Reducing electricity consumption in multi-tenant commercial buildings: The impact of behavioural change

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Abstract

Pressure to conserve energy in commercial buildings is increasing in order to meet nationwide greenhouse gas reduction targets. In the commercial building sector, tenants often receive yearly electricity bills based on their occupied floor area and not actual electricity consumption. This results in diffused responsibility and no incentive to curtail electricity consumption. In this thesis, two office towers in Eastern Ontario installed submeters to accurately bill tenants for their electricity use. This study uses a competition, in-person tenant meetings and suite walkthroughs and submetering paired with data measurement and verification to assess the effect of the interventions on energy use behaviour. Results demonstrate that commercial tenant electricity use, between tenants, is highly variable; that tenant loads are lower than ASHRAE design values; and, that tenant plug loads are not fully shut off at night. The project concludes, 15 months after implementation, that submetering does result in tenant electricity reductions.

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Glossary of Terms

Bulkmetering	The measuring of electricity consumed where there is less than one meter per tenant, with billing divided proportionally based on leased floor area.
Cumulative Sum (CUSUM)	A CUSUM control chart is a statistical tool used to determine if a change has occurred in sequential data that has a known baseline.
Diversity Factor	A ratio of demand, relating the maximum demand of individual system components to the maximum demand of the whole system.
ENERGY STAR	An energy rating system that can be applied to office equipment and buildings.
Energy Use Intensity (EUI)	A measure of electricity consumed over one year per unit of floor area.
Interquartile Range (IQR)	A measure of variability that captures the range spanning from the lowest to highest quartiles of the data set.
Submetering	The measuring of electricity consumed where (ideally) there is at least one meter per commercial tenant for the purpose of fair billing.

1. Introduction

In Canada, commercial energy consumption has grown by 37% since 1990 and 49% of total commercial greenhouse gas emissions come from building electricity use [1]. Targeting conservation in the commercial building sector can therefore be an important step towards reaching Canada's 30% greenhouse gas reduction goal by 2030 [2].

In a commercial building, there are many opportunities to reduce electricity consumption. Some of the most impactful and commonly applied energy reduction strategies are technological interventions, including upgrades to base building equipment, such as efficient chillers, or switching to variable frequency drives (VFDs) for ventilation. These equipment upgrades come with robust estimates of how much electricity will be saved and can easily be assessed for their return on investment.

In a high-performance commercial building that has already completed all financially viable base building upgrades, the next step to reduce electricity use is often unclear. As the base building operations become more efficient the portion of this electricity end use, compared with total use, diminishes. The result is a higher electricity end use portion consumed by building tenants. The base building end use includes all equipment required to operate the building, controlled by operations management, including elevators, common space and emergency lighting, ventilation and chillers; the tenant end use includes all plug, light and equipment loads that are not included in the base building end use, and are directly controlled by tenants. As the tenant end use fraction increases, it becomes a more viable target for electricity reduction strategies. In Canada, the typical commercial building already uses more than half (57%) of its yearly electricity consumption on tenant end use [1]. Therefore, focusing energy reduction messaging on commercial tenants is an important next step to conserve energy.

Investigating the effectiveness of behavioural interventions on electricity consumption is important in a multi-tenant commercial setting, as tenants have significant control over their electricity use. Tenant behavioural change can include a wide variety of measures, from a one-time behaviour to a persistent change in office culture.

This thesis documents a case study on electricity consumption and the effect of multiple behavioural interventions focused on tenants and occupants, with the goal of energy conservation. First the thesis outlines current electricity consumption in the case study buildings. Then the impact of two behavioural interventions, the implementation of submetering and the gamification of energy reductions through a competition, are measured. The thesis is concluded with observations and challenges unique to a multi-tenant commercial setting and a summary of results.

1.1. Problem Statement

Office space has the fifth highest energy use intensity (EUI) of all building types in Canada, where building energy use is on the rise [3] [4]. Simultaneously, energy reductions are required to meet country-wide greenhouse gas targets [2]. Therefore, reducing electricity consumption in commercial buildings is an important component to reducing our environmental impact and reducing strain on the electrical grid.

This study aims to reduce electricity use exclusively through behavioural interventions in the context of a multi-tenant commercial building.

In multi-tenant commercial buildings, tenants are frequently bulkmetered, meaning tenants pay a fraction of total electricity use determined by the floor area they occupy. This means there is no individual tenant feedback on electricity use in the form of utility bills. Lack of individual electricity use feedback results in diffused responsibility and no monetary incentive to reduce consumption. Lack of individual tenant feedback is a common problem, where, in the US, only half of commercial tenants are financially responsible for their actual electricity use [5].

To combat the problem of excessive electricity consumption, tenants can be submetered, where their actual electricity use is recorded and billed directly to each respective tenant. The implementation of submeters is a change in billing scheme, but it is also an electricity conservation measure since individual tenants are expected to reduce long-term electricity use.

Although submetering can influence tenant behaviour change, it is difficult to predict how much and when electricity savings will occur. This study analyzed electricity consumption and post-submetering implementation for 15 months to assess whether electricity use reductions were occurring.

The tenant behaviour change that would lead to maximum electricity savings exists on two main levels: the tenant representative or management level and the employee level. The tenant representatives and management have the authority to make large and permanent changes in the office, whereas the employees have the ability to reduce electricity use through a persistent change in behaviour.

A challenge in a multi-tenant commercial building is effectively communicating and promoting energy reductions to all personnel to trigger behaviour change (Figure 1-1). In this multi-tenant context, a change to the submetering billing scheme may only be acknowledged by a few representatives for each tenant; therefore, an additional intervention is required to reach the employee and occupant level. This study uses gamification through an electricity reduction competition and incentivised draw to reach individual building occupants. This study analyzed changes to electricity consumption during a one-month competition to determine the impact of individual occupants.

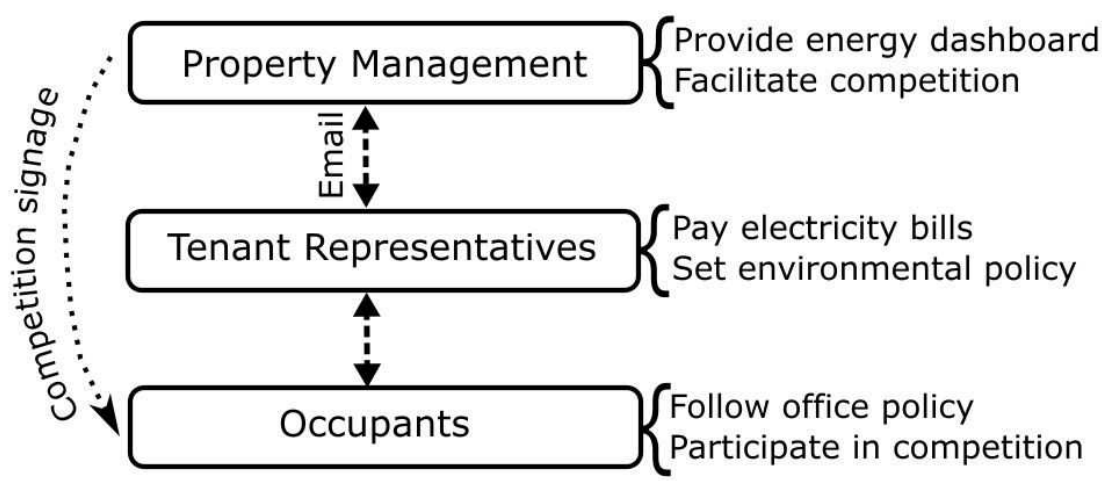


Figure 1-1: Hierarchy of electricity conservation in a multi-tenant commercial building, with arrows indicating lines of communication.

1.2. Research Questions

The research questions this thesis investigated include:

- What is a typical tenant electricity use profile?
- How does tenant electricity use compare to typical modelling assumptions?
- Does gamification of electricity reductions impact electricity use?
- Does submetering impact electricity use behaviour?
- What challenges to electricity reduction strategies exist in a multi-tenant commercial building?
- What submetering granularity is most appropriate for a multi-tenant commercial building?

1.3. Case Study

To answer the research questions, submeters were installed in two multi-tenant commercial office towers to collect tenant electricity consumption interval data. The resulting 15 months of interval data was analyzed to determine tenant electricity use profiles and to determine if electricity use changed over the study.

Data was collected from 14 commercial floors in Tower A and 18 commercial floors in Tower B, their floor areas are 1680 m^2 and 1790 m^2, respectively. Tower A and B are highly representative of Canadian commercial buildings, with similar electricity end use portions consumed by the base building functions, 43%, and leased tenant space, 57%, including light, plug and exceptional loads [1]. The full year electricity end use breakdown is presented in Figure 1-2, where heating energy is excluded, as it uses an alternative energy source in Tower A and B.

Determining if individual tenant end uses are representative of the building stock is uncertain, as plug, light, and exceptional loads are highly varied in research, for example combined tenant plug and exceptional loads can vary from 13% to 44% [6]. One of the case buildings, Tower B, has a combined tenant plug and exceptional load of 47%, which is slightly higher than the existing research. This is contrasted with research by Mercier and Moorfield [7] that determine plug loads alone are 23% of building end use, similar to Tower B with 25% of total use. The light load end use in Tower B is significantly lower, at 12%, than in a typical Canadian commercial building that consumes 22% of the total electricity use [1].

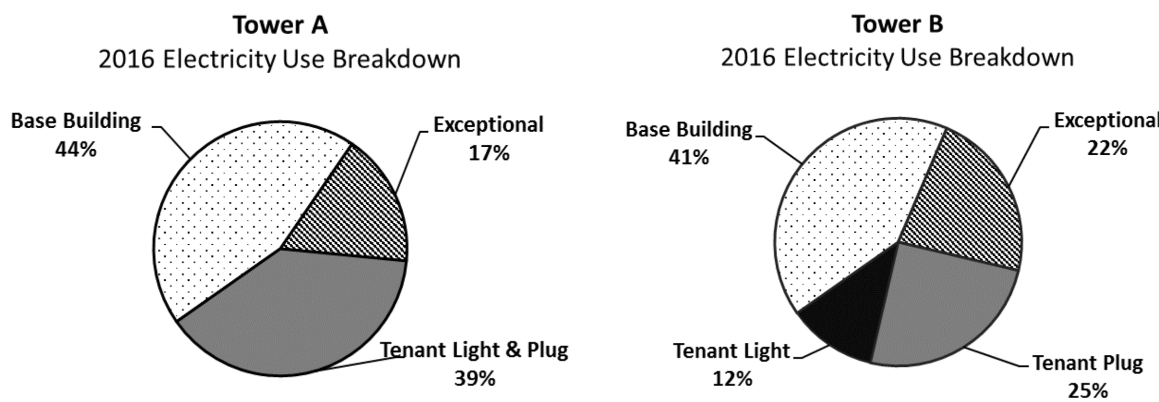


Figure 1-2: Electricity end use consumption for Tower A and B

The case study buildings, Tower A and B are suitable for this thesis because they are high performance buildings that have completed all practical and feasible base building upgrades. The next logical step to further reduce energy use is to isolate and target the tenant electricity consumption.

Both Tower A and B are certified LEED Gold for existing buildings and BOMA BEST Gold (formerly Level 3) and achieved an ENERGY STAR score of 96 in 2015. Due to these certifications, the base building load in this study is expected to be lower than other buildings of the same size. Tower A and B are under the same operations management, who have been focused on electricity reductions, resulting in a declining EUI over the past 10 years (Figure 1-3).

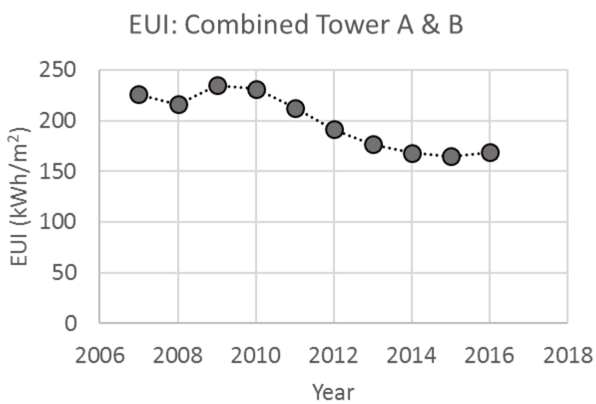


Figure 1-3: Historic EUI for Tower A and B

The implementation of submetering was incentivized financially by the local electricity distributor. This financial incentive has components that are both prescriptive, with a fixed rebate for each installed meter, and performance based, with an incentive that scales up with greater electricity reductions.

1.4. Literature Review

A brief literature review is provided here, while more in-depth literature reviews are paired with each subsequent main chapter. The scope of the current literature review includes a high-level overview of energy reducing strategies targeted at commercial tenants and occupants, from installing submeters, to electricity use gamification, to the provision of energy use feedback.

1.4.1. Commercial Electricity use

Commercial buildings are expensive to build and even more expensive to run. After 30 years, the costs to operate a building and pay employee salaries is five times more expensive than the cost to construct the physical building [8]. In order to reduce the life cycle cost of our existing commercial building stock, initial investments aimed at improving energy efficiency can make a significant long-term impact. After switching to efficient building operations, a larger portion of end use energy is consumed by occupants; therefore, focusing on tenant and occupant energy efficiency can result in significant energy reductions [9].

The implementation of submetering allows for building performance reviews that can track current energy consumption trends, electricity reductions and help identify electricity and cost saving interventions [10]. Submetering, and the associated financial responsibility for tenant electricity consumption, can result in motivation to reduce consumption and adopt pro-environmental behaviours.

Many strategies used to promote pro-environmental behaviours to reduce electricity use are received differently in the residential and commercial settings. Individuals in a residential context have a high level of control to adapt within their environment, have agency to change the environment to increase efficiency, and usually have financial responsibility for their utilities. In a commercial context, individuals typically have less ability to adapt within the work environment, no ability to change the environment, and no feedback or financial responsibility for their utilities. When comparing these two settings, social modelling, where individuals imitate the pro-environmental behaviours of others, an effective behaviour change strategy, has greater success in a residential context over a commercial context [11]. In an office, prompting pro-environmental behaviours and providing electricity use feedback are more effective than in the residential setting [11].

The response to submetering on the tenant level may be different in a rented suite than in an owner-occupied building. An owner-occupied building would be highly motivated to implement energy saving measures at every level of the company in order to get a return on investment for the upfront cost of submetering. In a tenant occupied building, the tenant may not want submetering or may not pay the upfront cost for installation, so they can have varying levels in engagement and commitment. In addition, a standard commercial lease acts as a significant barrier to tenants working alone or with property management to reduce electricity consumption [12]. The challenges to reducing electricity use in a commercial tenant suite are: leases normally do not encourage reductions, lack of effective communication between property management and tenants, uncertainty over tenant responsibility and the distribution of cost reductions from pro-environmental actions [12]. These challenges are especially noted in multi-tenant buildings, where many tenants have competing interests, and where a building investment from property managers or change to billing scheme will affect tenants unequally [12].

1.4.2. Occupant And Tenant behaviour

In the design of new office buildings, energy use can be predicted by models, but once occupied, buildings usually underperform by consuming greater electricity than predicted, by as much at 60% [13]. A significant component of the performance gap can be attributed to poor model assumptions, wasted electricity and tenant behaviour, for example, longer occupied hours correlates to higher energy use [13], [14].

Both individual employees and management contribute to overall occupant variability. Management can choose to remove vending machines or have computers automatically shut down at night. Management can also choose renovation priorities, such as choosing between expensive finishes and furnishings or motion sensing light switches and efficient LED fixtures. Individuals can shut off personal printers, lights, electronics, as well as communal equipment, coffee machines and hallway lighting.

When targeting energy savings, there are many options to investigate in a commercial office setting. Some options are a one-time behaviour from the tenant, such as an investment in efficient equipment, where others rely on individual employees switching to new behaviours permanently, and many interventions require the participation of both parties.

One example that requires engagement from both tenant and employees, is the switch to efficient office equipment. The use of Energy Star office equipment can reduce energy use, primarily through the use of power management, where equipment will automatically enter a low power mode [15]. The positive effects of purchasing efficient equipment may not fully be realized since the power management settings can be overridden manually by users and automatically in computers by operating systems [15]. Therefore, offices should be encouraged to both purchase energy efficient appliances and workers should be educated and prompted on maintaining and using the energy efficient settings [16].

