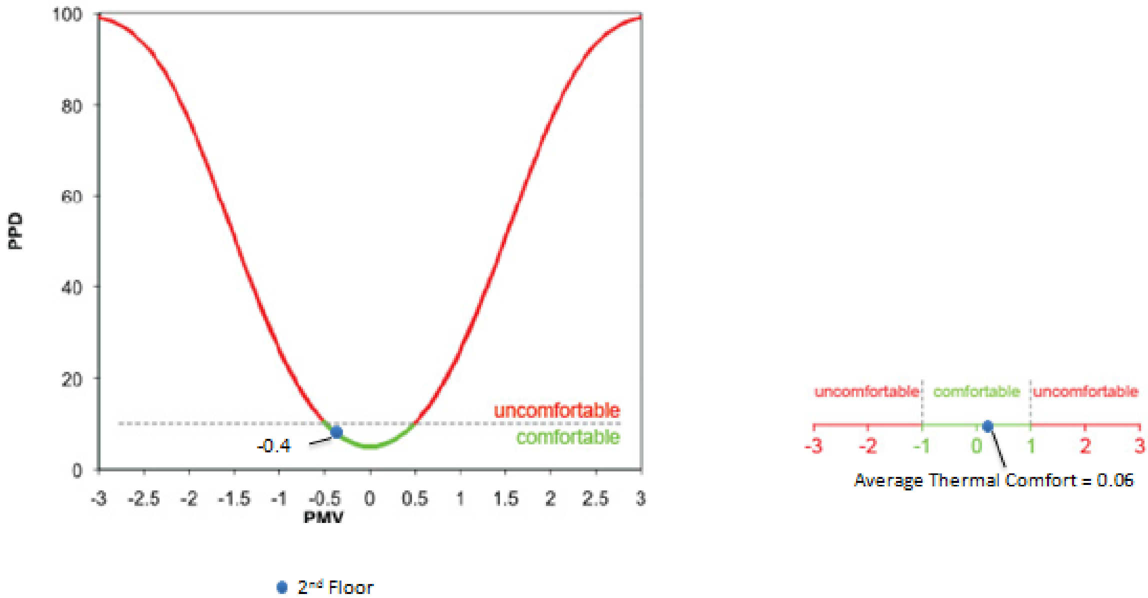


Figure 22: This figure illustrates thermal comfort for the 2nd floor of Y2E2. The scale on the right provides a visual comparison of the actual average thermal comfort reported by occupants to the Predicted Mean Vote derived by the PMV calculator.

Result: Occupants on the second floor appear to be in Comfort Class B, a normal thermal comfort range. Both the Predicted Mean Vote and the occupants' personal classification of their thermal comfort fall in the normal comfort ranges. However, the Predicted Mean Vote indicates that the occupants are slightly cold and the occupants' personal classification of their thermal comfort indicates that they are slightly warm.

Further, analysis of the second floor indicated that rooms 202 (office), 266 (architecture work room), and 276 (computer classroom) are warmer than the rest of the rooms surveyed on this floor, which are in the neutral ranges.

Discussion:

- 202: This space is used as the main server room for an entire department. Among the rooms audited on the 2nd floor, this space had higher plug loads than other rooms. The occupant reported leaving the lights off most of the time due to thermal discomfort caused by the equipment in the room. Figure 24 illustrates estimates of 2nd floor plug loads of rooms in which complete thermal comfort surveys were completed. Additionally, the average plug load for all the rooms in which energy audits were completed (i.e., not necessarily where thermal comfort surveys were completed) was around 143.7 Wh/day/sqft. Estimates show that room 202 has an average plug load of 272.43 Wh/day/sqft, which exceeds the average of all the audited rooms.

- Room 266: This space has lower lighting and plug loads than the other audited rooms on the 2nd floor as indicated by Figures 24 and 25. An alternative reason for the higher perceived temperature by the occupant could have been the effect of the surrounding rooms. Room 266 is surrounded by three other rooms audited by the research team, Rooms 268, 269C, and 269B (See Figure 23). However, the plug loads for these rooms are each less than the average of all the rooms audited by the research team. Therefore equipment use may not be a plausible reason for this occupant's discomfort. Alternatively, this individual's personal preferences for thermal comfort may be extreme. This may be a more plausible assumption because the surrounding rooms on the floor indicate that their thermal comforts are within the neutral range. (See Appendix B for 2nd Floor Plan)

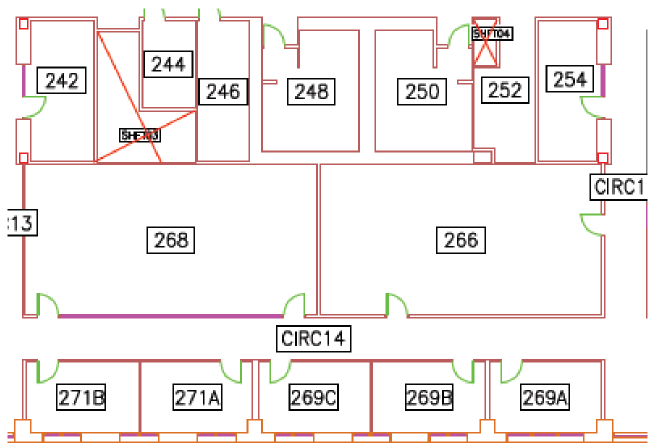


Figure 23: Snapshot of 2nd Floor Plan. Analysis of the surrounding rooms in relation to spaces that experience warmer temperatures may provide evidence for temperature variance in certain rooms. Room 266 indicated having extremely warm temperatures. The research team also audited the following rooms that surround Room 266: 268, 269C, and 269B.

- Room 276: This space has one of the lower lighting and plug loads among the audited rooms. Since Room 276 is used as a computer room, assumptions can be made that these spaces have higher energy consumption. However, since this research took place during the summer months, this room probably did not have usual occupancy usage.

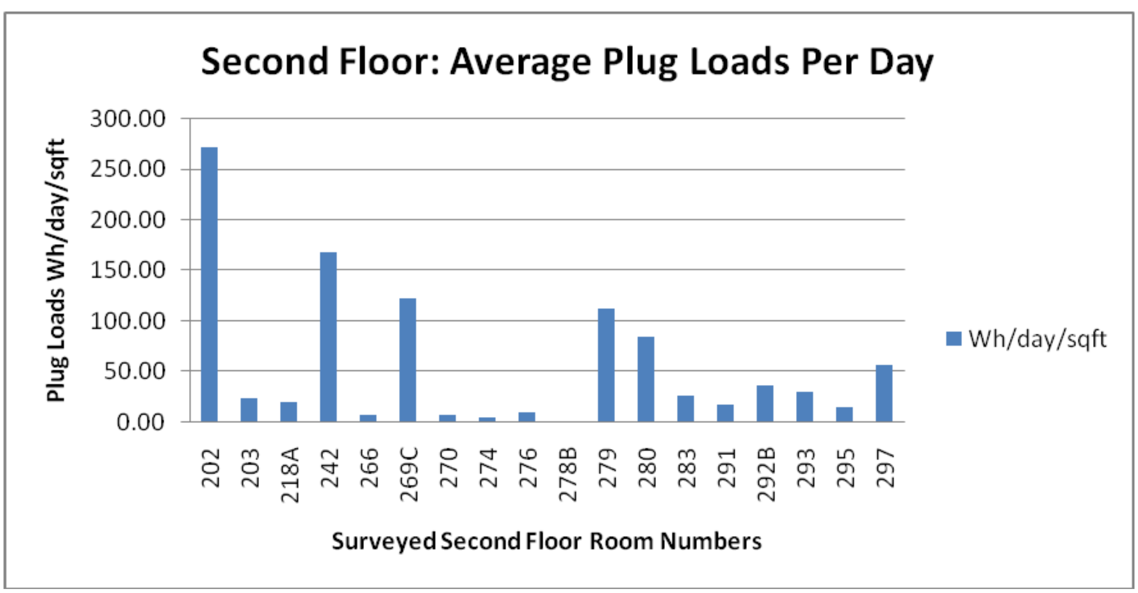


Figure 24: 2nd Floor Average Plug Loads Per Day. This figure illustrates the average energy consumption per day by room for plug loads. This visual representation helps provide some insight on why some rooms experience warmer temperatures.