Another example that relies on both individual employees and management to reduce energy is computer shut down procedures. Computers and displays account for almost 40% of the annual energy consumption of office building plug loads [17]. After hours 64% of desktop computers remain on, where only 6% of computers left on enter a power management mode [15]. This is contrasted with monitors, after hours 82% are left on and 75% of these enter a power management mode [15]. By automating office shut down procedures, electricity savings can reach 20% on a weekday, and up to 38% on a holiday [18]. The effect of leaving equipment running after-hours on energy consumption is compounded by the associated heat generation. When a space is actively cooled, one kW of power drawn by office equipment can result in an additional associated HVAC load between 0.2-0.5 kW [17].

1.4.3. Submetering

The submetering of tenant electricity use is increasing in popularity and recently has become part of local and federal legislation that encourages its use. In Seattle, commercial buildings over 1858 m^2 require metering on all end uses, including tenant light and plug loads [19]. In Australia, submetering is promoted through the Australian Building Energy Efficiency Disclosures Act, where submetered tenant loads and base building loads are rated and can be used as a leasing marketing tool [20].

Submetering in commercial buildings, paired with an electricity use feedback system, can effectively bring together tenants, operations management and owners, to work towards the same goal, energy reductions [21]. In a review of US state-level commercial office electricity demand, a one percent increase in tenants with submetered billing schemes corresponded with an equal, one percent, reduction in electricity use per capita [5].

Submetering alone, without any tenant billing or engagement can yield impressive results; the submetered electricity data paired with the building automation system (BAS) can help detect and correct operations problems, therefore minimizing wasted energy by up to 20% [22].

When the submetering feedback and costs are passed on directly to tenants there is incentive to consider energy reduction strategies as any return on investment (ROI) will directly benefit the tenant. For example, tenants may choose to install occupancy controlled lights, which have an electricity savings potential of 20% of lighting end use and payback period between one and five years [23].

For businesses, the cost of leasing space paired with operation and maintenance is small, around three percent, of the total cost to facilitate the work completed in the building, where the main cost is worker salaries [8]. Since the cost of the building is relatively low for businesses, the building comfort is often of higher priority than electricity conservation, especially since worker comfort is related to higher productivity.

1.4.4. Occupant Education

Education can be leveraged as a tool to create the desired behaviour change in office tenants and occupants, provided information can outline both opportunities and motivational reasons for positive change.

Spence et al. [24] found that encouraging pro-environmental behaviour change is most successful when the benefits are framed as CO_2 emission reductions opposed to kWh reductions or cost savings. Displaying electricity use reductions in equivalent emissions is more effective than costs, since the cost reduction of each individual behaviour change may be extremely small and not seem worth it, especially if prices of electricity are rising faster than behaviour change can mitigate [25]. In addition, the CO_2 emissions and environmental framing can result in spillover effects, where broad behaviour change can occur, not just the targeted changes in the study [24].

Using an information-only approach to promote electricity reduction in commercial offices has limited effects. In a residential study, Seligman and Darley [26] found that education paired with electricity feedback resulted in a 10.5% greater reduction than education alone. In an office study, no change in electricity was observed when education based emails were sent to employees as part of an information only energy reduction strategy [27].

1.4.5. Gamification

After individuals are given education and monetized energy use feedback to promote energy efficiency, they are no more likely to engage in energy reducing behaviours, especially if the information is not novel and behaviours are not based on financial motivators [16], [28]–[30].

Adding game elements to facilitate participation in new, pro-environmental behaviours may result in greater long-term behaviour change. Gamification of electricity reductions and behaviour change can take many forms, from goal setting, to social media style interfaces, to ranking energy performance, to competing against coworkers, to creating achievement points for every behaviour. By using gamification to promote participation, it can create the sense that energy efficient behaviour is the social norm, which can be a powerful tool to engage participants [30].

When participants pledge to complete an energy efficient behaviour change, they are more likely to follow through with the commitment [11], [16]. A computer power-off program, by the Urban Sustainability Director's Network, managed to increase the percentage of computers shut off at night from 58% to 72% by communicating with individuals via email, and with in-person written commitments that were affixed to the monitor as a prompt [16].

Feedback during a competition is useful to participants, both when results are compared to others and when feedback is publicly displayed [31]. Feedback on its own does not guarantee that an office will change its behaviour, it is more effective when it is used to track performance via an end game or goal, such as reducing the electricity bill or performance in a competition [16].

In a review of gamification studies of varying size and duration, electricity reductions of 5% are observed, where some programs have even higher savings [31]. Higher savings are typically associated with programs that go beyond behaviour change and encourage the purchase of energy efficient appliances and equipment.

Simply promoting energy reductions is not enough for a successful energy conservation strategy. Some individual behavioural changes must be identified and targeted so that participants feel control over their personal energy use [29]. Reminders within the office that are easily understood and promote the continuation of energy efficient behaviours are helpful as individuals tend to forget newly learned behaviours [16]. This is especially useful in offices where employee turnover is high, in order to pass on positive behaviours.

1.4.6. Data Presentation

The electricity use data should be presented clearly, concisely and with actionable items in order to encourage and facilitate electricity reductions.

One common data presentation method is through the use of web based energy dashboards. Unfortunately, these dashboards are used by very few consumers, but when leveraged the electricity use data results in reductions [32]. These findings were replicated by Jain, Taylor and Peschiera [33], where the number of energy dashboard logins are negatively correlated with energy use and presenting a comparison with previous electricity consumption results in higher logins.

1.5. Thesis Layout

This thesis is divided into three main topics centered around the implementation of submetering in the case study buildings.

The first topic, Chapter 2, analyzes the state of electricity consumption in Tower A and B. This electricity consumption is compared between individual tenants and to conventional assumptions of commercial electricity use. The goal is to determine if typical electricity profiles exist in the case study buildings, and if so, what are the profiles. This chapter is an in-progress publication and has been accepted with revisions as *Office building plug and light loads: Comparison of a multi-tenant office tower to conventional assumptions* in *Energy and Buildings*.

The second topic, Chapter 3, follows a one-month electricity reduction competition. This competition aimed to gamify electricity conservation behaviours and provide greater awareness of energy efficiency to all occupants and tenant representatives in the case buildings. This topic discusses the challenges and successes of promoting efficiency in a multi-tenant commercial building.

The third topic, Chapter 4, measures the effect of submetering on electricity consumption, 15 months after implementation. Two different methodologies are used to quantify the effect of submetering and the benefits and uncertainties of each method is discussed.

Finally, in Chapter 5, the lessons learned from each of the three topics concerning submetering of electricity are discussed. The discussion is formatted with the goal of providing relevant electricity consumption information targeted at the three main stakeholders in a commercial building environment, the property management, tenant representatives and the occupants.

The thesis concludes in Chapter 6 with a summary of the research questions paired with results. The conclusion also includes the main research contributions and recommendations for future studies that target electricity conservation within the context of a multi-tenant commercial building.

2. Office Building Plug and Light Loads: Comparison of A Multi-Tenant Office Tower to Conventional Assumptions

2.1. Introduction

In North America, the consumption of energy in buildings is increasing at a rate of 1.9% per annum [3]. Concurrently, many electricity distributers are in the process of phasing out carbon-intensive generation plants, such as coal burning facilities, to meet the United Nations Framework Conference on Climate Change (UNFCCC) Conference of the Parties 21 (COP21) goal to keep global warming below 2°C [34], [35]. A greater understanding of how this energy is being used can inform designers, operators, tenants and owners on where energy conservation measures will trigger real change.

In Canada, office space has the fifth highest energy use intensity of buildings at 333 $kWh/m^2 \cdot year$, after food stores, hospitals, nursing homes and hotels [4]. Offices can be a strain on the electrical grid, especially in summer with air conditioning driving peak electricity demand, where 78% of Canadian offices use electricity for space cooling, the remaining offices are equally divided between no space cooling and alternative energy sources [4], [36]. High plug loads caused by computers, printers, small servers, and kitchen appliances contribute to overall office electricity use and can be a major driver for cooling loads, compounding the need for office energy reduction [37].

Reducing electricity use in offices can be a challenge for individual tenants who may only receive electricity use feedback once per year. Many offices do not have adequate metering to analyze wasted energy, creating a challenge to identifying the most effective energy saving opportunities. Currently, only half of commercial tenants in the US are directly responsible for paying for their electricity use, this is due to the lack of installed submeters, and in some regions, due to electricity billing legislation [5]. Fortunately, regulations that encourage commercial submetering are becoming more widespread; in the US, submetering is required on all federal buildings and in the EU, submetering is encouraged in all new and renovated buildings [21]. Current regulation is transitioning towards mandatory end use metering in all public and private buildings. For example, in Seattle, commercial buildings over 1858 m^2 require metering on all end uses, including tenant light and plug load metering [19].

Research results on typical commercial energy use is highly varied. Office building total energy use intensity has been measured to range by a factor of 10, from 100 to 1000 $kWh/m^2 \cdot year$ [38]. Another study, focused solely on high performance buildings found energy use varied by a factor of six in the US and a factor of four in the EU [39]. Occupancy levels are a significant driver of variation between buildings; at the building level, increased occupancy results in a higher EUI but lower energy per occupant [40]. Office energy use intensity can vary depending on a number of additional factors, including the building's occupied hours, activity type, climate zone, height and size [4]. Climate significantly influences the variance in energy use, a result of space conditioning; this is indirectly controlled by tenants through temperature setpoint requests and hours of operation. Li and Hong [39] found that buildings in a cold climate (ASHRAE climate zones 6-7) on average perform worse at 184 $kWh/m^2 \cdot year$ than in a hot climate (ASHRAE climate zones 1-3) with an average of 126 $kWh/m^2 \cdot year$.

Comparing existing research on commercial electricity use can be a challenge due to varying sample sizes, observation periods and granularity of data. Some studies determine electricity use through surveys, calibrating self-reported equipment use patterns [41], [42]. Other studies collect electricity use on a few devices or individual offices to generalize [18], [37], [43], [44]. Manual data collection methods, including spot checking and observing equipment usage can collect only an instance of office electricity use [45], [46]. Other studies have large data sets over years, but only have building level energy use that yields little insight to daily office electricity use [4], [47]. Some existing research focus on only one type of office, such as academic or government buildings [43].

Plug load electricity is variable in an office setting and typically accounts for a significant portion of end use, from 13-44% [6]. In a study on small offices, plug loads accounted for 23% of the total office energy use, and of this, 69% is computers, 17% equipment, 9% monitors and 5% other [7]. When analyzing individual private offices, Gunay et al. [43] found that plug loads varied by a factor of 40, between 10 individuals, due to chosen equipment and usage patterns. In an office setting, individual electricity use patterns can differ wildly, but when individual behaviours are aggregated, load profiles converge towards a consistent usage schedule [44]. During typical office hours (9:00-17:00), there is low load diversity, where individual electricity consumption occurs simultaneously, and instantaneous electricity use nears peak demand [48].

When approximating office electricity use, building modellers typically use an average plug load equal to or less than 10.8 W/m^2 [42]. The 10.8 W/m^2 plug load is recommended by ASHRAE for offices, but this value is considered high to allow for future changes in space use [49], [50]. Research has suggested that this recommended plug load could be more than double observed plug loads [51]. Simply by having ubiquitous laptop use, the peak plug load could be as low as 2.7 W/m^2 [49].

In a study on energy modelling professionals and researchers, 44% of participants believe that discrepancies between modeled and actual building electricity use can be attributed to occupant behaviour [52]. A better understanding of office plug and light loads through post-occupancy evaluation (POE) can narrow the difference, to 6%, between modeled and actual use [13]. However, for building design, such detailed studies cannot be performed prior to construction if tenants and their equipment are undefined.

Occupancy schedule and behaviour is a major variable influencing plug and light loads [13]. In recent years working hours have become less consistent, with a quarter of employees working from home part-time, resulting in less predicable office load schedules [53]. Adding to the difficulty of estimating office plug loads, servers can now be found in over half of commercial office spaces, and they are often included with submetered plug loads [47]. However, such servers are often served by their own cooling system (separate from the main equipment). Thus, servers should not be included when using plug load predictions to size main building cooling equipment.

There are many energy saving opportunities in offices. One of the simplest is reducing plug loads during unoccupied hours or simply reporting the unoccupied end use fraction

[54]. These unoccupied loads can be as high as 75% of total plug load electricity [43]. Encouraging occupants to turn off computers can result in energy reductions in some offices, where 20-40% of computers do not get turned off, but for some employees this would interfere with remote desktop use [41], [43], [45].

Energy use behaviour can be identified with non-intrusive monitoring systems that determine the load type and behaviour based on electricity use patterns [55]. These monitoring systems can identify energy saving opportunities, for example, if equipment is being left on when not in use. In an office with plug load meters on all office equipment, 90% of interactions with these appliances were correctly predicted through automated interpretation of the interval data [44]. Recording occupancy data through sensors or Wi-Fi can give further insight into electricity use, but can infringe on occupant privacy [56], [57]. If the metering data is increasingly coarse then these systems have greater difficulty producing useful information [55]. To identify individual office equipment use, data sampling at one minute intervals may be required, with reduced accuracy at 10 minute intervals [58]. In addition, these systems must provide electricity use data as actionable items for office managers in order to effectively reduce energy [59].

Metering a whole building at the individual outlet level can be expensive and understanding every action in a workplace may be excessive when looking for significant energy reducing interventions. Metering at too low of a spatial resolution (e.g. building level) does not provide enough information or insight into energy use behaviour.

The objective of this paper is to provide new insights on predicting plug load schedules, magnitudes, and peak loads for use by building modellers, energy managers, and property managers – using a comprehensive high-resolution dataset from 32 office building floors. First, the methodology outlines the available data, submetering layout and high-level analysis methods. The results compare the case study buildings to the existing research and the discussion section makes further analysis based on anecdotal observations. This study provides new insights on whether existing plug load models reflect current office electricity use patterns and makes recommendations on the appropriate level of submetering for a commercial application.

2.2. Methodology

Commercial tenant electricity consumption was collected for a period of one year (01-01-2016, 31-12-2016) by Measurement Canada-certified meters (ensuring accuracy and reliability) located in two multi-tenant commercial buildings. Electricity consumption was recorded at 15-minute intervals and analyzed with both 15-minute and one-hour interval data.

2.2.1. Case Study Buildings

Energy use data was collected from two commercial office towers in Eastern Ontario, Canada. These office towers have 43 tenants including: financial institutions, engineering firms, marketing companies, TV broadcasting stations, law firms, accounting firms, technology companies, embassies and other office types. Both towers are certified LEED Gold for existing buildings, BOMA BEST Gold (formerly Level 3) and achieved an ENERGY STAR score of 96 in 2015. Due to these certifications, the base building load in this study is expected to be lower than other buildings of the same size. The building certifications do not directly affect the individual tenant electricity consumption, although it is possible that there is self-selection bias where a disproportionate number of environmentally conscious tenants choose to lease within Tower A and B.

For the two towers combined, the energy use intensity (EUI) is 169 $kWh/m^2 \cdot year$, including all building electricity use, but excluding heating energy (which is provided by natural gas). This is within ENERGY STAR's 5^{th} percentile for lowest energy use in office type buildings [14]. Since 2007, the complex has reduced its EUI by 25%, largely through upgrades to more efficiency heating, ventilation and air conditioning (HVAC) systems (Figure 2-1). These savings are greater than ENERGY STAR's observations, finding that buildings with energy benchmarking tools on average reduce their EUI by 2.4% each year [60]. As the performance of the case study buildings improves with time, yearly energy reductions get smaller. This is consistent with other research, indicating that buildings with low energy use have lower yearly reductions [60].

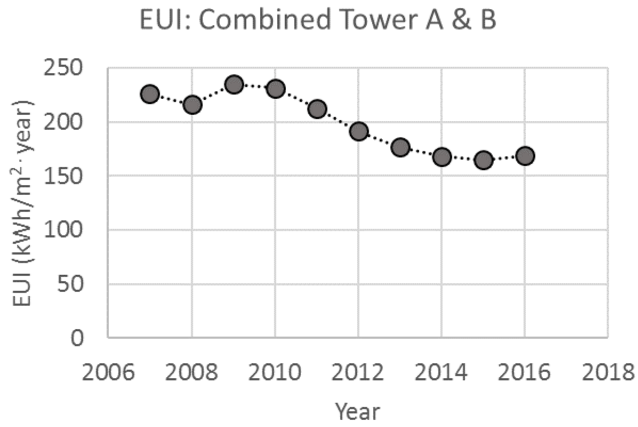


Figure 2-1: Building electricity EUI over time, without weather normalization.

2.2.2. Submetering Layout

These two office towers completed the installation of submeters in January 2016. The office towers are named Tower A and B and each floor is assigned a number to ensure anonymity to the businesses included in this study. The average floor area is given in Table 2-1, this includes the total leased area on each floor and varies based on hallway sizes, leasing agreements and floor plate size.

Table 2-1: Building data

	Commercial Floors	Average Floor Area [m^2]	Number of Commercial Tenants	Number of Commercial Submeters
Tower A	14	1680	12	25
Tower B	18	1790	31	52

The standard submeter layout in Tower A includes one submeter on each floor that records the combined tenant plug and light loads. Tower B has two submeters on each floor recording plug and light loads separately. The light load includes overhead lights for the whole floor, including hallways and bathrooms, and excluding task lighting and emergency lights that always stay on. Plug loads include anything plugged into receptacles for each floor. For tenants with exceptionally high loads, both on single- and multi-tenant floors, their suite is fitted with additional submeters to record specific equipment, this is denoted as the 'exceptional' load in this study. Exceptional loads correspond to servers or computing equipment and associated cooling equipment within tenant space or located on the roof. Small server closets that can operate with existing base building HVAC systems, for cooling, are not submetered individually. Zone level air handling units, condenser units and fans are metered separately from the tenant controlled loads and are part of the base building end use. Within the leased tenant space personal heaters are prohibited in the building, but personal fans are allowed in workstations. The building level HVAC system includes two metered chillers and motor control centers in each tower.

For the floors with multiple tenants that are not individually metered, the recorded electricity consumption was divided between the tenants based on floor area, for utility billing purposes. The tenant EUIs are the same for multiple tenants sharing submeters on a single floor, therefore these tenants are referred to as duplicates. In Tower A, there are three shared submeters; each shared meter serves two tenants, resulting in three duplicates. In Tower B, there are five shared submeters; three submeters serve two tenants and two submeters serve four tenants, resulting in nine duplicates.

2.2.3. Building Features

Tower A and B are part of the 6.1% of buildings in the Canadian commercial building stock with an energy conservation awareness program and an energy management control system for HVAC and lighting [4]. The base building lights in tenant suites turn off automatically at 19:00. Outside of business hours, lights must be manually triggered, and then will automatically turn off after two hours. This is expected to result in lower nighttime light load consumption compared to a typical commercial building.

2.2.4. Tenant Interaction

The 43 tenants in both commercial towers were informed of the new submetering billing scheme in February, 2016. Each tenant was given access to an internet-based energy dashboard to help track electricity use, costs and to compare use to other tenants. Of the tenants, 27 had in-person meetings with the researchers (authors of this paper) and property management to introduce the energy dashboard. Of the tenants that had in-person meetings, 19 had informal energy audits to discuss appropriate efficiency and energy reduction strategies.

2.2.5. Data Analysis

Total building and individual tenant electricity use was analyzed at one-hour intervals spanning the full year.

The peak power demand was assessed in both Tower A and B separately and over three different time intervals: yearly, monthly, and weekly. The yearly peak power was defined as the greatest one-hour electricity demand in 2016, and was determined for the total building load and for the tenant load, which includes plug and light end uses for each building floor.

The peak monthly demand is defined as the greatest one-hour electricity demand assessed for the total building load for each month of 2016. The peak monthly demand is a metric used by the local electricity distributor for calculating utility prices.

The peak weekly demand is defined as the greatest one-hour demand for each week of the year for each tenant-occupied floor, including plug and light end uses. The weeks are numbered starting with the first day of the year with each new week staring on a Sunday. Week one is excluded as it only contains two days. For each weekly peak, for each floor, the day type (e.g. Wednesday) and time (e.g. 13:00) of these peak loads were recorded to determine the probability that tenant peak loads will be concurrent.

2.2.5.1. Load Diversity

The load diversity is a function of time and is a measure of coincident tenant peak loads, it is determined with Equation (1).

$$Diversity\ Factor(t) = \frac{\sum Individual\ tenant\ yearly\ maximum\ demand}{Demand(t)} \qquad \text{Equation (1)}$$

where demand(t) refers to the demand over a one-hour period that the tenants are using simultaneously, whereas the summation of the individual tenant yearly maximum demand adds the maximum demand for each tenant, resulting in a diversity factor that is always equal to or greater than one. For example, if there are three tenants, each with a yearly maximum demand of 10 MWh, and the greatest yearly demand occurs when the three tenants are simultaneously using 10, 8 and 7 MWh, respectively, then the diversity factor is calculated by dividing 30 MWh by 25 MWh, resulting in a diversity factor of 1.2.

Typically, the diversity factor is only assessed at the time of maximum demand of the system; this is to determine the required system capacity relative individual peak loads. In this application, the diversity factor is also assessed for each one-hour interval to give measure to a typical day's tenant load diversity.

2.2.5.2. Average Electricity Demand Profile

A typical electricity demand schedule is determined for weekdays, Saturdays, Sundays and holidays. There are 10 holidays in Ontario during the data collection period (Jan-01, Feb-15, Mar-25, May-23, Jul-01, Aug-01, Sep-05, Oct-10, Dec-25, Dec-26).

For each day type, the average demand is taken across each one-hour period for the full year. This method is applied to each commercial floor in both buildings for the tenant plug and light loads. For Tower B, this method is also applied to the separated plug and light loads.

For each building, the range in demand is assessed for each hour as the difference between the lowest and highest consumption, for the average day on each commercial floor. The median demand profile for the building is taken as the average of each floor's typical day, calculated at each one-hour interval. The steps are as follows

1) For each tenant and each day type, the average demand is determined for each one-hour period to create full day profiles for each tenant. For example, the average demand is determined for Tenant A for all Sundays from 9 am to 10 am.

2) The demand profiles for each tenant are used to find the range in tenant demand. The lowest and highest demand for each day type and hour is recoded. For example, for Sunday from 9 am to 10 am, the lowest demand is from Tenant C and the highest demand is from Tenant B, this is the range.
3) The median tenant load profile is the median for each hour across tenants. For example, for Sunday from 9 am to 10 am, the median load for tenants A, B and C is the demand from Tenant A.

The average day for each tenant is assessed over the full year cycle. This method of averaging days is only applicable if like days (weekdays or weekends) are similar. The periodicity between weekdays was assessed with an autocorrelation of 15-minute power consumption for each tenant. When the data set for workdays is comparing adjacent workdays, the average autocorrelation coefficient is 0.851 across all tenants, ranging from 0.740 to 0.934. This indicates that workdays follow a repeating electricity use schedule. When weekends are included in the autocorrelation, each week is similar, with the highest correlation repeating weekly (0.824 first week, 0.787 second week).

This strong autocorrelation between workdays persists but trends towards zero over a period of two months, indicating some long-term variation. This variation can affect the precision of the average demand at each one-hour interval. To determine the variability, the inter-quartile range (IQR) is determined for each floor at each hour. This is used to confirm that the average demand schedule is showing typical daily energy use with a relatively small IQR during days and not an averaging of highly varied atypical energy use.

The average electricity demand profile is compared with existing profiles in the literature. The design demand for light and plug loads are determined by the ASHRAE building area method [50] as 10.8 W/m^2 for both load types and the hourly use profiles are determined to be similar to Deru et al. [61] profiles for small businesses.

2.2.5.3. Estimated Occupancy Schedule

Typical occupancy is estimated using the average daily profiles for each commercial floor. Occupancy is estimated based on electricity use data in order to test non-intrusive occupancy determination methods. In this building privacy concerns prohibit the use of occupancy sensors.

The mean arrival time is estimated as the greatest electricity increase between consecutive hours during the period from 5:00 to 10:00; the mean departure time is estimated as the greatest decrease between 16:00 and 23:00. For any floor with an estimated change in occupancy that falls on the time boundaries, the load profile is manually checked to ensure the change in occupancy does not occur outside the bounds. This method is applied to the combined tenant plug and light loads for both towers, and on the separated plug and light loads for Tower B.

2.3. Analysis & Results

This section includes additional analysis methods and presents the electricity use results for the tenants' total electricity use and floor level consumption patterns, for tenant controlled plug and light loads. This electricity use data from Tower A and B is compared with conventional assumptions of electricity use patterns, using ASHRAE design loads and schedules from Deru et al. [50], [61].

2.3.1. End Use

The electricity use patterns in Tower A and B are similar over the one-year span and the buildings have an EUI of 145 $kWh/m^2 \cdot year$ and 184 $kWh/m^2 \cdot year$, respectively. The portion of electricity consumed by tenants and the base building are also similar between Tower A and B, as seen in Figure 2-2. The base building load accounts for just under half of the yearly electricity use, including air conditioning, ventilation, pumps and fans, water heating, elevator operation, emergency lights, and lobby lights. The exceptional load indicates tenants with an atypical equipment load which is metered separately; this includes large servers and its dedicated cooling equipment. The tenant light and plug loads are tenant-controlled, they account for overhead lighting and office equipment, such as computers, within each commercial suite.

The base building electricity end use portion is consistent with the Canadian building stock, 43%, where building heating is excluded for comparison purposes [1]. In the Canadian building stock, light loads account for 22%, and tenant plug and exceptional loads account for 35% of end use [1]. Here, the Canadian building stock combined total of tenant controlled loads (light, plug and exceptional) are comparable to findings in Figure 2-2. The light load end use in Tower B is only 12% of total electricity, much lower than in the Canadian building stock.

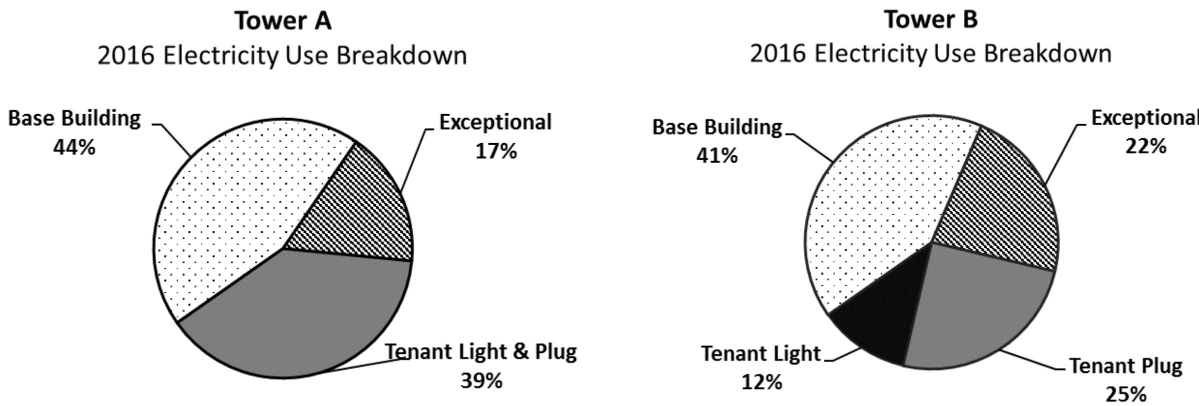


Figure 2-2: Electricity end use

2.3.1.1. Tenant EUI

This section on tenant EUI is the only section within this paper that analyzes electricity consumption by leased floor area, as opposed to individually submetered floor. The purpose of analyzing by leased area is to group electricity consumption by business, especially for companies that rent multiple floors or have exceptional loads. When analyzing the total tenant loads, including their plug, light and exceptional loads across all occupied floors, the tenants' EUIs vary widely (Figure 2-3). The resulting tenant electricity use can be grouped into typical office consumption and outliers. The outliers are labelled in Figure 2-3 and Figure 2-4; they are tenants that: are a TV station (outlier 1, 2 and 4), have a call center (outlier 3) and have computing equipment and servers (outlier 5). Outliers 2 and 5 are located in Tower A, whereas outliers 1, 3 and 4 are located in Tower B.

Annual electricity use across all tenant suites is weakly correlated to floor area, with a coefficient of determination of R^2=0.3085. When the five outliers and duplicate EUIs from multi-tenant floors are removed, the tenant electricity use is strongly correlated to floor area, R^2=0.9843. This shows that by omitting exceptional server loads, variation between tenants may not be extreme and therefore, the typical tenant electricity use could be generalizable. The slope of the best-fit line that excludes the outliers and duplicate EUIs from multi-tenant floors indicates that the typical tenant EUI is approximately 75.8 $kWh/m^2 \cdot year$. Annual electricity use is also correlated to design occupancy, R^2=0.8955, with a consumption of 1.36 MWh/occupant · year. When comparing occupancy with annual electricity use, outlier 5 based on EUI, no longer appears as an outlier in Figure 2-5, since the tenant has a very high occupant density.

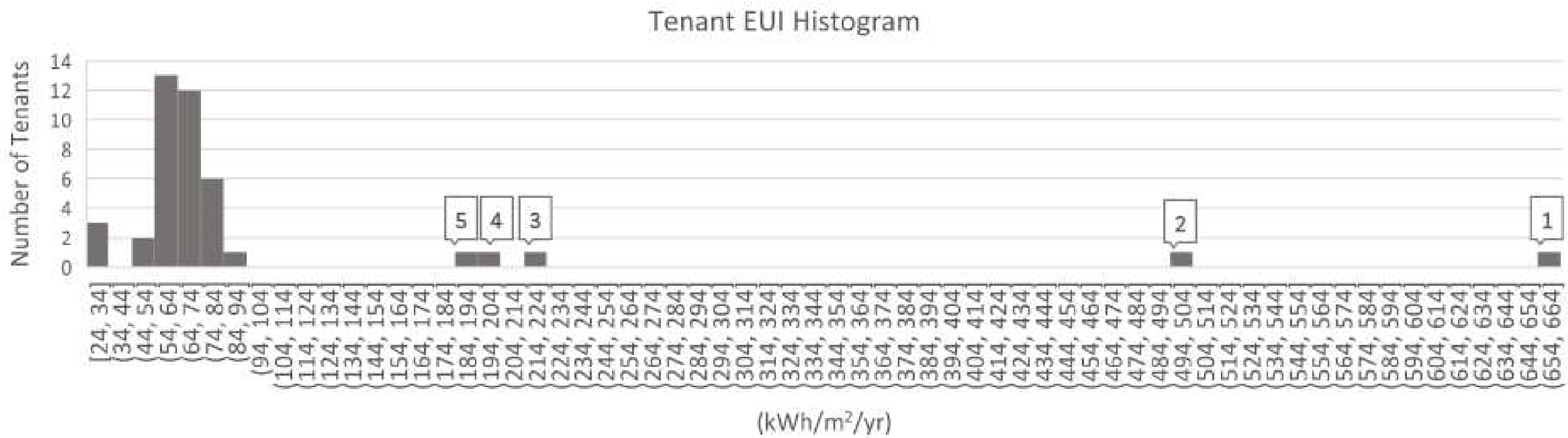


Figure 2-3: Tenant EUI, with five labeled high users.

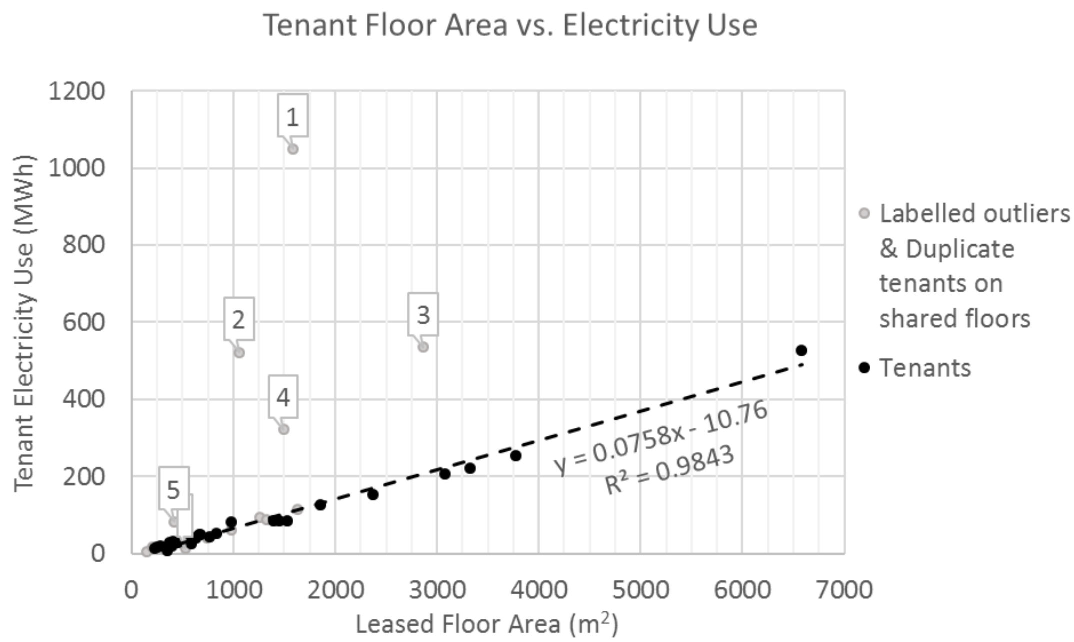


Figure 2-4: Tenant floor area versus annual electricity use, with numbered outliers. Tenants on shared floors with shared meters have the same EUI and are considered duplicates. There are three duplicates in Tower A and nine duplicates in Tower B, are separated from the linear best-fit.