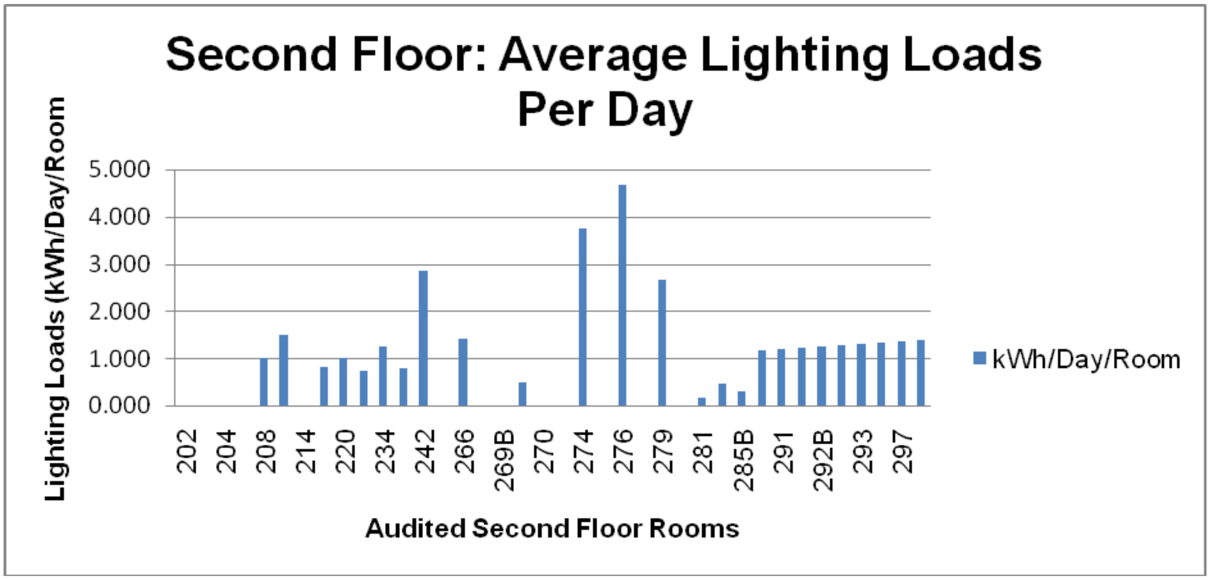


Figure 25: 2nd Floor Average Lighting Loads Per Day. This figure illustrates the average energy consumption per day by room for lighting loads. This visual representation helps provide some insight on why some rooms experience warmer temperatures.

Comparing PMV to Actual Mean Vote for Surveyed 3rd Floor Occupants

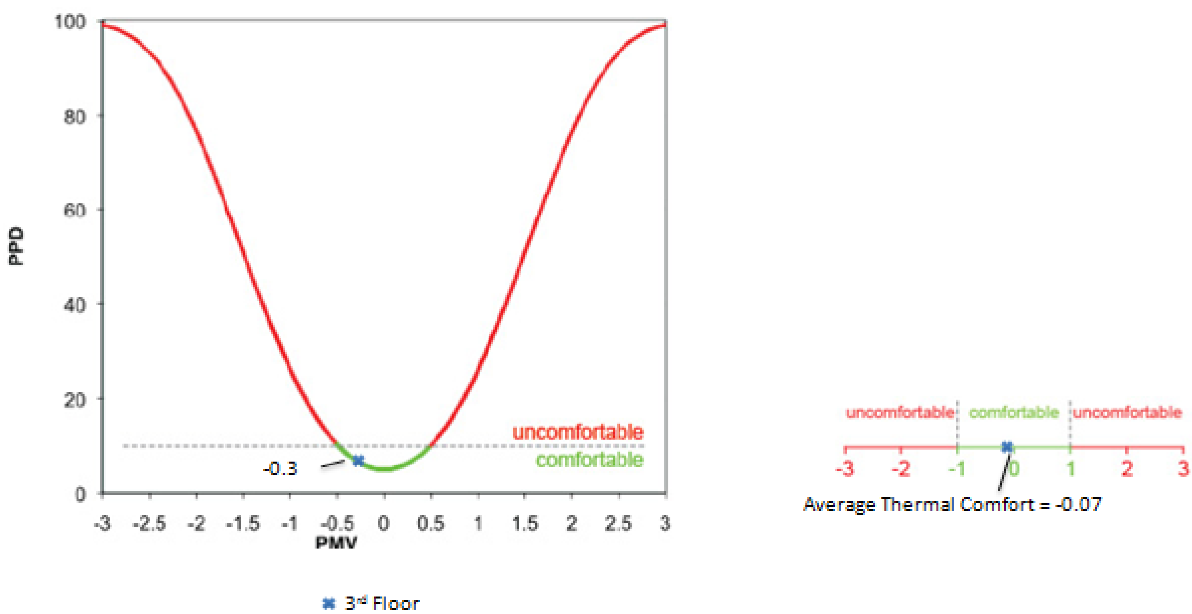


Figure 26: This figure illustrates thermal comfort for the 3rd floor rooms in Y2E2 with Constant Volume Subcomponents. The scale on the right provides a visual comparison of the actual Average Thermal Comfort reported by occupants to the Predicted Mean Vote derived by the PMV calculator.

Result: The PMV falls in Comfort Class B and the Actual Mean Vote is in the normal thermal comfort ranges. Thus, up to 10% of occupants, according to the calculated PMV, would be dissatisfied with their thermal comfort. Both the PMV and the actual Average Thermal Comfort vote reveal that occupants experience slightly cold temperatures.

Discussion: Room 384 appeared to be extremely hot compared to the rest of the rooms. This room is used as an office. Plug load energy consumption for this room is very small compared to those of other rooms on the 3rd floor. Room 384 also has negligible lighting loads compared to those of other rooms on the 3rd floor. This space is also not surrounded by any other rooms that are consuming greater amounts of energy when using lighting and plug loads as indicators.

Comparing PMV to Actual Mean Vote for 3rd Floor w/ with Variable Air Volume & Exhaust Constant Volume Sub Components

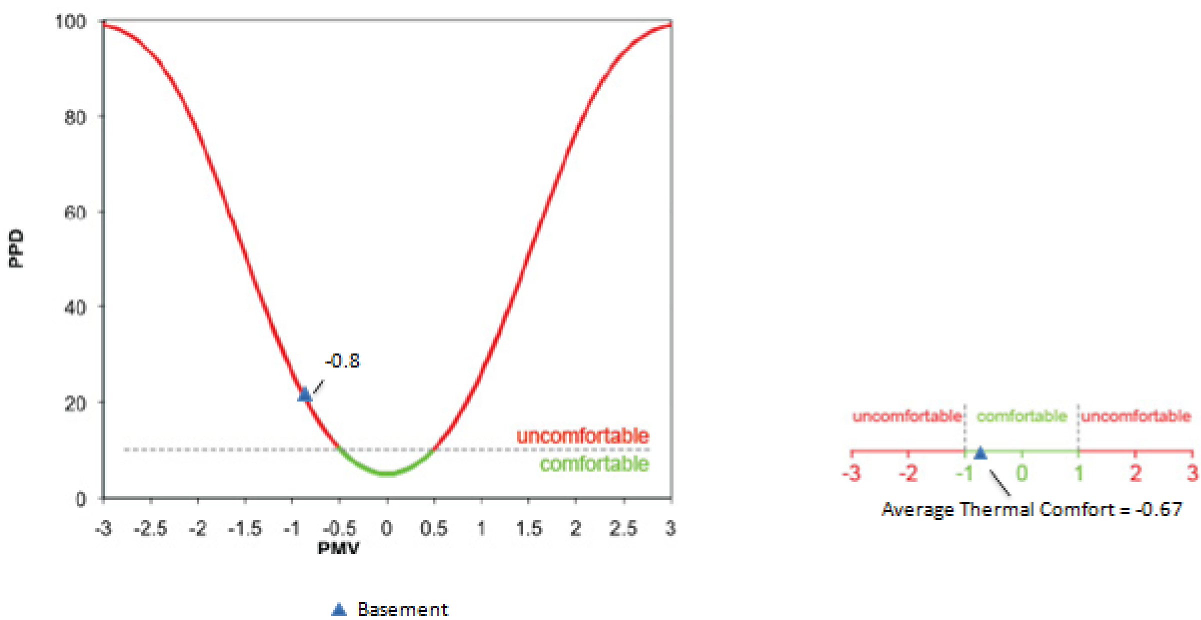


Figure 27: This figure illustrates thermal comfort for 3rd floor rooms of Y2E2 with Variable Air Volume & Exhaust Constant Volume Sub Components. The scale on the right provides a visual comparison of the actual average thermal comfort reported by occupants to the Predicted Mean Vote derived by the PMV calculator.

Result: The PMV does not lie in any of the defined comfort classes, which indicates a higher percentage of dissatisfied occupants than normal; almost 19% of occupants would be dissatisfied in this zone. However, the actual Average Thermal Comfort vote indicates that the occupants are in the normal comfort range. Both the PMV and the actual vote reveal that occupants feel colder.

Discussion: Only two people were surveyed in this zone which is why the results appear to show an extreme case of thermal discomfort. The occupants in this zone had the lowest clo value of all three zones in the basement.