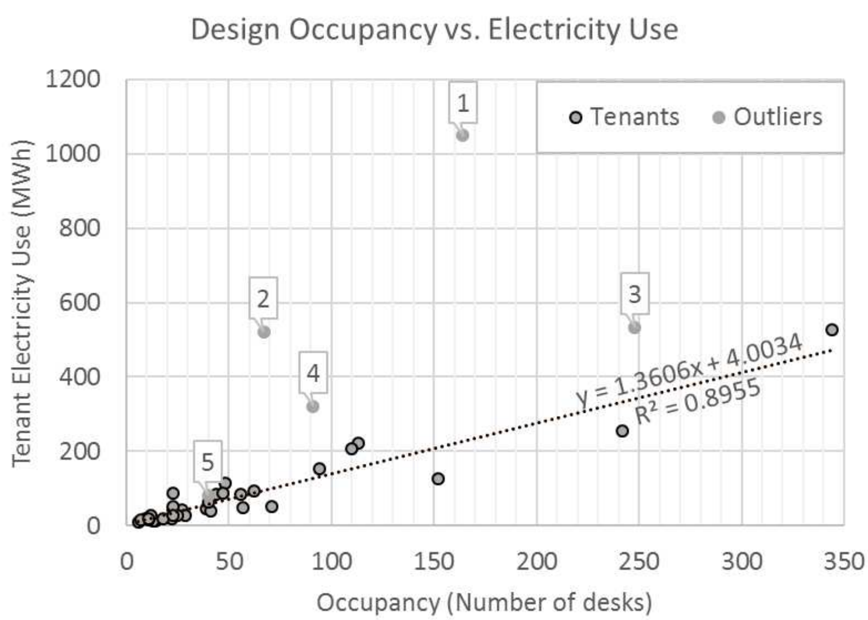


Figure 2-5: Tenant occupancy versus annual electricity consumption. The numbered outliers are based on EUI.

2.3.2. Peak Loads

Coincident tenant peak loads can cause an increase in electricity costs for the building as a whole because prices are affected by both total electricity consumption and peak demand [62]. Tower A and B use their interval meters to pay the fluctuating hourly electricity price determined by the Independent Electricity System Operator (IESO). The peak monthly demand determines the rates for auxiliary electricity fees (e.g. for maintaining transmission lines) added per each kW of demand, kWh of consumption, or as a fixed price, depending on the fee type [62]. Peak loads are analyzed to determine if peak building loads correspond with peak tenant loads. If tenant peak loads are a significant portion of building peak loads, then utility cost reductions are possible though targeting reductions or changing the time of tenant peak loads.

At the building level, Tower A and B had their highest demand for the year on June 20th at 12:00 and June 27th at 14:00, respectively. At the peak times, the base building load accounts for the majority of demand: 64% and 63% for Tower A and B. This instantaneous base building demand is significantly higher than the yearly base building end use, 44% and 41% for Tower A and B. At the peak times, the outdoor temperature and relative humidity (RH) is recorded at 31.2°C with 39% RH for Tower A, and 28.6°C with 62% RH for Tower B. Therefore, the main driver of yearly building peak loads is determined to be the air conditioning and ventilation load, not the tenant controlled load. This conclusion is further supported by the seasonal timing of the individual tenant yearly peak loads; only two of 32 floors have a peak occurring between May and

September (see Figure 2-6). The tenant controlled peak demand occurring outside of summer months could be influenced by providing improved occupant comfort, but since personal heaters are not permitted in the leased tenant space, a more likely explanation is that businesses are not fully occupied in summer months due to employee holidays.

The diversity factor is a measure to determine if tenant peak loads are coincident, with a factor of 1.12 and 1.09 for Tower A and B, respectively. These factors indicate that tenants are using a very high portion of their individual peak loads at the same time. Over the course of the year, calculated at hourly intervals, the average diversity factors are 2.45 and 2.18 for Tower A and B, meaning that the sum of yearly tenant peak loads, or maximum possible tenant demand, is more than double the average combined tenant loads.

To determine when instances of high demand due to coincident peak loads are occurring, the tenant weekly peak loads on each commercial floor are identified by day type and time. The probability that a tenant peak load will occur on a given week day or time is presented in Figure 2-7 and Figure 2-8 as a fraction of total weekly peaks, the number of weeks multiplied by tenant occupied floors.

For the tenant peak demand, all but two floors have lower yearly peak loads than the ASHRAE design values (Figure 2-9) [50], [61]. The highest loads, consumed during the “top 1%” of hours in the year, correspond to the peak 1.7 hours in each five-day business week, are on average 115% higher than the median load. For these commercial tenants, the difference between the peak 1% and median load is most likely a measure of daily equipment shut off procedures. Here the median load corresponds to a typically unoccupied period, so this metric indicates that a significant portion of daytime loads are being shut off for nights and weekends. These results are lower than the ASHRAE design values and the Deru et al. office schedules, yielding a difference of 260% [50], [61]. This suggests that the case study towers are turning off much fewer loads than the design values estimate.

To measure if yearly peak loads are significantly higher than weekly peak loads, the upper and lower bounds of the "top 1%" are compared (Figure 2-9). On average, the yearly peak is 13% higher than the "top 1%" of loads, with a maximum of 40% higher. This indicates that these loads are very infrequent during the year and they could be targeted for peak load reduction strategies.

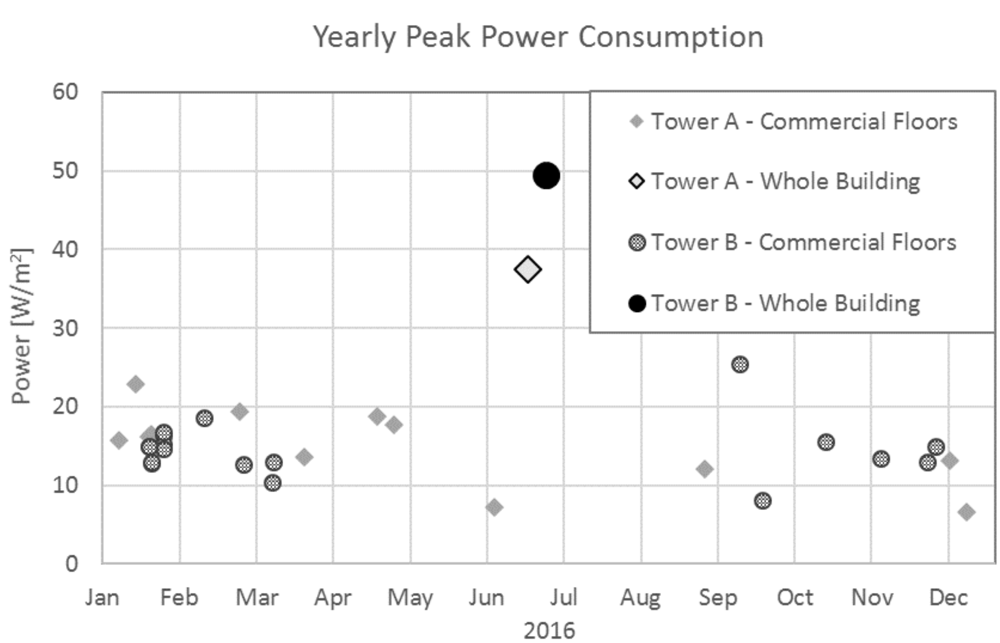


Figure 2-6: Yearly peak power for the building and tenant controlled light and plug loads on each commercial floor

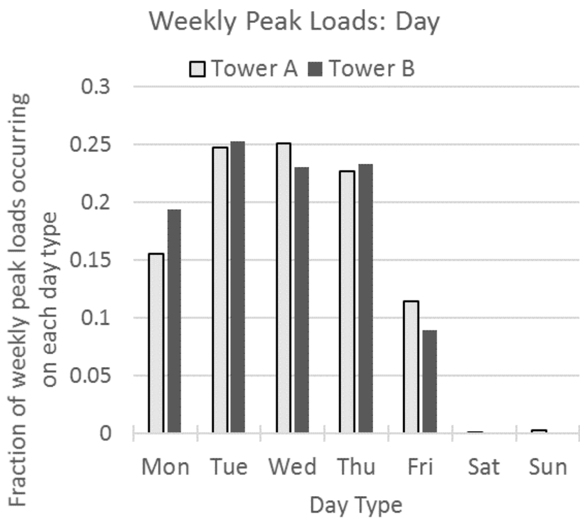


Figure 2-7: Day of tenant peak loads, assessed for each tenant occupied floor. The number of weekly peak loads is equal to 51 weeks multiplied by the number of tenant occupied floors, for each building respectively.

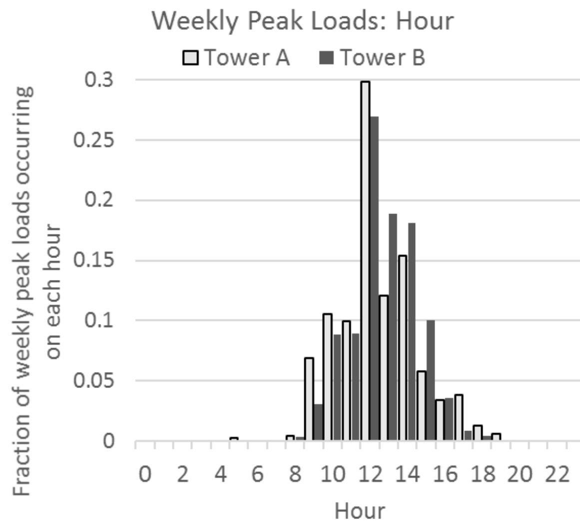


Figure 2-8: Hour of tenant peak loads, assessed for each tenant occupied floor.

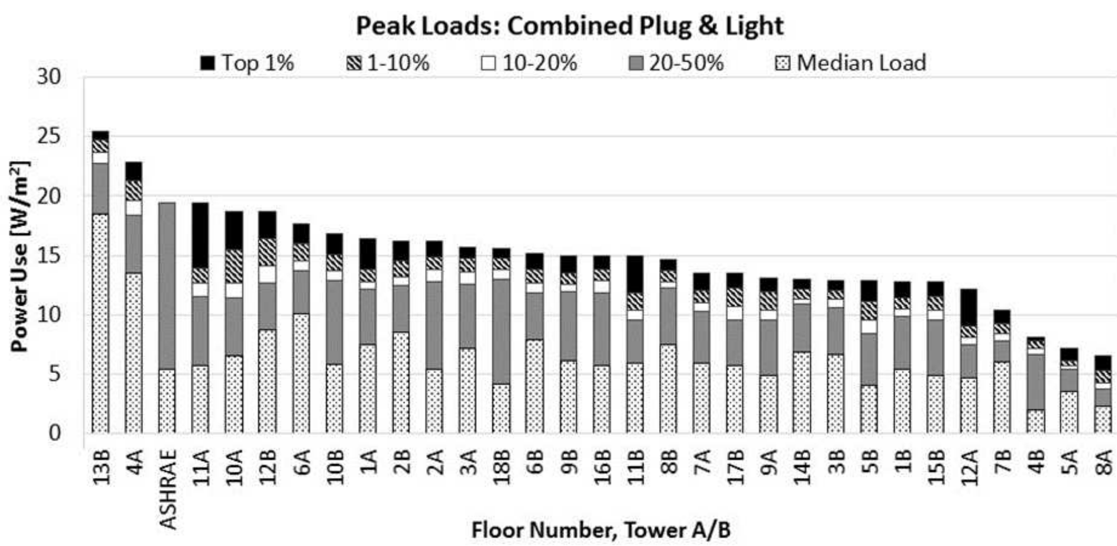


Figure 2-9: Tenant hourly loads for 2016, shading indicates the duration of high demand. The "top 1%" of loads occur during 1% of the year, this corresponds to the highest 88 hours of electricity demand for the year. The "1-10%" of loads correspond to the next highest loads, during this fraction of the year, and so on. The "Median Load" corresponds to the top 50% of loads for the year, where half of the year the electricity demand will fall above this level, this is the same as the base load for most tenants.

To determine if there is a clear divide in electricity use between occupied and unoccupied times, load duration curves are plotted with hourly power consumption sorted from lowest to highest for the year (Figure 2-10). It is hypothesised that two plateaus will appear: one low, corresponding to an unoccupied base load, and another higher corresponding to high use, fully occupied periods. A transitional period between plateaus is expected and would indicate periods with lower use than peak business hours (e.g., partially occupied in early morning, early evening, or Saturdays).

This hypothesised pattern is observed in the plotted ASHRAE design values paired with the Deru et al. schedules [50], [61], where an increase in power consumption occurs at 75% of the year. This indicates that power consumption is at a higher plateau during business hours, accounting for the top 25% of the year for a nine-hour business day (for 252 business days per year).

The power demand data from Tower A and B differ significantly from the consumption trend resulting from paired ASHRAE design demand and Deru at al. schedules. Here, the tenant loads transition from a low plateau to higher demand earlier (further to the left in Figure 2-10), indicating a greater number of hours with elevated power consumption. This could suggest either long work hours, with elevated electricity use on weekends and evenings, or that loads that are infrequently shut off. The latter explanation - infrequent equipment and light shut off procedures - is supported by the smaller difference between high and low power use in the observed data.

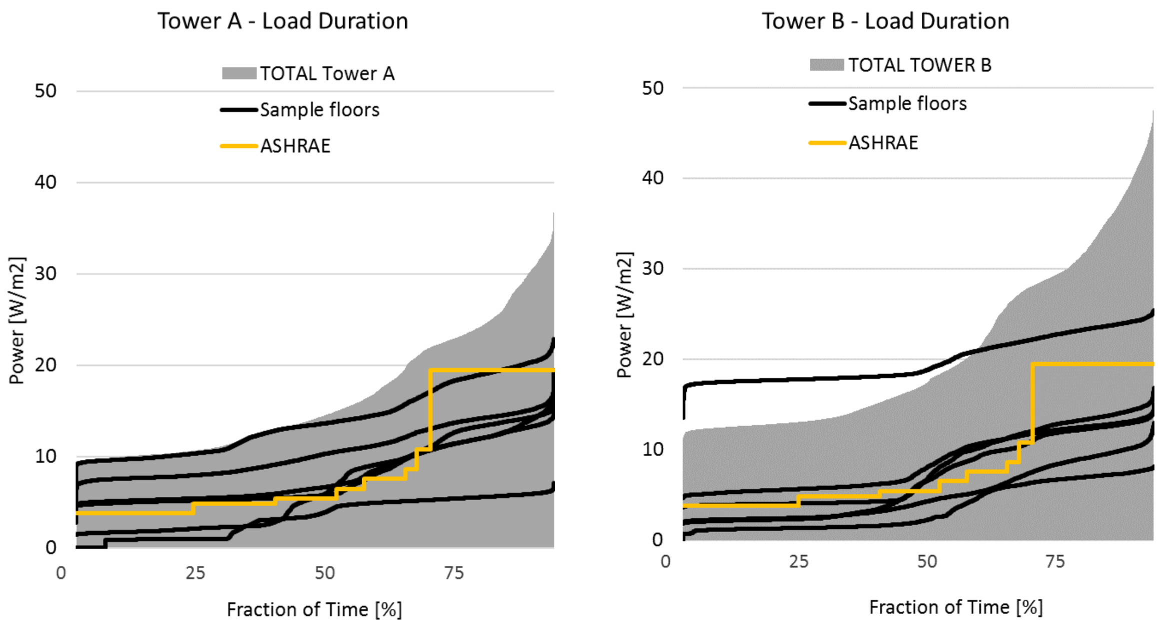


Figure 2-10: Load duration curves, with 2016 hourly electricity demand ordered from lowest to highest. The total load for Tower A and B include tenant load and base building load.

2.3.2.1. Peak Plug Loads

Peak plug loads are a useful metric for property managers since prospective tenants can negotiate the available plug load power density in their suite. Tenants often request a very high minimum plug load capacity, as high as 43 W/m^2 to 170 W/m^2, in their leases [63]. Building managers must increase the plug load capacity up to the minima dictated in the lease or renegotiate. Therefore, determining the typical and high user plug load peaks can assist both prospective tenants and facilities managers negotiate an appropriate plug load capacity. The typical floors in Tower A and B have a yearly plug load peak of 8.57 W/m^2, where the high user office has a peak of 21.0 W/m^2 (see Section 2.3.4.2 for high user differentiation).