Comparing PMV to Actual Average Thermal Comfort Vote for Basement w/ Variable Air Volume & Exhaust Variable Air Volume Subcomponents

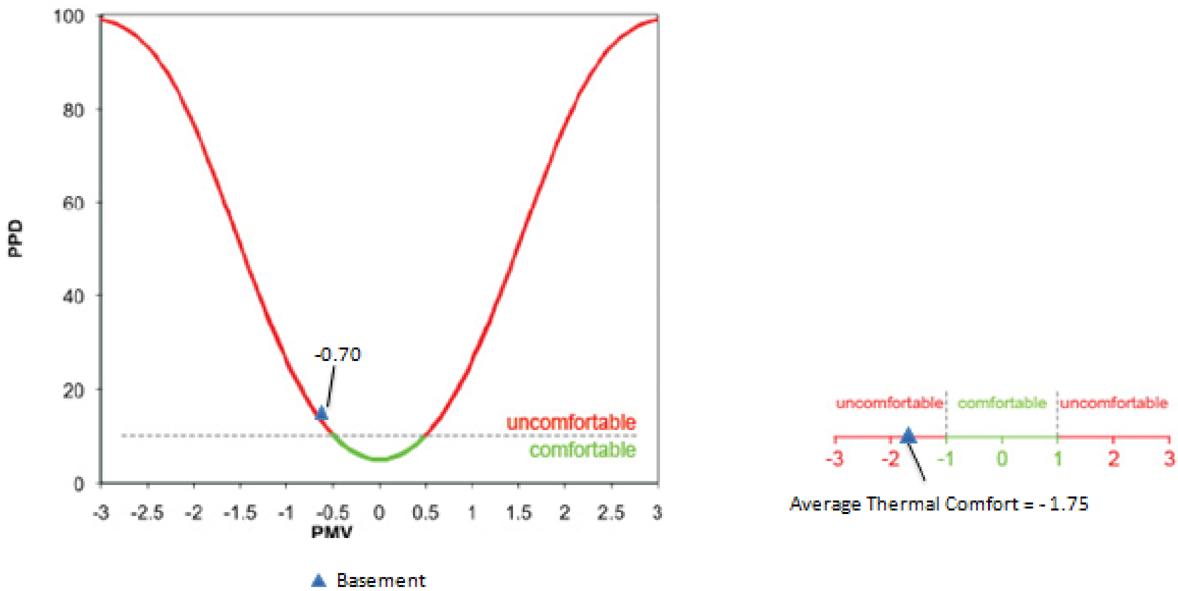


Figure 28: This figure illustrates thermal comfort for basement rooms of Y2E2 with Variable Air Volume & Exhaust Variable Air Volume Subcomponents. The scale on the right provides a visual comparison of the actual average thermal comfort reported by occupants to the Predicted Mean Vote derived by the PMV calculator.

Result: Predicted Mean Vote of the occupants in the basement zone with VAV and EVAV subcomponents fall in Comfort Class C, which ASHRAE predicts 15% or less of occupants in this zone are dissatisfied. Correspondingly, the actual Average Thermal Comfort demonstrates an extreme case of discomfort.

Discussion: The reason for the observed extreme is that only two people were surveyed in this zone. The occupants surveyed who indicated that they were the coldest possible value on the thermal sensation scale were in these rooms (See Appendix C for Basement Floor Plans).

Comparing PMV to Actual Average Thermal Comfort Vote for Basement (w/ Exhaust Constant Volume & Constant Volume)

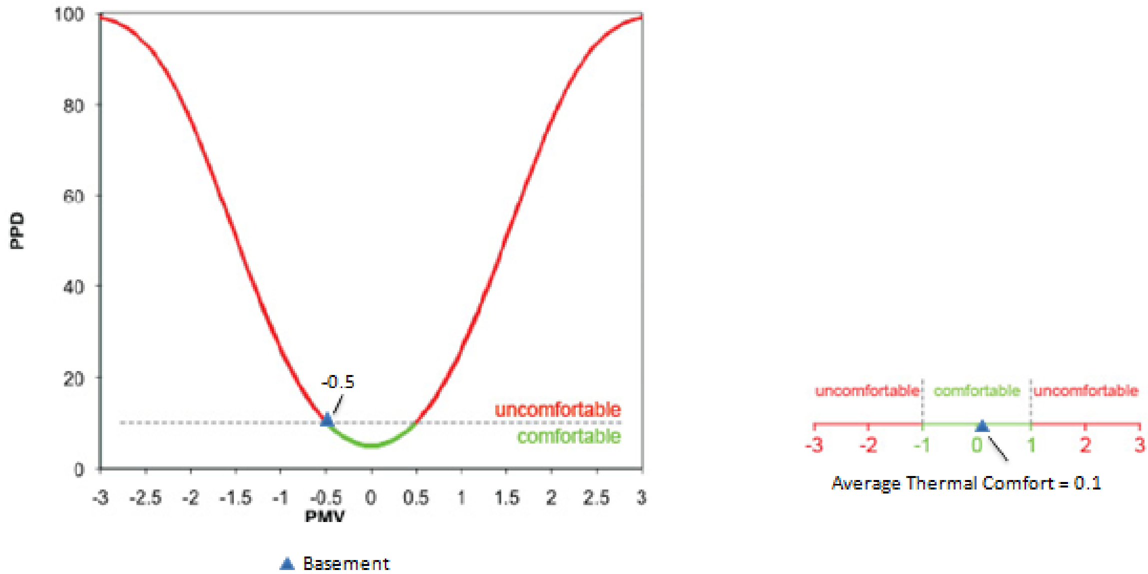


Figure 29: This figure illustrates thermal comfort for basement rooms in Y2E2 with Exhaust Constant Volume & Constant Volume Subcomponents. The scale on the right provides a visual comparison of the actual average thermal comfort reported by occupants to the Predicted Mean Vote derived by the PMV calculator.

Result: The PMV appears to fall in Comfort Class A, according to ASHRAE standard. Thus, 6% or less of the occupants in this zone are dissatisfied. The PMV also indicates that the zone is slightly cold. The actual Average Thermal Comfort corresponds with the PMV in that it falls within comfortable ranges. However, the actual Average Thermal Comfort indicates that the occupants experience slightly warmer temperatures rather than colder temperatures.

Natural Ventilation Results

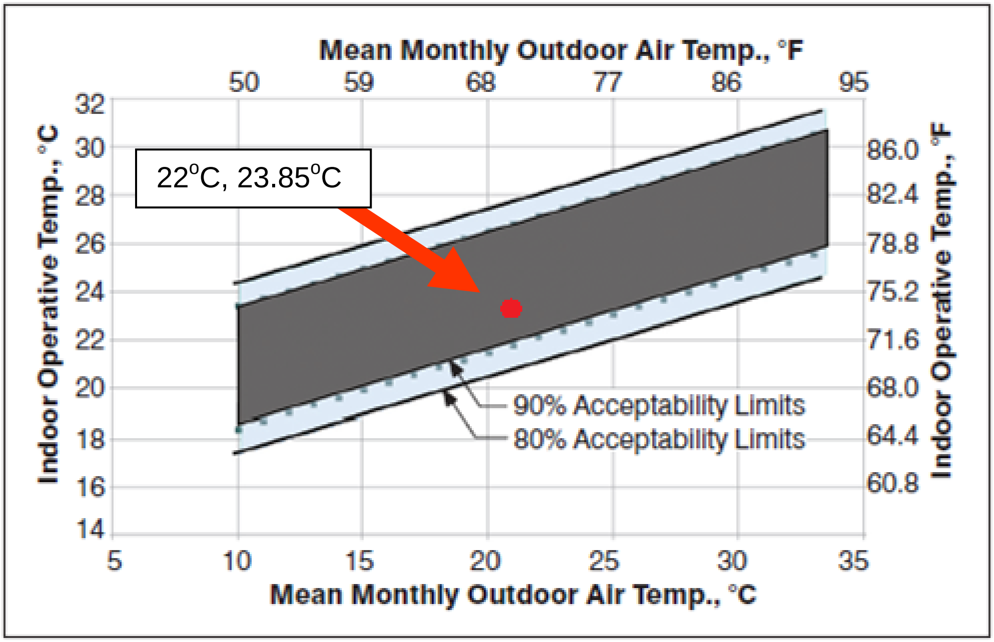


Figure 30: This graphical representation is used for spaces in Y2E2 that are naturally ventilated; thus they do not have mechanical systems. The result is based on an average monthly temperature of 22°C.*This graphical representation indicates the percentage of occupants that regard their thermal comfort as acceptable (See Appendix B, Calculations).*

Result: According to the graphed results, 90% of occupants in naturally ventilated zones would be comfortable.

Discussion: These findings may not yield accurate results because of the small sample size. The research team completed only four surveys for naturally ventilated rooms.

8 Conclusion & Future Work

8.1 Conclusions

Plug Loads

Overall, Plug Load analysis corresponds with stated predictions. Specifically, while Research Labs make up a relatively small portion of the entire building by area (18%), they contribute a disproportionate amount to the plug loads of the building (53%). While Offices make up the next largest user of plug loads (29%), this is expected, as they make up a comparable portion of the entire building (26%). These numbers could be useful in predicting future energy costs of a new building, based on the allocation of building spaces by area.

The study also demonstrates that an energy audit performed by hand with a relatively small sample size could make a fairly accurate determination of relative energy consumption, as compared to the SEE-IT data by floors. However, the methods and assumptions used to extrapolate the data resulted in an overestimation of approximately 150% compared to the SEE-IT data. Also, after the ten-week study, it was very difficult to get much more than one average value for total plug load draw, while the sensor data can easily report time-scale data over any given time interval in just seconds. As long as this data can be proved reliable (See 8.2 Recommendations), this could be a very valuable tool to researchers analyzing the energy use of Y2E2 in an accurate manner.

Lighting

The main finding of the Lighting study is that Circulation Spaces have far too much installed lighting and those lights are on too often. Future buildings should drastically cut down on this unnecessary lighting. Our assessment also found that while the building as a whole meets the LPD standards set by ASHRAE, there is room for improvement in certain room types, notably Circulation Spaces, Kitchens, and Copy Rooms, all of which exceed the ASHRAE's limits.

Based on the findings of the Illuminance study, it appears that occupants of Y2E2 are taking advantage of daylighting opportunities where they are available to them, primarily on the exterior offices and those with large windows facing the atria. The few perimeter offices with insufficient daylighting were likely due to blinds being closed to reduce glare or solar heat gains. The only spaces that seemed to ignore the daylighting opportunities were the kitchens, which often have light switches always in the "On" position, waiting to be triggered by the occupancy sensors.

Thermal Comfort

The results from the thermal comfort assessment as a means of evaluating the efficiency of the HVAC system in Y2E2 correspond with the assumption that the uniquely designed HVAC system is energy efficient. Furthermore, the unique design indicates in this analysis that the system effectively meets the needs of occupants. The results reveal that the average respondent experiences a comfortable range of temperatures. Although, the results overwhelmingly support the predictions drafted by the research team, there were some outliers in the results that suggest a need for further investigation. Additionally, a definite conclusion cannot be made from this analysis because the sample is too small. For many of the various HVAC system components the research team only surveyed a sample of one or two rooms from which to analyze. Due to the small sample size, there is considerable evidence that the results might have been skewed. There were also other factors that might have given a clearer gauge of an individuals' comfort that the research team did not take into consideration, such as gender. See 8.2 Recommendations).

Nevertheless, these findings still provide some understanding of thermal satisfaction, which can be used to make changes to the building to better accommodate the occupants. For example, some rooms experienced very cold temperatures when the windows automatically open during certain hours for ventilation or night purge. These types of problems can easily be resolved through open communication with the building manager. A possible remedy could be to change the time schedule for the automatic windows. Overall, these findings and observations suggest that when occupants experience thermal dissatisfaction, the problems arose from poor planning (i.e., improper uses of building spaces – regular offices for computer clusters) rather than from the inadequacy of the HVAC design.

8.2 Recommendations

Energy Study

While the results of the lighting survey were promising in that occupants appear to be taking advantage of daylighting opportunities, a more thorough investigation could still be conducted. A study focusing on lighting could survey every room, rather than just a sample. If daylighting is the primary interest, future researchers would be better off skipping the basement, as almost no rooms on that floor have sufficient daylighting. It would also be of interest to take illuminance data over a wider range of times of day for each room to achieve a better idea of the threshold below which occupants turn to artificial lighting.

If future researchers are interested in comparing data gathered in an energy audit by hand versus that recorded by building sensors, a narrow focus on just the “representative offices” of the building would be beneficial. These rooms (145, 341, 371, and 393) have additional sensors, including those to measure Lighting Loads and Plug Load Current, which can provide more granular data; this allows for verification of the calibration of these sensors with very few assumptions or extrapolations, if any. However, previous research performed by students in the CEE 243 course showed that these rooms have very low occupancy rates and therefore provide little useful information in their current state (CEE 243 Wiki).

In part, this energy audit served as a rough assessment of certain sensor energy data of Y2E2. However, a complete assessment of the building’s sensors has not been performed recently. An assessment of sensors should be carried out to ensure validity of the collected energy data of Y2E2. Calibrating sensors and mapping data points would definitely improve the reliability of Y2E2’s energy data. In addition, careful mapping of these points would identify and eliminate any double counting of data.

Three specific issues were discovered during this energy audit. First, the CO_2 sensor in conference room 299 displayed negative values in parts per million (ppm); this sensor is not working properly and it should be calibrated. In addition, other CO_2 sensors are not necessarily calibration and should also be checked to ensure that they are working properly. Second, the data corresponding to the plug load demand of the 3rd floor west, measured by meter T3NW, is significantly distorted from LON to SQL conversion. The T3NW data points should be mapped between these two gateways to point out the specific problem and determine the best solution. Third, the data corresponding to the lighting demand of the 2nd floor, measured by meter 2NHE, is lost from the modbus to LON conversion. Similarly to T3NW, the 2NHE data points should be mapped between these two gateways to point out the specific problem and determine the best solution.

SEE-IT is a useful tool for anyone who wants to quickly export the energy data of Y2E2. In order to maximize its benefits, the software and SQL database should be periodically updated. Based on the experience from this energy audit, the SQL database has not been cleaned up or adjusted in a while, as several sensors listed in SEE-IT were found to be inactive or inaccurate. For example, SEE-IT listed three or four different sensors for each floor section corresponding to plug load demand. However, only one of them provided non-zero values with the correct units. Cleaning up the SQL database would help future researchers by eliminating confusion and ensuring validity of energy data.

Regarding the plug load demand of the 3rd floor, the way that the PV panels were split between the two meters makes it difficult to determine the true plug load demand of the 3rd floor east and west, measured by meters T3NE and T3NW respectively. Having direct access through the SQL database to the historical data of power generated by every PV panel individually would help future researchers to quickly determine the true plug load demand of both sections on the third floor, as well as provide data to research the effectiveness of the PV panels.

Thermal Comfort Study

In the future, several improvements are necessary to get a clearer result of the efficiency of the HVAC system. First and foremost, a larger team to collect data and longer time period to conduct the research is integral. A couple of reasons for the small sample sizes used in this research were the limited time and number of researchers to conduct a more extensive work. Because the goals of this project required choosing rooms from a large variety of subsystems, very few rooms of each type were chosen, leading to even smaller sample sizes and potentially unreliable data. If time and/or resources are limited, the research team would suggest focusing solely on one subsystem, but collecting data from every room on that particular subsystem.

Given more time, the research team could get a more accurate gauge of thermal comfort during different times of the day and possibly during different seasons. Occupants surveyed may have a much different response about their thermal comfort in the winter months than they might have in the fall. Additionally, the research team did not include gender as parameter of varying thermal comfort.

Lastly, another comparison could have been made between electricity bills and the responses concerning thermal comfort to determine their correlation.

9 Acknowledgments

The research team would like to thank the following people for their contributions to this project:

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Appendix A – Assumptions and Limitations

The following includes notes on two aspects related to the process of the study: assumptions and limitations. Included in these sections are only those that have major impacts on the study and/or are referenced throughout the rest of this paper.

Data Collection Process

Assumptions

The largest assumption made in this study is that a carefully selected sample of rooms will represent the entire building, to an acceptable degree of accuracy. By choosing an equal number of rooms from each HVAC subsystem and approximately the same portion of rooms by space type for each floor, it is assumed that measured data such as comfort, lighting, and energy use could be extrapolated by simply assuming the rooms that were not surveyed would have had similar responses to those of the same space type. Similarly, because rooms were chosen without checking whether or not they were occupied, it is assumed that the occupancy patterns of audited rooms are representative of that of the entire building.

Limitations

The primary limitation of this study is that it was conducted in the middle of the summer over only a two-week period. This means that occupancy patterns are likely drastically different from that during the Academic Year. Also, weather variation was fairly limited, likely near the upper end of the temperature ranges experienced by the building, which may have skewed the results of the comfort survey. Because of time and manpower constraints, several major assumptions had to be made, as detailed in the previous section.

Due to limitations including time and the inability to directly measure power draw in an unobtrusive way, equipment power use was often determined by checking the nameplate power of the device, either on the label or on specification sheets for the given model. In some cases, this was not possible, and the power draw of a device would need to be estimated based on that of similar equipment.

Quantitative Energy Evaluation: Plug Loads & Lighting

Assumptions

Plug Loads

It is assumed that rooms of the same type have a power draw per unit area that, on average, only differs by the portion of time that each room is occupied.

Occupants had to be trusted to accurately estimate their usage of the equipment in their own room. This assumption, while it is likely valid in the office setting, may have been less so in larger spaces, such as labs, where not all occupants are necessarily aware of their co-occupants' behaviors and equipment use. In other shared spaces, such as Computer Labs and Kitchens, the status of equipment (On, Off, Standby) was recorded on each EveryTime audit and used to estimate the average usage of equipment in those rooms. Each piece of equipment recorded as "On" was assumed to have stayed in that state for 2 hours.

Other space types also did not have rooms that were audited.
The space types of: 011, DUCT SPACE
012, JANITOR CLOSET
013, ELECTRICAL EQUIP RM
014, MECHANICAL EQUIP. RM
015, TELEPHONE EQUIP. RM
040, STRUCTURAL
084, UNFINISHED AREA
261, CHEMICAL STORAGE ROOM
461, DEPARTMENT LIBRARY
635, FOOD FACILITY SERVICE
711, COMPUTER/NETWORKING FACILITY
720, SHOPS
733, STORAGE ROOM, GENERAL
were assumed to have zero kW plug load usage.

In comparing data to the sensed data from SEE-IT, the research team noticed that the data from the West side of the 3rd floor was inaccurate (See 7.2 Electric Metering Results). To compensate, the team assumed that the 3rd floor would have a similar ratio of East-to-West plug loads (55%) as the other floors, and estimated accordingly.