The typical office floors are comparable to values found in previous research and the high user peak plug load is consistent with extremely high equipment densities (Figure

2-11). The office peak plug load is much higher than the 2.7 W/m^2, suggested by Wilkins and Hosni [49], who challenge the validity of the relatively high ASHRAE design standard. Metzger et al. [27] determined the peak plug load by measuring equipment loads for individual offices and applying diversity factors, resulting in 9.7 W/m^2. Sheppy et al. [63] found the peak plug load for offices without servers to be 5.4 W/m^2 and 9.5 W/m^2 for offices including servers; the offices including server loads are comparable to the typical office peak plug loads in Tower B. This high plug load could suggest that there are servers on some office floors, creating a higher peak plug load. This is consistent with observations in Tower A and B that suggest that small servers are common in the building (in 9 of 19 observed floors).

When modelling an office with very dense equipment and no load diversity, the peak power could be as high as 21.5 W/m^2, this is comparable to the high user in Tower B [49].

The peak-to-average ratio for the typical floors is 1.98. This metric is indicative of the amount of equipment that is shut off outside of peak times. The current finding is similar to values provided by Deru et al. [61], who suggest a ratio of 2.03.

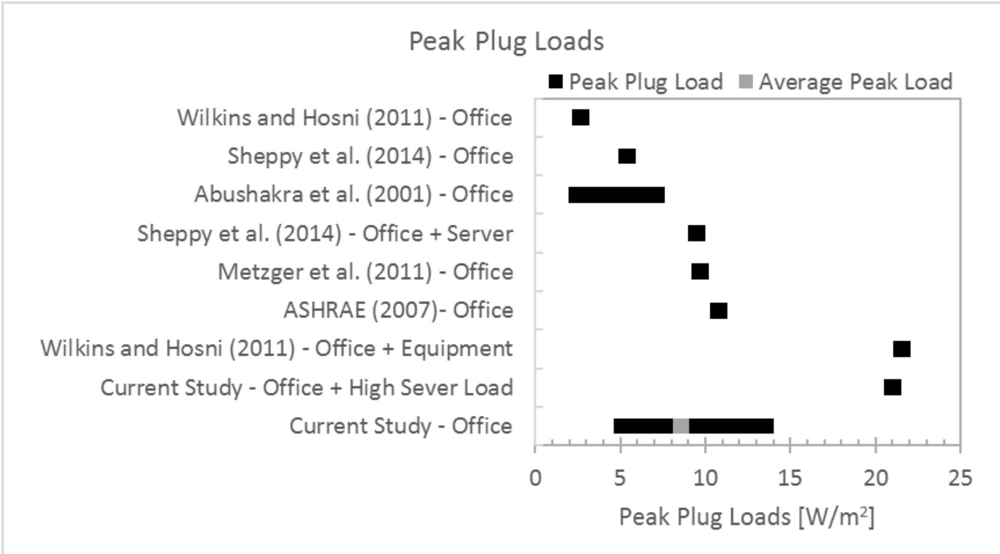


Figure 2-11: Peak plug loads compared to previous studies. One study finds a range of typical values, where others find one average peak load [27], [49], [50], [63], [64].

2.3.3. Average Loads

The average loads for each tenant are plotted in Figure 2-12 for Tower A and B, the demand profiles are similar, however, Tower B has one tenant with a higher baseload, which affects the data range. The demand profile using schedules from Deru et al. [61] and design demand from ASHRAE [50] shows an abrupt increase in electricity use in the morning and a more gradual decrease in the evening. This same trend occurs in Tower A and B, but with a significantly lower daily peak power use. Holiday electricity use is much greater in Tower B than Tower A and the compared design values. This indicates that Tower B may have more holiday working hours than in the compared literature and that holiday electricity use is highly variable between offices.

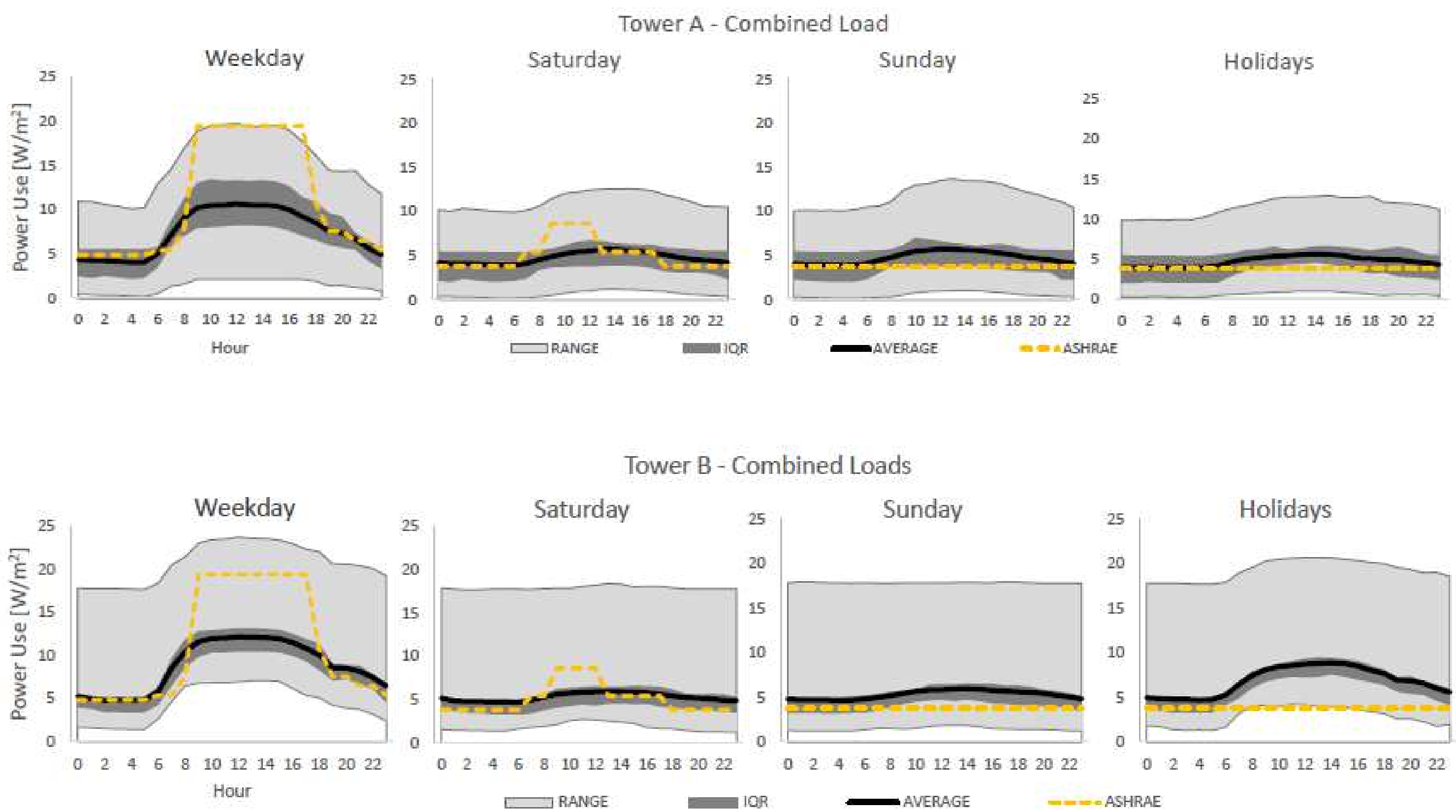


Figure 2-12: The average demand profile for each tenant is presented as a range, typified by the median demand profile. The combined tenant plug and light loads are compared with ASHRAE design loads and schedules from Deru et al. [50], [61].

2.3.4. Plug and Lighting Loads

For Tower B, light and plug loads are metered separately on each floor. There is a very weak correlation, R^2=0.089, between mean light and plug loads; this suggests that a high light load does not necessarily correspond with high plug load. Half the floors have higher mean light loads than plug loads on weekdays and each load type can be elevated independently of the other. Small servers could elevate tenant plug load, and tenants' chosen light fixtures and density could elevate loads while delivering similar illuminance and duration of lighting.

The average light and plug load profiles are compared with the ASHRAE design values paired with Deru et al. schedules, in Figure 2-13. The design values are 10.8 W/m^2 for both light and plug loads [50]. These design values are significantly higher than both the observed average light and plug load. The power schedules from Deru et al. [61] are consistent with this study, showing a low, but non-zero, light load at night and a significant night and weekend plug load.

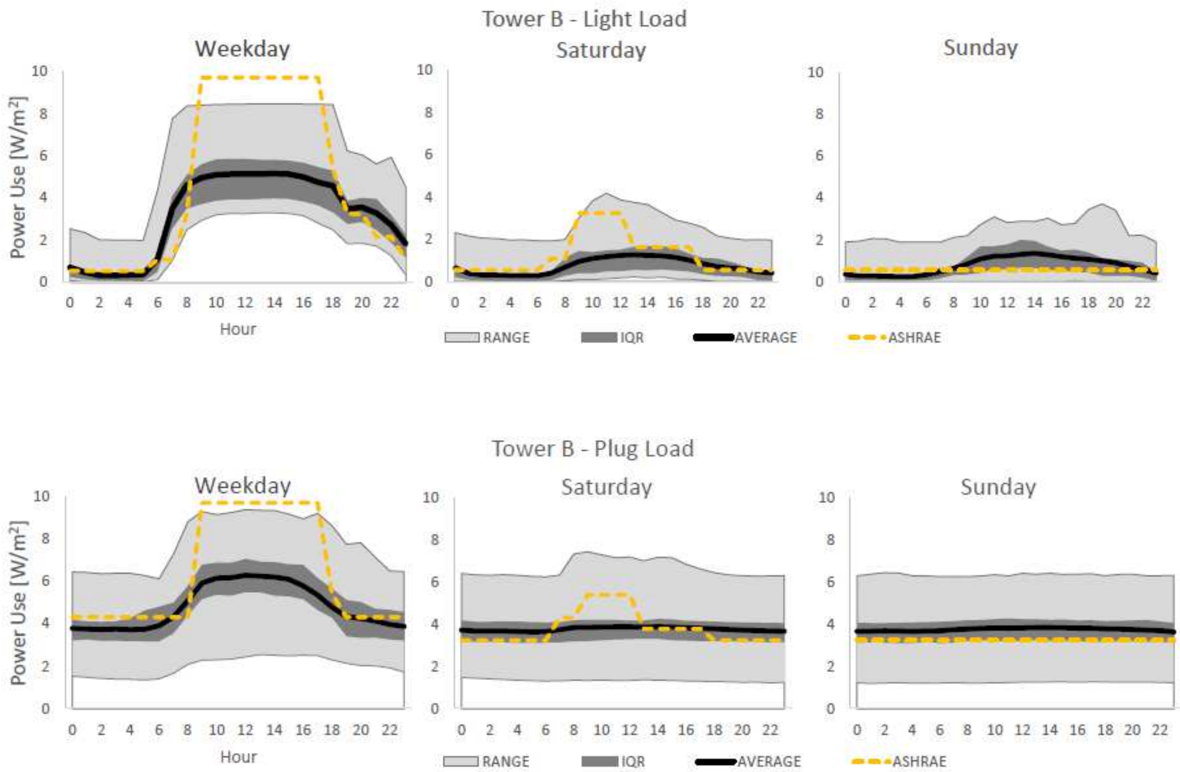


Figure 2-13: Plug and light load profiles compared to ASHRAE design values [50], [61]. *The 13th floor is omitted due to server loads.*

2.3.4.1. Lighting Loads

The light loads in Tower B have significantly lower power densities than the 10.8 W/m^2 in the compared literature [50]. The low recorded light load data is confirmed with a 2013 retro-commissioning report on Tower A and B, that finds the average light power density as 8.6 W/m^2. This is just outside the upper bounds of the light load power range of 8.5 W/m^2. These light loads account for overhead building lighting for the whole floor, including hallways and bathrooms, but do not include task lighting in workspaces or emergency lights that are permanently switched on.

Lighting power density could be lower than observed in the retro-commissioning report due to the introduction of LEDs for accent lights, tenants requesting the delamping of over-lit areas and motion sensing bathroom lighting. Tower B is also transitioning to LED hallway lights, which has been introduced to floor 4 and floor 7. In addition, some floors do not use the standard base building light system. On floor 11, all lighting is LED, controlled with motion sensing switches with a manual on, automated off functionality. This space uses the manual-on function to take advantage of natural lighting. Floor 3 also has lower light electricity use; one tenant, occupying half the floor, uses motion sensing light switches in all individual offices and boardrooms. In contrast, floor 10 operates as a bank with bright reception lighting, this is reflected in a higher average light load. Floor 2 is the same bank tenant (occupying 70% of the floor), which is observed to have a greater lighting density than other tenant suites; this lighting is controlled by only the standard four light switches for the whole floor.

The light load profile in Figure 2-13 shows a similar trend as the compared literature on Saturdays, where there is some observed light use in the mornings.

The lights in Tower B have an automated evening shut off feature at 19:00, and emergency lights are not on this circuit, so it is expected that zero power consumption should be within the IQR for all floors. For floors in Figure 2-15, where 0 W/m^2 is outside the IQR, this could indicate a problem, where some lights never shut off or other equipment is mistakenly on the circuit. In either case, this information can help reduce energy use by removing excess loads from the system.

Upon examining the lighting load curve for each floor, some floors display a pattern where there is a brief peak occurring late in the evening. This is apparent for floors 2, 12 15 and 16. Other floors show a stepped reduction in light loads, with higher variability as average light load decreases. To determine if the evening peak is happening every day or is the result of averaging across the year, box plots are created to show the variability in power use (Figure 2-14). Each of the four floors show a significant drop in lighting power use from 18:00 to 19:00, this is the result of the automatic light shut-off feature. After this time tenants may only be turning on lights in their zone.

Floor 2 shows high evening variability so the evening increase could be partially the result of averaging hourly light loads over the year. Floor 12 has less variability, half of this floor is dedicated to an office with very late operating hours resulting in a lower but consistent power consumption. Floors 15 and 16 have variability just after the automated shut off, but later increases to a higher power use at 20:00 and 21:00. This is likely the result of after-hours cleaning staff triggering the lights which stay on for two-hours if not manually shut off.

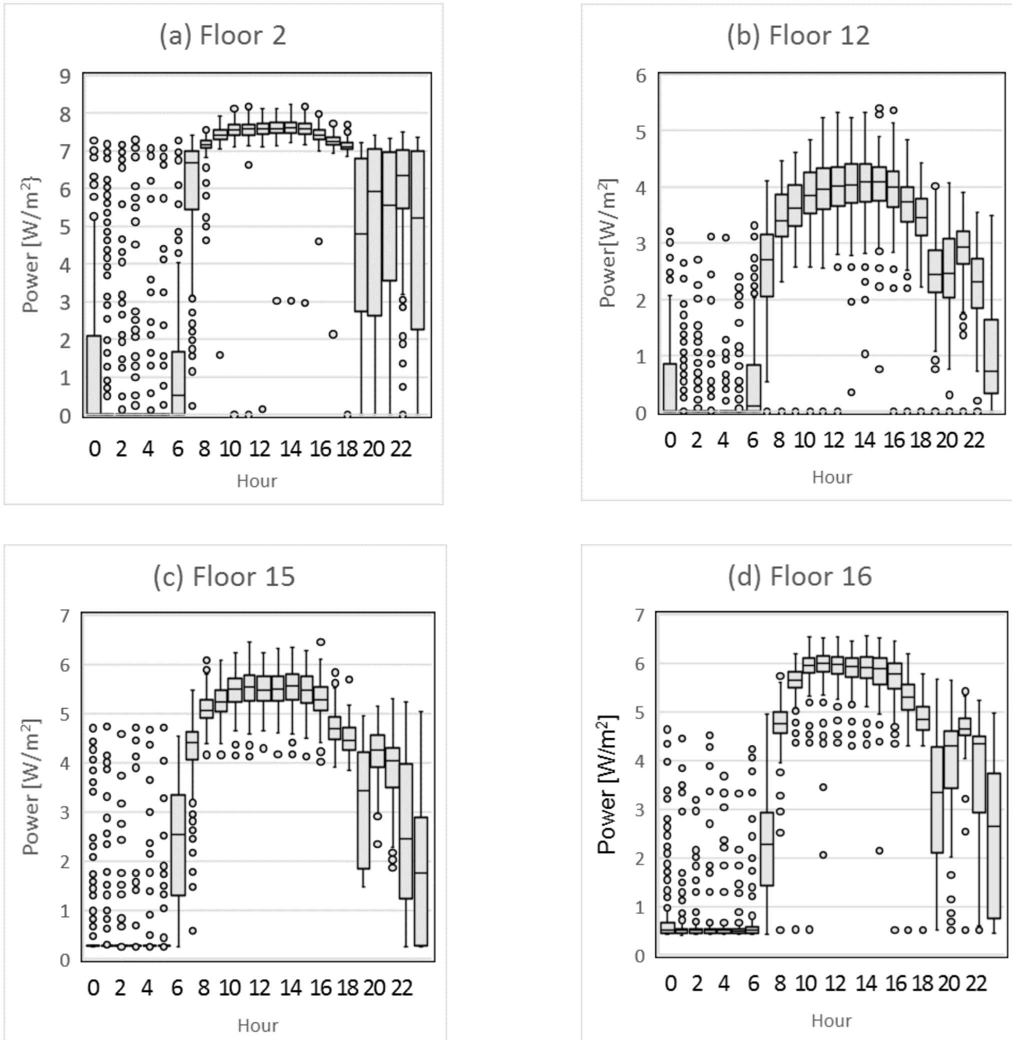


Figure 2-14: Weekday light load boxplots for each hour of 2016. The shaded boxes show IQR, whiskers show 1.5 IQR above and below Q1 and Q3, and circles show outliers.