Lighting

Given no other information from the occupants during the OneTime energy audit, the EveryTime occupancy and lighting on/off audit was used to estimate the hours. It was assumed that each time the lights were recorded as "ON" (at 9 a.m., 1 p.m., 5 p.m., 9 p.m.), the data point was representative of the lights being on for 4 hours. The lighting on/off data was taken over a period of one week for each of the two weeks and averaged for an average hrs/wk. To gauge the validity/effectiveness of the assumption, the lighting averages in hrs/wk were estimated using the above method for several rooms that already had lighting data from the occupants' responses during the OneTime energy audit. The results for the hrs/wk value were compared and were found to produce roughly similar results (within +/- 8 hrs/wk).

Space types were divided into two categories based on assumptions of whether the space type had approximately the same square footage in each space (fixed lighting), or whether the space type had variable room sizes (lighting on floor area basis). An average kW/room was determined for the following room types: office (all types except student), office service, restroom, kitchen, and cafeteria/dining area. The averages were then used to estimate the lighting energy usage of rooms of the same type based on the count. An average kW/sqft was determined for the following room types: office (student), lab (all types), conference room, classroom, lounge, department circulation, and lab research. The averages were then used to estimate the lighting energy usage of rooms of the same type based on square footage.

Several types of offices did not have rooms that were audited.
The office types of: 313, OFFICE-PROFESS STAFF
326, OFFICE-EMERITUS FACULTY
367, OFFICE-VISITING SCHOLAR
368, OFFICE-RSCH ASSOC/LECT
were assumed to have the same kW lighting usage as 321, OFFICE-FACULTY.
The office type of: 366, OFFICE-POST DOC. FELLOW

was assumed to have the same kW lighting usage as 322, OFFICE-STUDENT.

Other space types also did not have rooms that were audited.
The space types of: 011, DUCT SPACE
012, JANITOR CLOSET
013, ELECTRICAL EQUIP RM
014, MECHANICAL EQUIP. RM
015, TELEPHONE EQUIP. RM
040, STRUCTURAL
084, UNFINISHED AREA
261, CHEMICAL STORAGE ROOM
461, DEPARTMENT LIBRARY
635, FOOD FACILITY SERVICE
711, COMPUTER/NETWORKING FACILITY
720, SHOPS
733, STORAGE ROOM, GENERAL
were assumed to have zero kW lighting usage.

An audit for lighting in the circulation spaces was performed for the 2nd floor. The 2nd floor data was used to compute the percentage of lights that were on for each type of luminaire. Based on these values, it was assumed that 65% of hallway lights are on for H.E. Williams 2' x 2' Direct/Indirect Shallow fixtures and 85% of hallway lights are on for Infinity PH75 7.5" Round Downlight - Horizontal Lamp. All lighting in the building circulation spaces (hallways, corridors, atria, and entryways) was assumed to be on 24 hrs/day. The building code for emergency lighting in the circulation spaces was assumed to be 50% of lights in each circulation space.

In comparison of Y2E2 LPD values and ASHRAE 90.1-2004 standards, the "Copy Rooms" value was compared to the "Office - Open Plan" standard and the "Computer Labs" value was compared to the "Office - Enclosed" standard since standards for the two space types were not set in ASHRAE 90.1-2004. A standard for the whole building was obtained by taking an average of the ASHRAE specifications for a school/university building (1.2 W/sqft) and an office building (1.0 W/sqft). This assumption was made to take into account the classrooms, labs, offices, and conference rooms that compose Y2E2.

Qualitative Energy Assessment: Comfort & HVAC

Assumptions

The research team was able to collect data for all of the parameters affecting thermal comfort except air speed. The team did not have the equipment to predict air speed; therefore, a conservative estimate of 0.1 m/s was made, which accounts for the higher air speeds in the laboratories. The team also assumed that the mean radiant temperature was the surface temperature of the desk. Surface temperature measurements were taken for the floor, desk, and head level. The mean radiant temperature is the weighted mean temperature of all the objects surrounding the body.

The research team used a combination of two methods originating from the ASHRAE Standard to determine clo values. The following methods were used (See Appendix C, Audit Survey Guide):

- Method 1: a list of the insulation provided by a variety of common clothing ensembles. If the ensemble in question matches reasonably well with one of the ensembles in this table, then the indicated value of clo should be used.
- Method 3: A complete clothing ensemble may be defined using a combination of the garments listed. The insulation of the ensemble is estimated as the sum of the individual values listed. For example, the estimated insulation of an ensemble consisting of overalls worn with a flannel shirt, T-shirt, briefs, boots, and calf-length socks is clo = 0.30 + 0.34 + 0.08 + 0.04 + 0.10 + 0.03 = 0.89 clo.

HVAC Subcomponent Functions

HVAC Subcomponents	Functions
Constant Volume	Variations in the thermal requirements of a space are satisfied by changing the temperature of a constant volume of air delivered to the space. A constant fraction of outdoor air will mean that a constant volume of outdoor air will be delivered to occupied spaces. This volume can be set to satisfy applicable ventilation standards. CV systems are less energy efficient than VAV systems, but controls for outdoor air delivery are simpler to manage.
Exhaust Variable Air and Exhaust Volume Control	**Exhaust Systems**- in general, slightly more outdoor air should be brought into the building than the exhaust air and relief air of the HVAC system. This will insure that the building remains under slight positive pressure. • Exhaust intake should be located as close to the source as possible. • Fan should draw sufficient air to keep the room in which the exhaust is located under negative pressure relative to the surrounding spaces, including wall cavities and plenums. • Air should flow into, but not out of, the exhaust area, which may require louvered panels in doors or walls to provide an unobstructed pathway for replacement air. • The integrity of walls and ceilings of rooms to be exhausted must be well maintained to prevent contaminated air from escaping into the return air plenum. • Provisions must be made for replacing all air exhausted out of the building with make-up outside air.
Variable Air Volume	a VAV box in the occupied space regulates the amount of supply air delivered to the space, based on the thermal needs of the space. Malfunctioning VAV boxes can result in thermal discomfort and fail to prevent buildup of indoor air contaminants. VAV box minimum settings (e.g., 30% of peak flow) combined with the outdoor air fraction must provide enough supply air so that sufficient outdoor air enters the space at partial loads.

Figure A1: HVAC Sub-component Functions. This background information was provided by the U.S. Environmental Protection Agency. The figure makes distinctions between the various types of HVAC sub-components. This information is useful because the descriptions provide deeper knowledge on why occupants may experience differences in thermal comfort.

Appendix B – Calculations

Quantitative Energy Evaluation: Plug Loads & Lighting

Overall	Type	Room	W/person
Yellow	Yellow	B07	41.37
Yellow	Green	B21	11.92
Green	Green	B25	2.54
Red	Red	B26	325.84
Yellow	Green	B33	14.85
Red	Red	B34	89.37
Red	Yellow	B36	49.16
Green	Green	B37	0.90
Green	Yellow	101	1.06
Green	Yellow	105	2.14
Yellow	Yellow	107	18.41
Green	Yellow	109A	0.00
Green	Yellow	111	0.50
Red	Yellow	128	53.15
Red	Red	134	67.52
Yellow	Yellow	140	12.56
Yellow	Yellow	143	18.97
Green	Yellow	148	0.00
Green	Yellow	150	0.00
Red	Yellow	152	59.10
Green	Green	154	5.83
Green	Green	164	0.14
Green	Green	167	4.64
Green	Yellow	184	7.91
Green	Green	190	0.04
Red	Red	202	111.51
Green	Green	203	4.16
Red	Yellow	208	45.84
Red	Red	210	201.57
Yellow	Red	214	13.49
Green	Green	218A	5.93
Green	Yellow	220	0.00
Yellow	Yellow	230	39.74
Green	Yellow	234	0.00
Red	Red	236	187.73
Red	Red	242	50.52
Red	Red	266	53.43

Overall	Type	Room	W/person
Green	Red	269C	11.30
Green	Green	270	3.47
Green	Green	274	2.31
Yellow	Red	276	11.89
Green	Green	278B	0.25
Red	Red	279	57.51
Red	Red	280	458.50
Green	Yellow	283	10.56
Green	Yellow	285B	10.57
Green	Yellow	291	6.48
Green	Green	292A	0.51
Yellow	Yellow	292B	14.97
Yellow	Yellow	293	17.46
Red	Red	297	52.99
Green	Green	299	0.60
Green	Green	300	1.50
Red	Red	307	1623.91
Yellow	Yellow	324	18.99
Yellow	Green	326	12.80
Yellow	Yellow	328	25.08
Red	Red	334	73.99
Green	Red	338	5.77
Green	Yellow	344	0.00
Green	Green	346	0.00
Red	Red	348	90.40
Green	Green	366	3.48
Green	Green	369	3.37
Yellow	Yellow	370	17.64
Green	Yellow	379A	10.65
Yellow	Red	380	21.43
Green	Green	382	0.56
Yellow	Yellow	386	12.78
Green	Green	389	3.78
Yellow	Red	390A	12.70
Green	Green	390B	0.00
Yellow	Red	390C	28.29

Figure B1: Red, Yellow, Green Analysis of Individual Rooms by Plug Loads. Each room identified with a Green box in the left column uses less than half of the average W/person of the building. A Red box indicates using more than double the average, while Yellow is in between. The second column compares each room to rooms of a similar type. Rooms with Red in both columns are identified as rooms that may be using too much energy.

Overall	Type	Room	W/person
		B07	6.54
		B12	14.84
		B19	0.00
		B21	4.11
		B23	2.31
		B25	2.19
		B26	61.16
		B33	9.42
		B34	6.26
		B35	4.80
		B36	7.72
		B37	1.07
		B39	2.40
		B52	0.00
		B54	10.19
		B59	0.00
		101	10.91
		105	11.01
		107	1.06
		109A	3.20
		111	1.90
		128	30.60
		134	10.13
		140	2.60
		143	1.63
		148	12.57
		150	3.66
		152	34.11
		154	3.55
		164	3.29
		167	0.00
		170	0.00
		172	0.00
		173	0.00
		177	0.00
		181	0.00
		184	2.53
		187	0.00
		189	0.00
		190	4.43
		202	0.00
		203	0.00
		204	0.00
		206	0.00
		208	16.80
		210	16.00
		214	0.00
		218A	2.13
		220	16.80
		230	24.20
		234	16.80
		236	4.57
		242	6.38
		264	0.00

Overall	Type	Room	W/person
		266	18.72
		268	0.00
		269B	0.00
		269C	1.54
		270	0.00
		273	0.00
		274	6.75
		275A	0.00
		276	14.18
		278B	0.00
		279	5.57
		280	0.00
		281	1.73
		283	1.84
		285B	1.95
		287	0.00
		291	0.00
		292A	0.03
		292B	5.27
		292F	0.00
		293	0.00
		295	0.00
		297	0.00
		299	2.95
		300	1.44
		301	2.45
		307	30.00
		324	19.75
		326	10.00
		328	8.45
		334	4.40
		338	3.25
		344	56.00
		346	8.00
		348	35.80
		364	0.00
		366	1.73
		369	1.02
		370	5.60
		373	0.00
		375	0.00
		379A	0.00
		380	3.40
		382	2.20
		383	0.00
		384	2.60
		386	2.48
		389	2.23
		390A	8.27
		390B	0.00
		390C	5.60
		391	0.00
		396	0.00

Figure B2: Red, Yellow, Green Analysis of Individual Rooms by Lighting. Each room identified with a Green box in the left column uses less than half of the average W/person of the building. A Red box indicates using more than double the average, while Yellow is in between. The second column compares each room to rooms of a similar type. Rooms with Red in both columns are identified as rooms that may be using too much energy.

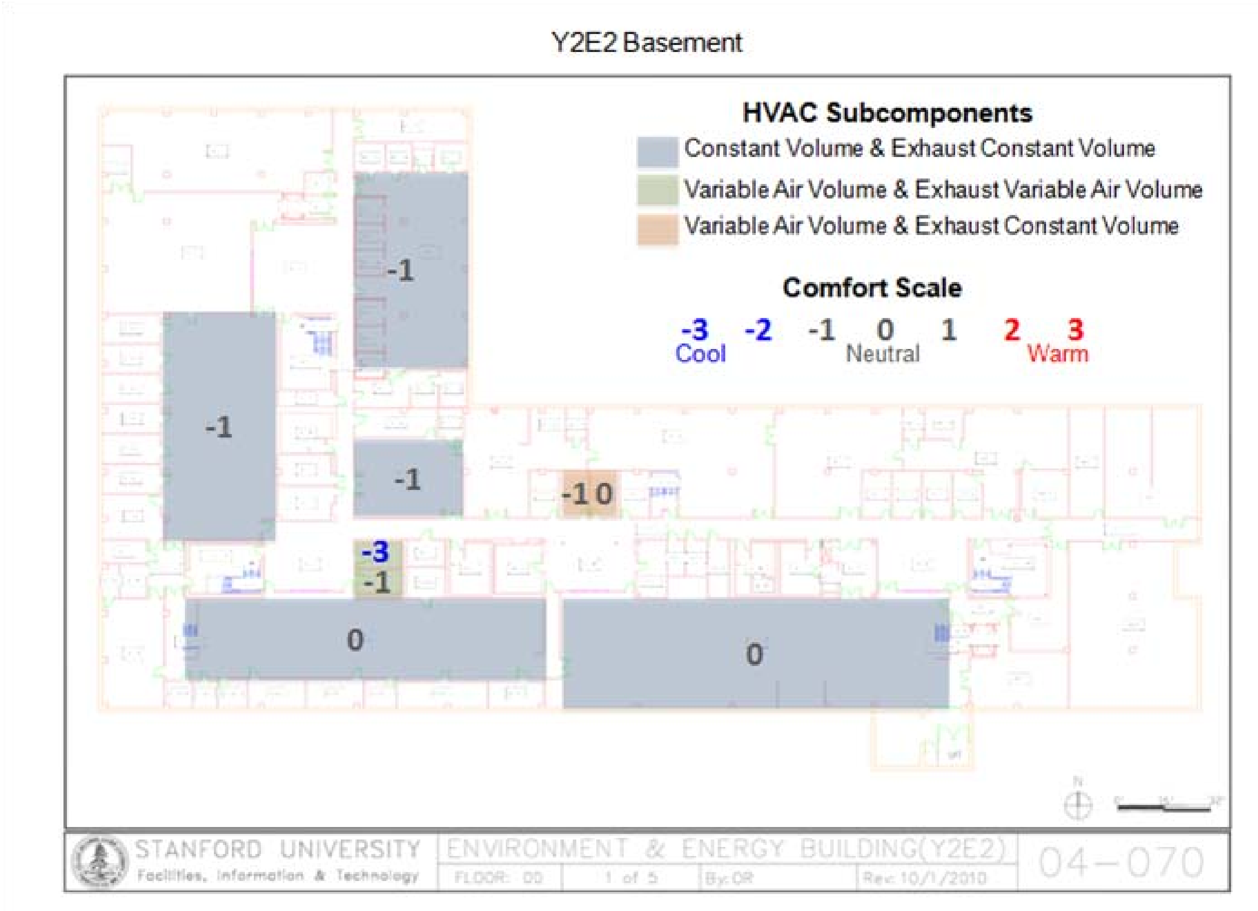
Qualitative Energy Assessment: Comfort & HVAC Assessment

PMV Calculations

Mechanical Systems Calculated Average Based on Surveys											
	Subcomponent	Total Surveys	clo	Air Temp (°C)	Radiant Temp (°C)	Activity (Met)	Relative Humidity	PMV (Calculated from PMV calculator)	Comfort Survey Results	PPD (Calculated from PMV Calculator)	Operative Temperature (C)
Whole Building		109	0.60	22.65	23.44	1.13	52.5%	-0.50	-0.21	10.20	23.05
Basement Total		16	0.67	21.73	22.41	1.27	54.9%	-0.20	-0.84	5.80	22.05
Basement	ECV, CV	9	0.71	21.82	22.20	1.40	53.4%	0.10	-0.50	5.20	22
Basement	VAV, ECV	3	0.51	22.25	22.81	1.10	63.7%	-0.80	-0.67	18.50	22.65
Basement	VAV, EVAV	4	0.69	21.27	22.57	1.10	51.8%	-0.70	-1.75	15.30	21.95
1st Floor Total		23	0.62	22.26	22.66	1.11	48.3%	-0.60	-0.35	12.50	22.65
1st Floor	CV	21	0.64	22.24	22.58	1.11	47.5%	-0.70	-0.33	15.30	22.4
1st Floor	EVC, CV	2	0.47	22.45	23.56	1.10	56.5%	-0.80	-0.50	18.60	23.05
2nd Floor Total	CV	42	0.59	22.88	24.11	1.06	54.6%	-0.40	0.06	8.30	23.5
3rd Floor Total	CV	28	0.56	23.13	23.65	1.16	51.4%	-0.30	-0.07	6.90	23.4
Naturally Conditioned Systems											
1st Floor		2	0.52	21.51	22.14	1.10	62.0%	-1.1	-0.50	30.5	21.8
2nd Floor		1	0.57	24.43	26.28	1.10	55.0%	0.2	0.00	5.8	25.35
3rd Floor		1	0.69	22.46	22.06	1.10	46.0%	-0.6	0.00	12.5	22.3
All		4	0.57	22.48	23.15	1.10	56.3%	-0.3	-0.25	6.9	23.85