2.3.4.2. Plug Loads

Plug load electricity consumption patterns differ from the light load, where the plug load never reduces to 0 W/m^2 throughout the year (Figure 2-16). In Figure 2-13, average plug load and light load use is similar at midday, but overall plug loads account for greater end use consumption. This is because equipment is consuming more electricity than lighting during unoccupied times, as indicated by the tight IQR seen in Figure 2-16. Weekends and holidays account for 31% days of the year and 26% of plug load electricity is used on these days. This could be an opportunity for increased savings as only 10% of lighting electricity is consumed in the same period.

The separate metering of plug loads uncovers an outlier (floor 13) with a much higher load, this indicates, correctly, that there is a significant server included in the plug load. Here, increased granularity of data gives more information about the office electricity use, indicating that floor 13 may not have typical office use due to a server.

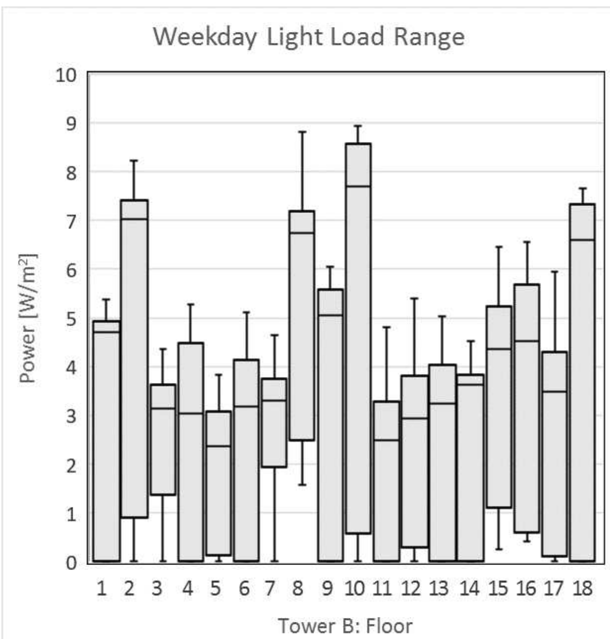


Figure 2-15: Full year of hourly light loads for each floor.

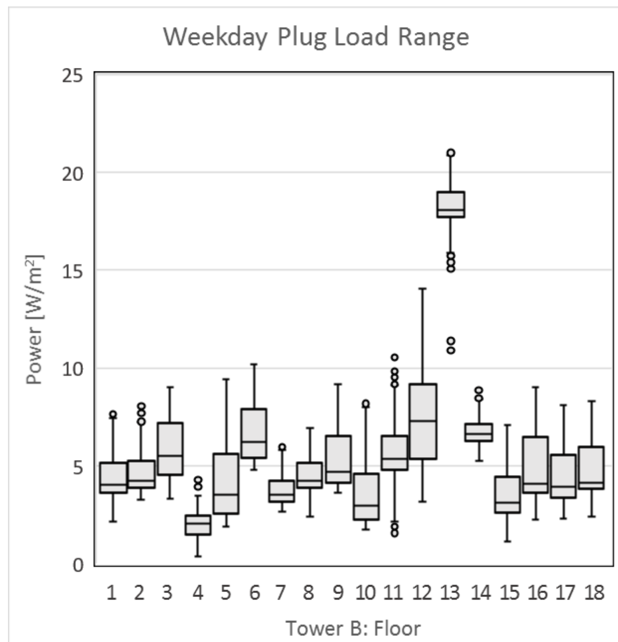


Figure 2-16: Full year of hourly plug loads for each floor.

2.3.5. Estimated Occupancy Schedule

Determining occupancy in an office space can help to better manage building electricity use, through the efficient delivery of space conditioning and lighting. The tenant electricity use data can be used to approximate the average weekday occupied hours on each floor, using a non-invasive methodology that requires no extra instrumentation.

This method is applied to separate and combined tenant plug and light loads; the efficacy is discussed in the following section.

2.3.5.1. Separated Loads

In Tower B, the light and plug loads are analyzed separately to estimate average occupancy schedules presented in Figure 2-17.

The lights must be manually turned on at the start of the day, so when lighting energy increases it is likely due to occupants arriving. However, the coarse granularity of the lighting controls (with a standard layout of only four light switches per floor) means that the presence of one occupant who needs light can result in a significant increase in lighting power. On average, the first occupants are estimated to arrive at 7:00, where the maximum light load increase between consecutive hours occurs (see Section 2.2.5.3). After the lighting indicates occupancy, the plug load increases as people begin arriving and working. On average, the maximum plug load increase between two consecutive hours, occurs at 8:30, providing more evidence that the space is occupied.

In the evening, the lights are either manually shut off or they automatically shut off at 19:00 unless manually triggered after this time (in which case the lights will stay on for two more hours). The automated light feature can obscure the time of departure. As per the methodology described in Section 2.5.3, on average, the plug load indicates that mean departure is at 17:20, and light loads indicate that it is 19:30. The estimated evening departure time has a large variation between floors, with a range from 16:00 to 22:00, based on light loads. In addition, on five floors there is significant difference (from four to six hours) between the occupancy schedules inferred from light and plug loads, where the light load estimation suggests much later occupancy. The plug loads can decrease while light loads stay elevated, if few occupants stay late and require full lighting.

In this case, with separated plug and lighting loads, the plug load is the better indicator of maximum daily occupancy, estimating an 8.9-hour business day, whereas light loads indicate partial occupancy and estimate a 12.6-hour day for Tower B. The variation between plug and light load estimates could indicate a flexible work schedule, where occupants arrive and depart on different schedules within the same office.

2.3.5.2. Combined Loads

When the combined light and plug load curves are used to estimate occupancy schedules, there is no insight into first arrival time versus full occupancy. Combined loads result in the same estimated arrival time as estimates based on light load alone. In the evening, there is more variation in the predicted occupancy, where the combined loads often estimate a later departure time than either plug or light load estimates, by one hour.

For Tower A and B, estimating occupancy for combined loads results in an average 13.3 hour working day. This is a long business day, longer than estimates base on separated loads, and suggests that combined loads are not as precise for estimating occupancy schedules.

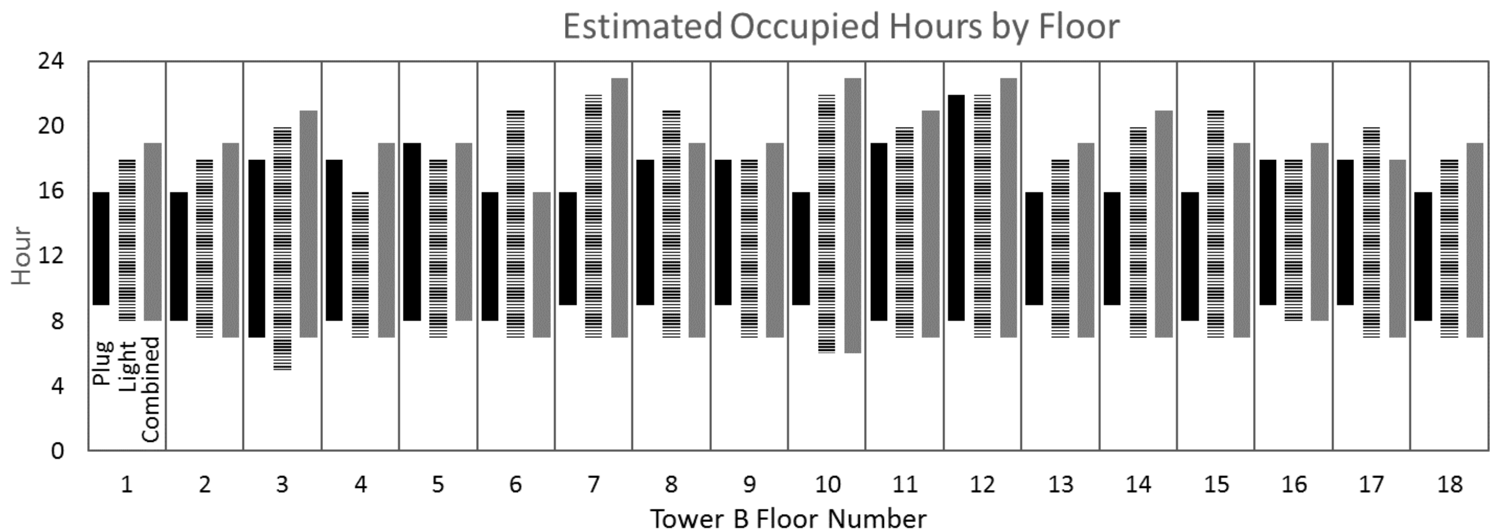


Figure 2-17: Tower B estimated occupancy

2.4. Discussion

This research provides a case study with a large data set spanning many tenants with a variety of typical business practices, encompassing a full year. The insights from this study can help building energy modellers bridge the gap between modelled and actual electricity use. Energy modellers can use the average tenant consumption profiles (Figure 2-12 or Figure 2-13) to model predicted energy use with confidence bounds at the IQR and at the outer range of electricity demand found in this study.

The submetering installation that allowed for this case study also resulted in a new billing scheme for tenants, with bills reflecting actual electricity consumption. The majority of tenants had a reduction or negligible increase in operating costs, while the high-users (outliers 1-5) were particularly financially burdened by the new billing scheme. The highest user from the two towers, outlier 1, had their electricity costs more than double and is looking at alternative commercial space, this could be in order to avoid the costs of electricity.

Tenants potentially leaving the building or prospective tenants moving elsewhere is a serious consequence of submetering in a market with many bulk metered leases available. The managers of Tower A and B strive to have only the most up-to-date buildings in their portfolio with the fairest billing schemes in order to attract high-end tenants. Therefore, the managers of Tower A and B find the up-front cost of submetering to be worthwhile.

2.4.1. Behaviour Change

The effect of submetering on tenant and occupant electricity use behaviour is challenging to quantify, especially since the metering was implemented at the year start and billing does not occur until year end.

There are anecdotal results that indicate some behaviour change has occurred since the implementation of submetering. Of the high users, outlier 3, has worked to reduce electricity use by increasing the cooling setpoint in the server rooms by 1 degree Celsius.

The tenant representative for floor 5 and 6 (Tower B) was highly motivated to reduce electricity use and made significant changes to their space. This included removing unnecessary loads in the workplace, such as old vending machines and approximately 40 excessive base building lights. For loads that could not be removed, efficiency settings were optimized. This included setting a sleep mode function for new coffee machines and shared photocopiers, reducing the time to enter sleep mode from 30 down to one minute on all desktop printers. For older coffee machines and microwave ovens with high standby loads, timed power bars were installed to automate evening and weekend shut off procedures. In addition, appliances without timed power bars are shut off at the end of each day. Energy efficiency was promoted within the office, reminding employees to shut off lights, monitors, electronics and to optimize shade use. It is noted that all computers remain on permanently in this tenant space for IT update purposes.

Another tenant (Tower A: Floor 10) made use of timed power bars to shut off vampire loads associated with tablet docking stations. The tenant was surprised to find docking stations, that lack lights or displays, continuously draw power. This tenant space also started manual shut off procedures, where employees were notified of the new office policy to manually turn off electronics and lights at the end of the day.

On floor 9 (Tower B), more modest behaviour change is noted, where all computers are turned off if they are not frequently in use, due to vacation time or if the workspace is unoccupied.

Another tenant (Tower B: Floor 10) switched from night to daytime cleaning. This is expected to reduce electricity use associated with turning on lights after hours for cleaning staff.

2.4.2. Server Load Disaggregation

Tenant consumption appears to vary significantly between floors when combining plug, lighting and metered servers, this observation is most prominent in tenant EUI range. In this case, there may be too many loads to apply load disaggregation techniques to separate out each load type. If tenants only receive their total electricity use, then typical office energy reductions, such as turning off computers at night, may not yield noticeable reductions if servers are the main consumer. Therefore, large server loads should be metered and reported to tenants separately.

In this study, the servers and their cooling systems that are separately metered draw a significant portion of power throughout the year and account for 17% and 22% of total electricity for Tower A and B. Smaller servers were observed on many other floors in both buildings; these server loads are combined with the regular meters.

In Tower B, the data from floor 13 is omitted from average and peak plug load analysis because the mean plug load is 2.5 times greater than the next highest in the building, due to a known server. This load only becomes apparent as an outlier when plug load is metered separately from light load. Here, it is clear that a server is causing the high baseload, but on other floors it is less certain.

There were nine small servers observed within the 19 observed tenant spaces. This observation is consistent with other research that found servers located in 55% of offices [47]. The tenant base load on each floor could be the result of typical office equipment, the result of servers or both. A high baseload could result from employees leaving typical office equipment on for the night. Alternatively, a low baseload could indicate a small server paired with relatively light office equipment. An example of light office equipment includes one tenant suite where employees worked from tablets paired with monitors. Since it is challenging to identify the small server loads on each floor, separating server load from the plug and lighting loads without proof of a server is not recommended.

Non-intrusive load monitoring techniques can be leveraged to disaggregate individual loads [65], [66]. Electricity data can be analyzed for steady-state events, which constitute changes or overlapping changes in power states (e.g. ON/OFF) [67]. Electricity demand data must be sampled frequently to capture all steady-state events, ideally sampling every second [68]. Transient methods exist to identify more complex power signatures with distinct patterns or duration, but this method may require electricity demand data as frequently as 1000 times per second [67]. Machine learning can result in the identification of power signatures from varied appliances on a complex circuit through unsupervised learning [68], [69]. Load disaggregation techniques decrease in accuracy as the devices on each circuit increase and as more low-power devices overlap their power signatures [67]. Therefore, load disaggregation for an office with many auxiliary electronics and only one submeter sampling data at 15-minute intervals can result in a high margin of error.

2.4.3. Metering Plug and Light Load

Separated plug and light load data can help track energy use anomalies. When light loads do not return to zero at night (or to the nominal nighttime level) it can indicate that a light is permanently staying on, or that the circuit needs to be checked for other load types.

Separate metering of plug and light loads is key to understanding tenant electricity use since these loads are not correlated in this case study. That is, the portion of load associated with plug and light loads cannot be determined from the combined load. If loads are combined, estimating the effect of an energy conservation measure on either lighting or plug loads is challenging.

The benefits of separate metering are only gained if tenants are interacting with the data and using it to make informed energy conservation decisions. Based on anecdotes from tenants and the relatively small number of energy dashboard logins, the managers of Tower A and B do not find the additional cost of metering plug and light load separately to be worth collecting additional data. Instead the managers of the current building will prioritize metering multiple-tenant floors in order to meter each tenant separately.

2.5. Conclusion

This study collected the electricity use patterns of 43 commercial tenants across 32 submetered floors, for one year. Submeters were used to separate significant equipment and server loads from other tenant controlled plug and light loads and to provide actual electricity use feedback and billing for each tenant.

The reception of the new submetered billing scheme was positive from most tenants, since the system is fairer and provides accurate electricity use and carbon footprint feedback. The five high-users did not want the new system because it came with higher bills after years of other tenants subsidising their high use.

The electricity data indicates that weekly peak tenant loads are likely to occur coincidently, on weekdays and distributed around noon. Over the year, the tenant peak loads are concentrated outside of summer months and are out of phase with the building peak loads which occur in late June. The building-wide peak electricity consumption is found to be driven more by base building loads, specifically air conditioning, than by coincident tenant loads.