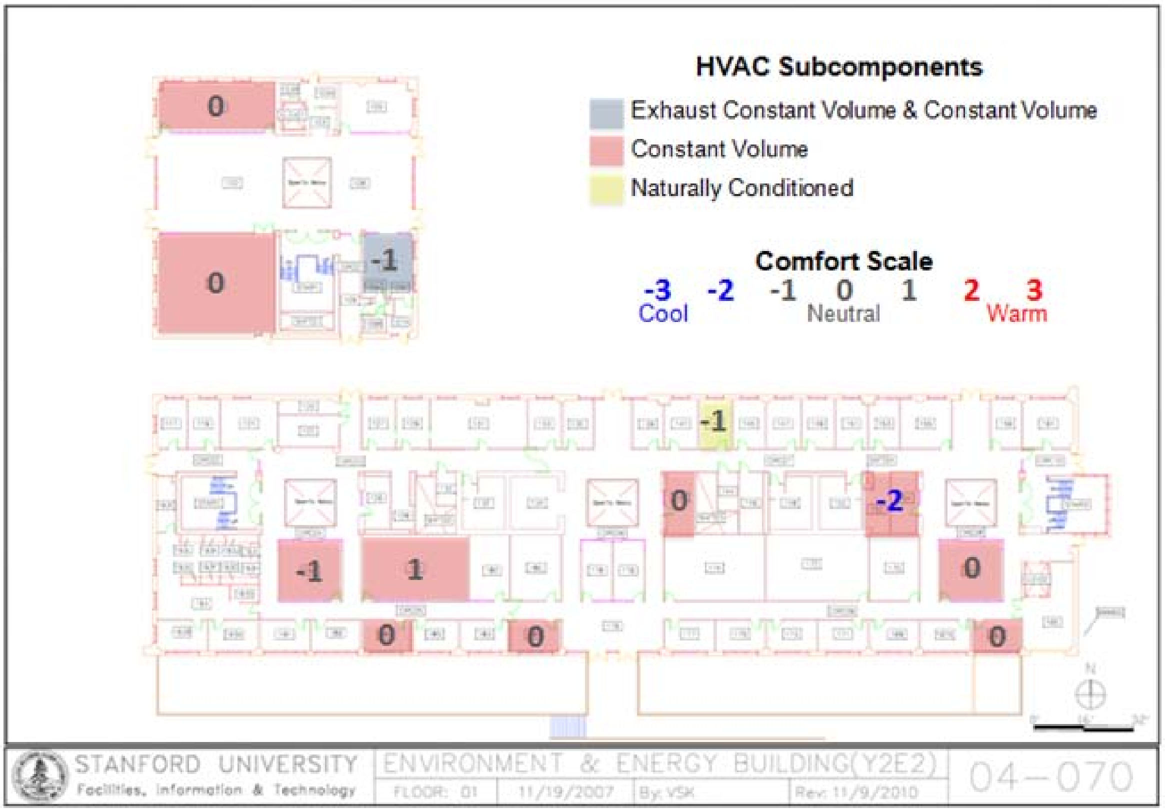
Figure B3: PMV Calculation. This figure illustrates the calculations derived from the PMV calculator. In this analysis, the data found from the PMV calculator was used to show graphical representations of thermal comfort. These graphical representations were used to show comparisons of rooms with similar HVAC subcomponents. This analysis provided evidence that was used to make conclusions on the effectiveness of the HVAC system on thermal comfort.

Floor Plans (Only rooms with complete surveys were mapped)



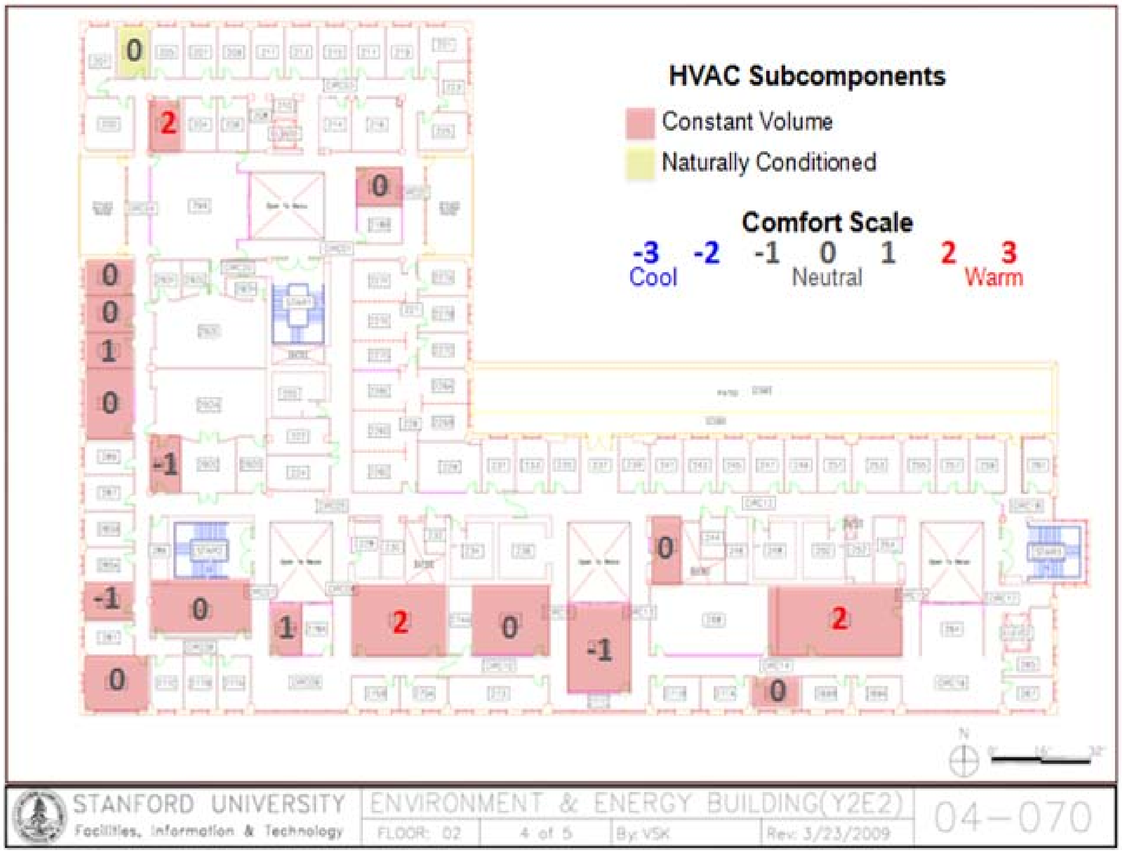
Rooms Surveyed: B07, B21, B26, **B23**, B25, B37, B39, B54

Y2E2 1st Floor



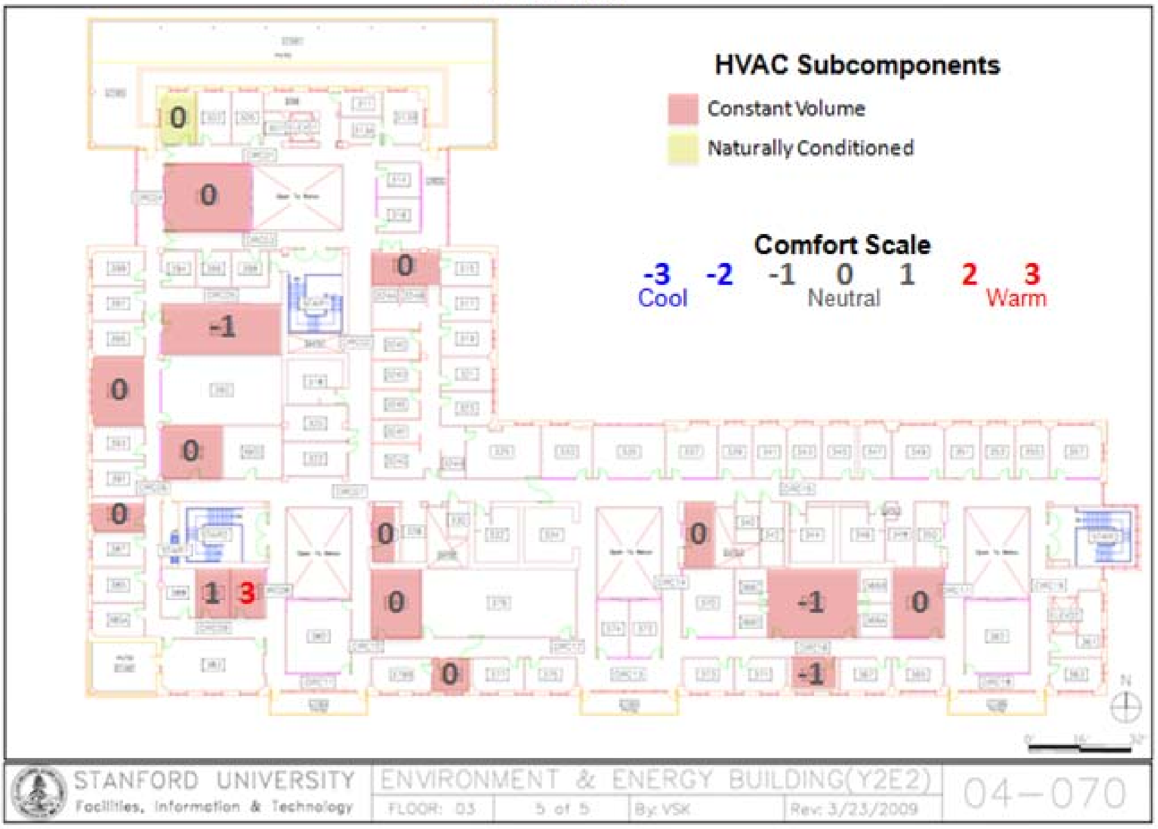
Rooms Surveyed: 101,107, 111, 140, 143, **154,** 164, 167, 181,184, 187,190