The average electricity demand profiles indicate a small IQR but a large range in electricity use between commercial floors. This large range in electricity use creates a challenge for energy modellers to predict usage and for building managers to estimate electricity costs for prospective tenants. Therefore, it is recommended that building managers provide a range of typical electricity consumption and costs to prospective tenants.

The average electricity demand profiles are similar, but consume less during occupied hours, than standard design values, sourcing demand from ASHRAE and schedules from Deru et al. [50], [61]. This study also found higher electricity use on holidays than in the compared design values. Since there is a disconnect between design values and observed electricity use, modelled electricity use projections may not accurately predict actual office use. Therefore, it is recommended that future commercial energy modelling use updated design values to reflect lower peak demand and use updated demand profiles to reflect current office schedules.

Due to the high variability in electricity use, the authors recommend the use of submetering in commercial buildings for fair billing. Submetering tenant servers, tenant light load and tenant plug load end uses separately is recommended to provide granular data. Granular electricity use data is useful for estimating benefits of energy conservation measures.

3. Electricity Reduction Competition in A Multi-Tenant Commercial Building: Insights and Barriers to Implementation

3.1. Introduction

This chapter details a building-wide intervention that targets the variable electricity use that is affected by human behaviour. In this commercial setting, the studied behaviour differs from a residential context, this chapter forms two distinct behavioural groups, the tenant representatives and the office occupants.

Understanding the end-users is the key to increasing energy efficient behaviours in a commercial office setting. The motivating factors to conserve are different in a commercial office than in a residential setting, where the occupant has financial responsibility and control of their environment. In a residential setting, when individuals are given information and energy use feedback to promote energy efficiency, they are no more likely to engage in energy reducing behaviours, especially if the information is not new and behaviours are not based on financial motivators [16], [28]–[30].

In a commercial setting, the design and implementation of an energy reduction competition can bring awareness and possibly behaviour change, but there is limited available research in a workplace setting, with results summarized in Table 3-1 [70]. In the office, switching to energy efficient behaviours can be motivated by creating the sense that energy efficient behaviour is the social norm. Specifically, a competition can give the appearance that many more people are engaged and that adopting energy efficient behaviour is normal [30]. In a competition, the participating offices can choose specific interventions that are easily accommodated in their own work space [71].

Significant electricity savings, in excess of 5%, are typically associated with programs that go beyond occupant behaviour change and encourage automation or the purchase of energy efficient appliances and equipment [31]. Significant electricity savings rely on both occupant and management to make lasting changes to the office culture and environment [70]. The level of engagement observed in office managers and leaders results in a similar type of engagement from their employees, so leaders play a significant role in either promoting or ignoring office electricity conservation [72].

Table 3-1: Summary of electricity reduction results from prior studies

Study	Strategy	Target / Timeframe	Results (reductions)	Notes
		Tenant Engagement		
10 for Change [31], [73]	Goal setting, competition, meetings, acknowledgement	10% energy reduction over 3 years	Year 1: 0% Year 2: 4% Year 3: 8%	Since 2011 more than 1000 businesses have taken part [73]
Energy Savings Challenge: Fire stations [74]	Competition, newsletters, ranking, acknowledgement	Greatest energy reduction in six months	Best building: 21% Total Savings: $8000	
Energy Savings Challenge: Libraries [74]	Competition, ranking, acknowledgement	Greatest energy reduction in one year	Best building: 19% Total Savings: $21000	

NEEA Market Partner Program [75], [76]	Personalized coaching	Measure energy management over 3 years	Total load: 4.8%	
NEEA Office Competition [75], [76]	Competition, acknowledgement	Measure energy management over 3 years	Total load: 3.9%	
Occupant Engagement				
Carrico and Riemer [77]	Education, feedback, peer educator	Track performance for 4 months	Total load: 7%	
Dixon et al. [78]	Competition, comparative feedback	Greatest reductions in one year	Total load: 6.5%	
Energy Chickens Game [79]	Gamification, education, monetary incentives	Plug load reductions for 12 weeks	Plug load: 13%	Savings were not persistent
Gustafson and Longland [80]	Targeted actions, education	Building load reduction over 2 years	Year 1: 5% Year 2: 9%	Behaviour change is linked to adoption of permanent technical changes
Kilowatt Cup 2012 [31]	Competition, acknowledgement, gamification	Engagement and plug load reductions over two weeks	Plug load: 14% Total load: 4%	Savings were not persistent
Metzger, Kandt and VanGeet [27]	Competition, feedback, education	Greatest reducing workstation (6-8 desks) for 1 month	Workstation plug load: 6%	

Metzger, Kandt and VanGeet [27]	Education only	Effect of weekly emails for 1 month	Workstation plug load: 0%	
Murtagh et al. [81]	Individual energy feedback	Track individual plug load for 4 months	Reductions only for second half of study	41% of participants do not look at feedback.

3.1.1. Effectiveness

A key component to creating an effective competition is through acknowledging and focusing on continued participation [31]. The goal is to engage all participants, even the worst performing, since some offices may have little ability to impact their overall energy usage with behavioural changes. For example, an office, with a server and associated air conditioning load that is greater than the general office use, may not have noticeable reductions from energy efficient behaviour change. Other offices with significant lighting loads could render noticeable results from occupants simply remembering to turn off the lights at the end of the day. Therefore, changing the focus from individual savings to including the results of all participants combined could engage low performers who could be discouraged by competition results.

Simply promoting energy reduction and competition is not enough for a successful energy reduction strategy. Some individual behavioural changes must be identified and targeted so that participants feel control over their personal energy use [29]. Desired behaviours should be encouraged with prompts and cues in the workplace so that the new behaviour is consistently used [11].

Another successful method for increasing program acceptance and altering human behaviour is delivering information from a trusted source, specifically a peer who can disseminate information that is relevant to the individual [30]. In this scenario, a representative within the tenant suite who has an interest in the environment would be ideal. A trusted source can be beneficial when a conflict of interest is possible, for example, if an efficiency program is promoting the investment in a proprietary technology, but derives funding from their manufacturers, the return on investment claims may be suspect.

When participants pledge to complete an energy efficient behaviour change, they are more likely to follow through with the commitment. A public commitment is more effective than a private written commitment which, in turn, is more effective than a verbal commitment [16]. A similar method for engaging office tenants is to ask offices to set energy reduction goals. For this method of engagement, those who are asked specific questions about how and when they will attain their goal are more successful, since they are already beginning the planning process of attaining their goal [16], [82].

Feedback during a competition is useful to participants, both when results are compared to others and when feedback is publicly displayed [31]. Feedback on its own does not guarantee that an office will change its behaviour, it is more effective when it is used as part of a goal, such as reducing the electricity bill or, in this case, performance in a competition [16].

3.1.2. Incentives

An incentive can increase the motivation of an individual to undertake pro-environmental behaviours in the short term, particularly when cost is a barrier to completing the behaviour [16]. Incentivised behavioural interventions are very important if the desired outcome is a one-time behaviour, such as choosing an electric car over a traditional model. For repetitive behaviours an incentive typically has no effect after the incentivized period is over [16].

If the incentive is not extremely desirable in itself, but is a smaller reward that has a main objective of acknowledging positive behaviour, then the incentive can increase the individual's intrinsic motivation [83]. An intrinsic motivation for energy efficient behaviours is more likely to result in continued behaviour after the contest is over, compared to extrinsic motivation where the motivating reward is eventually removed. Petersen et al. [84] found that the act of competing may be more important than the incentive, where less than 10% of the winning team collected their prize, admittance to a party.

3.1.3. Persistent Results

Few occupant engagement studies track the persistence of energy savings over time, and the few that do, find that energy savings fade with time [31], [79]. Energy reductions achieved during a competition are often more successful as long term changes when the competition is over a long period or subsequent behaviour interventions relate back to the original competition [31]. Long term energy efficiency messaging combats the participants' tendency to forget about changes they made during a short-term competition [16]. In addition, long term engagement can prompt participants to pass on positive behaviour to new employees and to endeavour on equipment or building upgrades that are permanent and go beyond individual behaviour change.

The current study implements an electricity reduction competition in a multi-tenant commercial building for one month. Based on prior electricity reduction studies, this competition seeks to increase electricity conservation awareness in tenants and occupants, reduce tenant electricity use, and prompt changes in the office that allow for persistent results. The goal of this study is to make recommendations on promoting energy efficiency and conservation specific to a multi-tenant commercial setting. The competition is targeted at both tenants and occupants and is informed by the following recommendations from previous research.

Competition design recommendations:

1) Provide information on how to reduce electricity [29]
2) Provide electricity use feedback [31], [70]
3) Have behaviour change commitments, preferably written and public [11], [16], [30]
4) Have an incentive, preferably as an acknowledgement of good performance [11], [16], [70], [83]
5) Information must come from a trusted source [30]
6) Build upon prior energy conservation information [31]
7) Maintain positive messaging [80]

This case study is unique because it tracks the results and barriers to promoting electricity reductions from a property management perspective within a multi-tenant commercial building. Prior studies have been launched primarily by cities [73], [74], by researchers studying a university [77], [78], [81] or by the company itself [27], [76], [80].

3.2. Methodology

An energy reduction competition was launched as part of the ongoing education and engagement strategy and following the implementation of submetering in two multi-tenant commercial buildings. A building-wide competition was part of a strategy to gamify energy conservation measures, to make the adoption of pro-environmental behaviour in the workplace an entertaining and desirable activity.

This competition ran for four weeks where top five energy reducing commercial floors were published each week. Comparing the performance of each commercial floor was modelled after the study by Gustafson and Longland [80]. In addition, building occupants could enter the competition with individual energy reduction pledges resulting in a weekly draw winner. The dual approach, using a competition and pledges, aims to engage occupant as well as management and tenant representatives who play a key role in electricity reductions [70].

This competition targeted immediate behaviour change to reduce energy consumption. A longer competition, occurring over a year or more, could capture electricity reductions associated with building and tenant space upgrades in addition to occupant behaviour change [31].

The goal of the competition was to both reduce energy and begin the conversation at the occupant (employee) level about what they can do to reduce energy and their environmental impact.

This competition used education, energy use feedback and pledged energy conservation behaviours to promote behaviour change. The competition incentives were in the form of a weekly prize draw, rewarding individual participation. The weekly energy reduction for each floor was also presented to incentivize team participation.

3.2.1. Tenant and Occupant Control

Occupants have limited control over total tenant electricity use, where they can control their own private space in their office. Some have control over turning computers off, but not all have this ability due to office policy. Occupants can control monitor use, personal printers, task lighting, auxiliary electronics, and kitchen appliances when not in use. Occupants can also use light switches and controls where available.

Tenant representatives control many aspects of the office suite and choose the level of control the individual occupants have over their electricity consumption. Tenants can decommission excessive lighting, choose efficient office equipment, create equipment shut off policies, allow or automate computer shut downs, choose accent lighting and can remove unnecessary TVs in breakrooms and reception areas. Tenants play a key role in office awareness and culture concerning energy efficiency.

When tenants first move into their suite they choose important fixtures, e.g. lighting controls; this is a critical decision-making stage that can significantly affect long-term electricity consumption. The majority of tenants chose to use the minimal provided light controls, four light switches spanning the 1850 m^2 (19900 ft^2) floor plate. Other tenants chose better controls ranging in granularity, from adding switches to infrequently used spaces, such as closets and boardrooms, to motion sensing switches in every office. Base building lighting fixtures in their standard layout and an automated evening light switch-off are building operator controlled. The tenant choice in lighting, whether standard or more granular, falls outside of the scope of this electricity reduction competition, so the type and layout was not recorded. Due to the minimal standard light controls, significant changes to light electricity was not expected. For tenants who previously chose granular lighting control, they may have had more efficient use of lighting during the competition.

Some tenants (9 of 19 visited suites) have small unmetered servers in their office or large metered servers, that are paired with additional chillers required to meet cooling needs. Tenants have little direct control over the server loads. Since the introduction of submetering, some tenants with large servers have changed server room cooling set-points, balancing between reducing cooling electricity costs and optimizing server performance. Tenants with large servers were consulted by the building management about reducing electricity in early 2016, so associated electricity reductions occur long before the electricity reduction competition.

The maximum possible electricity reduction during the competition is estimated at 12%. This was based on the assumption that tenants and occupants could fully shut off all plug load equipment between the hours of 20:00 and 6:00 on all of the weekdays of the competition. In reality, the maximum electricity reduction would be lower than 12% due to small servers that are included in the plug load metering and any equipment that cannot be unplugged. This nighttime plug use (determined for Tower B which meters each tenant end use) accounts for 37% of total plug loads, 21% of tenant plug and light loads and 12% of total tenant loads when including exceptional (large server) loads.

3.2.2. Energy Conservation Information and Feedback

Energy conservation information was provided via email to tenant representatives three times per year including monthly posters with a targeted conservation behaviour, a checklist and a goal setting framework for proposed improvements to the tenant suite. This educational platform is part of an ongoing energy awareness campaign that has run since 2010. In addition to the information platform, yearly activities promote conservation, such as sweater day, where select tenants voluntarily choose to reduce their suite temperature by one degree and wear sweaters.

This study built upon the existing conservation education platform to promote new and reinforce existing pro-environmental behaviour during this competition, as recommended by Vine and Jones [31].

Further information on the competition and how to conserve energy was available at an information booth accompanied by a researcher. The researcher acts as a neutral information source and intermediary between the building operator and individual offices, in order to give credibility to the competition [30]. A neutral source may be beneficial in this office setting, since there could be a conflict of interest. For example, if the building operator was promoting energy efficiency solely through an upgrade to LED lighting, paid for by offices, this would be suspect since the building operator is responsible for providing light fixtures.

Feedback on electricity consumption during the competition was communicated on a weekly basis to tenant representatives, via email.

In order to use public acknowledgement as a competition incentive, the best five performing office floors were published each week, as a symbolic prize instead of a prize with a monetary value. This shifts the motivating factor from a physical prize to a social reward for participating in the competition and increases the likelihood of persistent participation [83]. This public acknowledgement, limited to the best five floors, also allows for poor performers to remain fully anonymous and to avoid discouragement.

The weekly total building electricity reduction was also presented as feedback, measured in equivalent lightbulbs and average Canadian homes removed from the electrical grid for the same week. Whole building performance was presented to keep results positive and to promote participation in order to have a successful competition [31].

3.2.3. Communication Methods

The dissemination of competition information took a multi-faceted approach to reach as many building occupants as possible. This included emails, a webpage, posters and an information booth with a researcher representative.

Email communications were sent from the buildings' operations manager, who had access to tenant representative(s) from each tenant space. The tenant representatives create a significant communication barrier, where some forwarded the emails weekly to their whole office, where others did not even open the emails. Instances of email opening and forwarding were monitored by Mailchimp.

Tenant representatives were notified about the competition Sept. 28 via email. The initial email introduced the competition and included: a suggestion for electricity reduction, current year total building electricity reduction (of 3.6%) compared with the previous year, and the link to the competition website.

Weekly results emails were sent, including: the number of occupants who pledged weekly to make a behaviour change, the top five electricity reducing floors and the whole building electricity reduction. A positive email was chosen as it may be more likely to be forwarded on to the whole office.

Emails to tenant representatives were the only method of communication for the existing conservation education platform. This competition uses other communication methods to go beyond the existing conservation education platform to engage additional building occupants.

A webpage was created and operational for the extent of the competition. The webpage included information on the competition and a link to SurveyMonkey to pledge to reduce energy. Occupants could find the link to the webpage in any of the competition emails, posters and on the business cards handed out at the competition information booth.

Large posters displayed on easels promoting the competition were placed by the elevators in each building starting Sept. 28 and remained in place (excepting three days in week 3) until the completion of the competition.

An information booth was set up once a week in each building during the competition. The booth was accompanied with a researcher for an average of 3.5 hours per setup, split between morning arrival (~8:00) and lunch (~12:00). The booth was set up next to the posters and gave out 360 business cards advertising the competition and building management branded chocolate.

The first booth setup in Tower B included a laptop for occupants to directly pledge to reduce energy on the SurveyMonkey link. This fist set up yielded the most entries in one day and is the recommended practise. Unfortunately, due to WiFi connectivity issues by the elevators, this setup was limited to one day.

3.2.4. Energy Conservation Pledge

To engage individual occupants an incentivized draw was created. Occupants entered the energy reduction behaviour they pledged to complete, each week during the contest, through a SurveyMonkey form linked in the emails and webpage. The schedule of weekly entries was chosen to encourage occupants to think up a new energy saving measure each week, therefore building on prior entries and reinforcing conservation behaviours beyond one week [31]. These written commitments may have been more effective if publicly displayed on the competition webpage, but a public display was determined to be a privacy issue.

The draw prizes included two Nest thermostats and two iPads of comparable value. Based on occupant anecdotes, the nest thermostats were the more desirable prize among entrants, although less widely known.