Y2E2 2nd Floor



Rooms Surveyed: **202**, 203, 218A, 242, **266**, 269C, 270, 274, **276**, 278B,279, 280, 283, 291, 292B, 293, 295, 297

Y2E2 3rd Floor



Rooms Surveyed: 300, 301, 326, 338, 364, 366, 369, 380, 384, 386, 389, 390A, 390B, 390C

Appendix C – Survey Documents

Y2E2 Energy Audit Survey Guide

General Thermal Comfort	Thermal Sensation Scale
[Ask using General Thermal Comfort descriptions, then record as number on the Thermal Sensation Scale.]	
Hot	+3
Warm	+2
Slightly Warm	+1
Neutral	0
Slightly Cool	-1
Cool	-2
Cold	-3

Discomfort Descriptions	Letter Codes
[Ask "Now" for discomfort at the moment. Ask "Ever" for discomfort felt in the room in the past year.] [Ask "Now" for PerTime survey. Ask "Ever" for OneTime survey.]	
Thermal Discomfort	
Too warm (match thermal sensation scale)	A
Too cool (match thermal sensation scale)	B
Local Thermal Discomfort	
Draft	C
Vertical air temperature difference	D
Warm/cool floors	F
Warm/cool ceilings	G
Cyclic temperature variation / Temp. variation with time	H

Clothing Insulation Values for Typical Ensembles		
[Note clothing being worn, then record as numerical value in clo.]		
Clothing Description	**Garments Included**	**I_{cl} (clo)**
Trousers	Trousers, short-sleeve shirt	0.57
	Trousers, long-sleeve shirt	0.61
	Trousers, long-sleeve shirt plus suit jacket	0.96
	Trousers, long-sleeve shirt plus suit jacket, vest, T-shirt	1.14
	Trousers, long-sleeve shirt plus long sleeve sweater, T-shirt	1.01
	Trousers, long-sleeve shirt plus long sleeve sweater, T-shirt plus suit jacket, long underwear bottoms	1.30

Skirts/Dresses	Knee-length skirt, short-sleeve shirt (sandals)	0.54
	Knee-length skirt, long-sleeve shirt, full slip	0.67
	Knee-length skirt, long-sleeve shirt, half slip, long sleeve sweater	1.10
	Knee-length skirt, long-sleeve shirt, half slip, suit jacket	1.04
	Ankle-length skirt, long-sleeve shirt, suit jacket	1.10
Shorts	Walking shorts, short-sleeve shirt	0.36
Athletic	Sweat pants, long-sleeve sweatshirt	0.74

Occupant Activity Level	**Metabolic Rates (met)**
[For offices, assume seated office work, specify otherwise.] [For other spaces, specify room activity.]	
Resting	
Reclining	0.8
Seated, quiet	1.0
Standing, relaxed	1.2
Office Activities	
Seated, reading or writing	1.0
Typing	1.1
Filing, seated	1.2
Filing, standing	1.4
Walking about	1.7
Lifting/packing	2.1
Meeting/Conference/Class/Studio Room Activities	
Meeting	
Presentation (projector use)	
Class, Lesson	
Studying	

Space Temperature Measurement Locations	
[Check appropriate box based on whether occupant is seated or standing.] [Measure space temperature at respective height levels for seated or standing.]	
Occupancy Determinable	At workstation or seating area
Occupancy Undeterminable	Center of room
	1.0m inward from center of each wall
Height Levels (seated)	Ankle level (0.1m = 4in) Waist level (0.6m = 24in) Head level (1.1m = 43in) Ceiling level (surface temperature)

Height Levels (standing)	Ankle level (0.1m = 4in) Waist level (1.1m = 43in) Head level (1.7m = 67in) Ceiling level (surface temperature)

Absolute Humidity Measurement Locations
One location for each occupied zone in each occupied room/HVAC controlled zone
Can assume to have low variation within the spaces

Light Fixtures						
[Determine lamp type. Refer to spec sheets in O&M Lighting Manual for drawings and specifications.]						
Lamp	**Diameter (in.)**	**Watts**	**Lumens**	**Lumens/ Watt**	**CRI**	**Lifetime (hrs)**
T-12	1.5	34	2650	78	60+	20,000
T-8 standard	1	32	2800	88	70+	20,000
T-8 high performance	1	32	3100	97	80+	24 000
T-8 high performance	1	28	2750	98	80+	24,000
T-5 standard	5/8	28	2900	103	80+	20,000
T-5 high performance	5/8	28	3050	109	80+	20,000
T-5HO (high output)	5/8	54	5000	93	80+	20,000

Frequency Sensor / Ballast Checker	
Type	*Indicator Light Color on Ballast Checker*
Magnetic	Red
Electric	Green

Basic Energy Consumption Characteristics for Electrical Equipment	
For reference only and to check plugload measurements with a basic estimate.	
Type of Equipment	**Estimated Wattage**
Desktop Computer	175
Laptop Computer	70
Copy Machine (small desktop)	800
Fax Machine (thermal)	400
Fax Machine (inkjet)	125
Monitor (CRT)	85
Printer (inkjet)	40
Printer (Laser)	250
Router/DSL/Cable Modem	6
Coffee Maker (drip style-brew cycle)	1500
Coffee Maker (drip style-wam cycle	70

Coffee Maker (percolater style-brew cycle)	600
Coffee Maker (percolater style-warm cycle	80
Small trash compactor	400
Microwave Oven	600-1200
Toaster Oven	500-1500
Dehumidifier	50
Air Conditioner- Window Style (6,000 btu/hour)	800
Air Conditioner -Window Style (10,000 btu/hour)	1350
Air Conditioner -Window Style (12,000 btu/hour)	1585
Air Conditioner -Window Style (14,000 btu/hour)	1875
Air Conditioner -Window Style (16,000 btu/hour)	2125
Air Conditioner -Window Style (18,000 btu/hour)	2395
Air Conditioner -Window Style (20,000 btu/hour)	2675
Central Air Conditioner (1 1/2 Ton)	2250
Central Air Conditioner (2 Ton)	3000
Central Air Conditioner (2 1/2 Ton)	3750
Central Air Conditioner (3 Ton)	4500
Central Air Conditioner (4 Ton)	6000
Central Air Conditioner (5 Ton)	7500
Heat Pump (2 Ton)	3200
Heat Pump (3 Ton)	4800
Heat Pump (4 Ton)	6400
Heat Pump (5 Ton)	8000

Figure C1: Audit Guide

Y2E2 Energy Audit Survey [Offices / Labs Every Time]					
Date:		Time Start:		Time End:	
Building: Y2E2		Floor(s):		Atrium:	
Overall Conditions					
Sky:		Outside Air Temp Start:		Outside Air Temp End:	
Notes:		Relative Humidity Start:		Relative Humidity End:	
Location:		**Location:**		**Location:**	
Occupancy	Lights On/Off	Occupancy	Lights On/Off	Occupancy	Lights On/Off
Time:					

Figure C2: EveryTime Audit Survey for Offices and Labs.

Y2E2 Energy Audit Survey [Other Rooms / Building Spaces Every Time]			
Date:		Time Start:	Time End:
Building: Y2E2		Floor(s):	Atrium:
Overall Conditions			
Sky:		Outside Air Temp Start:	Outside Air Temp End:
Notes:		Relative Humidity Start:	Relative Humidity End:
Location:			
Occupancy	Lights On/Off	Equipment On	

Figure C3: EveryTime Audit Survey for Building Spaces.

Y2E2 Energy Audit Survey [Offices / Labs One Time]			
Date:		Time Start:	Time End:
Building: Y2E2		Floor(s):	Atrium:
Overall Conditions			
Sky:		Outside Air Temp Start:	Outside Air Temp End:
Notes:		Relative Humidity Start:	Relative Humidity End:
Location:			
Occupancy	Occupied Hours	Notes:	

Fixture Type	Ballast Type	# Units	Hrs/day	Illuminance (fc) with lights			
				On:			
				On:			
				All on:		All off:	
Equipment, Model	Mode	# Units	Hrs/day	Power (Watts)		Current (Amps)	
				Measured	Nameplate	Measured	Nameplate

Figure C4: OneTime Audit Survey.

Y2E2 Energy Audit Survey [Rooms Per Time]					
Date:		Time Start:		Time End:	
Building: Y2E2		Floor(s):		Atrium:	
Overall Conditions					
Sky:		Outside Air Temp Start:		Outside Air Temp End:	
Notes:		Relative Humidity Start:		Relative Humidity End:	
Location:					
Occupancy	Lights On/Off	Comfort (-3 to +3)	Clothing (in clo)	Activity (if other than seated office)	
Discomfort (letter codes)		Floor Temp (°F)	Desk Temp (°F)	Ceiling Temp (°F)	Rel. Humidity (%)
Now:					
Occupant Level	Space Temp. (°F) (by height level)			Thermostat	
☐ Seated	Ankle level	Desk level	Head level	Dial (-4 to +4)	CO2 level (ppm)
☐ Standing					
Notes:					
Time:					

Figure C5: Once Per Time Slot Audit Survey.