The goal of the pledge ballots was to encourage occupants to analyze their workplace and their impact within it. The ideas from occupants can show the biggest and most common opportunities available for energy reduction that can be pursued in the future.

3.2.5. Experimental Design

There are a number of experimental designs that are appropriate for analyzing the effectiveness of a competition. The most scientifically robust methods are often the most difficult to implement in a case study and few competitions incorporate experimental or quasi-experimental methodologies [31].

Measuring the effectiveness of a competition to promote energy efficiency can prove challenging. The most rigorous form of evaluation is a randomized controlled trial (RCT), where offices are randomly assigned to participate in the competition. In this instance, where participating offices are all housed in the same complex, spillover effects may be observed. This is where the energy efficiency messages directed at competing offices are affecting the offices that are randomly assigned to the control group [85]. In a case study where the goal is to maximize energy reduction this methodology may not be attractive since increasing the number of participants could improve energy reductions.

Another approach is a quasi-experimental competition design. When offices voluntarily participate or opt-out of the competition, the control group is self-selecting and may not accurately represent the overall sample and thus is a quasi-experimental design [85]. Offices that believe they will perform poorly may choose not to participate, whereas offices already enacting energy saving measures may choose to participate.

An alternative method for assessing the effectiveness of the competition can be determined by analyzing energy use before and after the start of the competition [85]. This method can be problematic when determining causation of any energy efficiency changes. External events can affect the sample, offices may naturally change their behaviour over time, and the energy use may regress towards a mean that does not reflect changes from participation in the competition [85]. For example, an external event, such as loud construction, could reduce energy use by an increase of employees working from home or leaving early due to the sound.

In this case study, a reduction of energy over time is possible due to energy efficiency messaging from the building operator that predates the competition. A regression towards a lower mean could be observed if the energy use data prior to the competition is collected in peak operating season and the competition data is collected during a less busy season where an above average number of employees are on vacation. Any causation between the implementation of the competition and reduction in energy use must be carefully analyzed to avoid any possible confounding factors.

3.2.6. Presenting Tenant Electricity Reduction

The measurement system used to present tenant electricity reductions should rank both high users and low users equally and use a method that does not unfairly favor any tenants. Therefore, a percentage reduction in total weekly electricity use is an attractive option (Equation (2)). The weekly electricity use only includes weekdays, so that tenants with variable weekend use do not get penalized.

For a percentage reduction, an appropriate baseline for each tenant must be determined. The baseline should be representative of the tenant's usage but also provide attainable reductions. Attainable reductions are part of maintaining positive competition messaging [80]. If the baseline is too challenging of a goal, then the competition may feel futile to tenants and occupants, especially for tenants with large base loads that cannot be changed.

The baseline took the average weekly total electricity use for each tenant (from Feb. 01 to Sept. 30) and added 15% of the standard deviation (Equation (4)).

Increasing the baseline with a portion of the standard deviation helps to account for tenants who had low average use but a relatively large standard deviation from seasonal changes, this is most notably due to consuming less electricity during summer months where employee vacations are more common. The addition of 15% of the standard deviation was determined based on the tenant electricity changes observed in week 1. This addition forces 10/30 tenants to show electricity reductions, up from 9/30 when comparing to the average only. The addition inflates the maximum week 1 tenant electricity reduction to 7.4%, up from 6.7%. The goal is to slightly inflate the baseline, without significantly changing electricity consumption results.

Since the baseline was derived using average electricity use, it was expected that in any given week half of tenants will be increasing and half will be decreasing their electricity consumption; this was not the case for competition week 1. In order to have balanced increasing and decreasing tenant electricity use, the baseline would have to be the average plus 53% of the standard deviation. Adding 53% of the standard deviation is not chosen as part of the baseline since this significantly changes results. Furthermore, the baseline was developed during week 1, and it was not known if week 1 was a representative week for the entire competition, so a conservative baseline (adding 15% not 53% of the standard deviation) was preferred.

This baseline excludes January since there were two tenants moving in at the beginning of the month and may not have representative electricity use during this period (Figure 3-1). In addition, weeks containing a holiday were omitted from the baseline (15-Feb, 25-Mar, 23-May, 01-Jul, 01-Aug, 05-Sep).

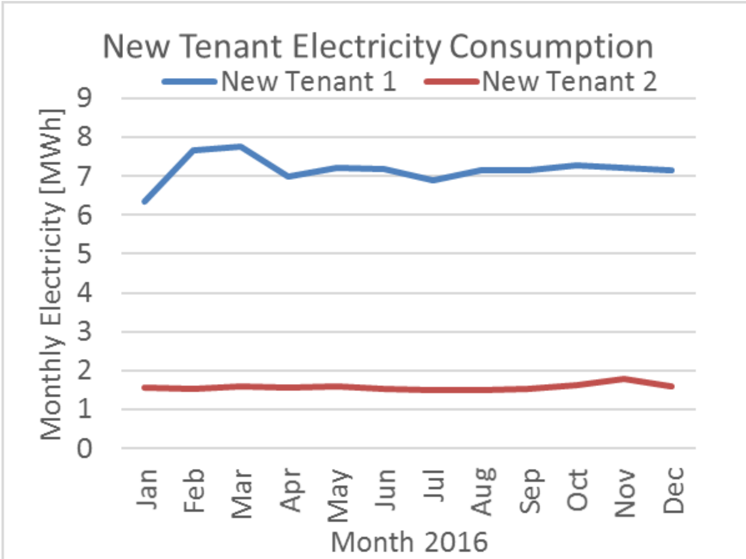


Figure 3-1: New tenant January electricity use and following months.

$$Percent\ Difference_i\ [\%] = 100\% * \frac{CompetitionWeek_{i,a} - BaselineWeek_i}{BaselineWeek_i} \quad \text{Equation (2)}$$

$$CompetitionWeek_{i,a} = \sum_{j=1}^{5} Total\ Daily\ Electricity\ Use_j\ [kWh] \quad \text{Equation (3)}$$

$$BaselineWeek_i = \overline{WeeklyE} + 0.15\left(\sqrt{\frac{\sum WeeklyE - \overline{WeeklyE}}{\#\ of\ weeks - 1}}\right) \quad \text{Equation (4)}$$

$$BaselineWeek_{i,a=2} = \frac{4}{5}\left(\overline{WeeklyE}\right) + 0.15\left(\sqrt{\frac{\sum WeeklyE - \overline{WeeklyE}}{\#\ of\ weeks - 1}}\right) \quad \text{Equation (5)}$$

where i is the tenant number, a is the competition week number, *j* is the business day of the week, *WeeklyE* is the total electricity used on business days each week for each tenant.

For week two of the energy reduction competition, the baseline is adjusted to the four-day work week in Equation (5), and for the competition week electricity use, the Thanksgiving holiday is omitted from Equation (3).

The average of weekly electricity use is a good baseline for tenant electricity use, since the majority of tenants do not have seasonal fluctuations in electricity use. This is shown in Figure 3-2, where monthly tenant electricity use is similar throughout the year. Conversely, base building electricity use has significant fluctuations between summer months and October, so the baseline will not capture electricity reductions for the base building.

The weekly electricity use data is also checked for normality using the Kolmogorov-Smirnov test. All tenants have normally distributed energy use within a 5% significance level. Normally distributed data validates the competition baseline because it is a function of the average electricity and standard deviation that represent normally distributed data. Non-normal data would be better represented with median values and quartiles, especially in cases where positive and negative variation from the median have significantly different ranges.

A drawback to this method of calculating a baseline is that it will favor tenants with large fluctuations in their energy use and may not exclusively capture tenants that use energy conservation measures.

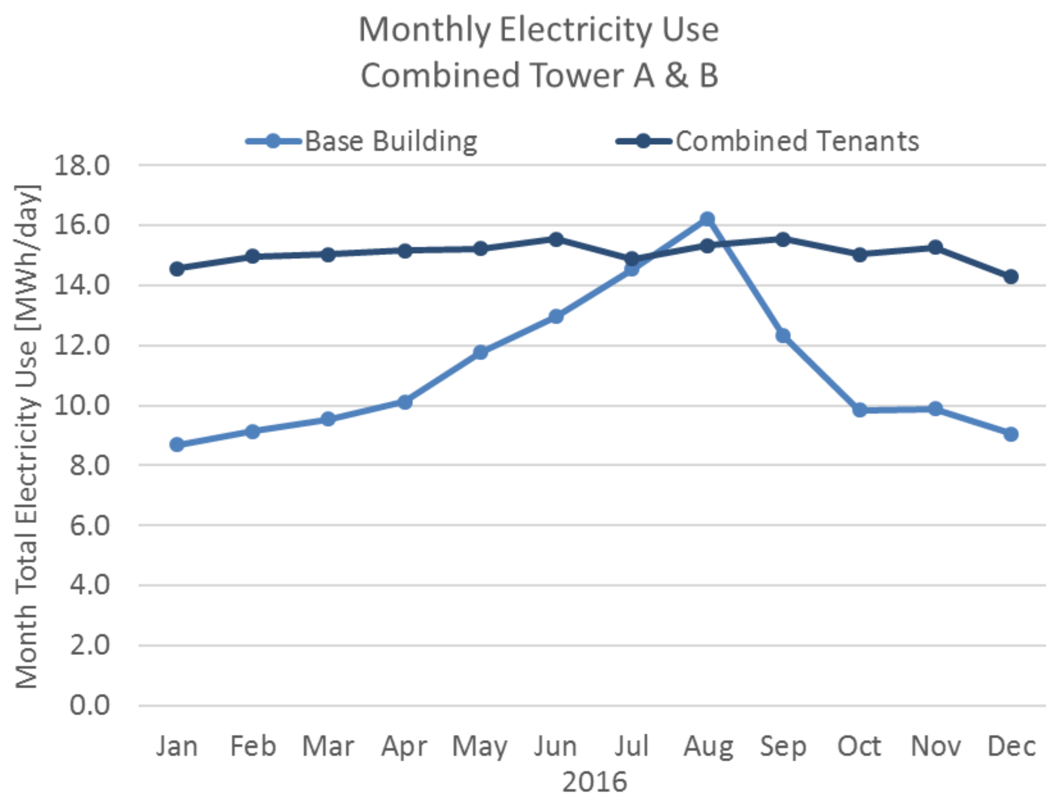


Figure 3-2: Monthly electricity use

3.2.7. Determining Significance

For tenants that increase or decrease their electricity use during the competition, their electricity consumption is assessed for significance by finding the probability that their electricity use falls outside of typical variations.

For each tenant the probability is determined using the Student t-distribution (Equation (6)) since there is a small sampling of 29 baseline weeks ($n < 30$) [86]. The probability, a one-sided 95% confidence interval (CI), is assessed for where electricity use will be above -t, where t=1.701, to determine significance of electricity reductions, and above +t for increases [86]. The weekly electricity consumption $x_{tenant\ i}$ in kWh is the threshold below which there is a 95% CI that there is an electricity reduction. The threshold is calculated with Equation (7) for each tenant where $s_{tenant\ i}$ is the tenant electricity use standard deviation and $\mu_{tenant\ i}$ is the tenant mean electricity use. The threshold is converted to a percent change in Equation (8) to allow for simple comparison between tenants, the results are tabulated in Table 3-2.

For tenants with an average electricity reduction during the 4 week competition in excess of the 95% CI the confidence interval is determined with Equation (6) and interpolated from t-distribution tables [86].

$$t = \frac{x_{tenant\ i} - \mu_{tenant\ i}}{s_{tenant\ i}/\sqrt{n}} \qquad \textit{Equation (6)}$$

$$x_{tenant\ i} = -1.701\left(\frac{s_{tenant\ i}}{\sqrt{29}}\right) + \mu_{tenant\ i} \qquad \textit{Equation (7)}$$

$$[percent\ change] = (x_{tenant\ i} - baseline)/baseline \qquad \textit{Equation (8)}$$

3.3. Analysis & Results

First the results discuss the electricity reduction pledges and effectiveness of promoting the individual competition in Tower A and B. Next, the electricity consumption for all tenants is presented along with the change in electricity use for light and plug load end uses for Tower B.

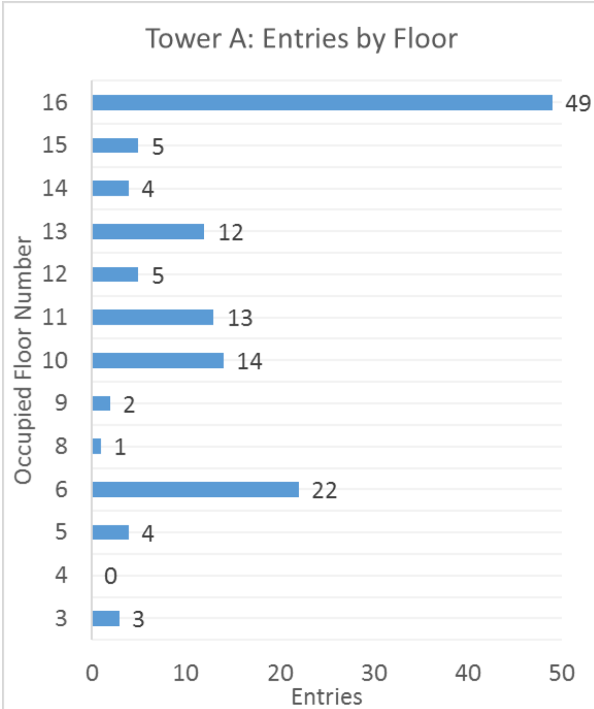
3.3.1. Electricity Reduction Pledges

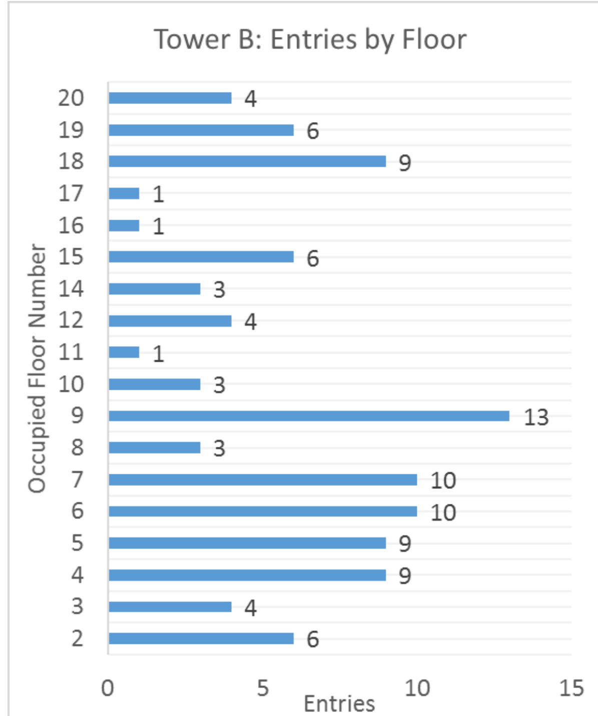
During the full month of October, there were 236 electricity reduction pledges. These pledges came from 144 different people, for an average of 1.27 entries each. Of these, 42 people entered more than once, for an average of 3.19 entries each.

A similar level of engagement is seen in both buildings, with 134 and 102 entries, from Tower A and B respectively. The distribution of entries by floor is markedly different between buildings (Figure 3-3). In Tower A, number of entries per floor range from 0 to 49. This shows that some floors are very engaged and are likely receiving competition promotional material from every communication method.

Floors 15 and 16 in Tower A are the same tenant, where more entrants indicated that the work on the 16th floor. This could be a result of a disproportionate number of personal offices on the 16th floor, with breakrooms, boardrooms and reception areas on the 15th floor (this layout is observed in other multi-floor tenant spaces). The high number of entries from this tenant is no surprise since they have a strong environmental platform and have a sustainability consultant as a staff member.

The 6th floor in Tower A also shows a large number of entries, this tenant occupies the full floor and has a pro-environmental tenant representative who met with researches for an informal energy audit. This tenant is also transitioning to off-site servers to reduce electricity consumption in their space.





Omitting unoccupied 7th floor.

Note: there is no 13th floor

Figure 3-3: Entries by building and floor number

The persistence of draw entries throughout the month also indicates a significant difference between Tower A and B (Figure 3-4). The biggest difference was seen during the three-day pre-competition time period, where the effect of different communication methods is seen. During the pre-competition days, Tower A had 3 entries and Tower B had 51. On September 28th, the competition introduction email was sent to all tenant representatives and posters were placed in both buildings. These strategies yielded three entries in each tower, showing that emails and posters alone were relatively ineffective at promoting the competition to individual occupants. On September 29th, a competition information booth was set up in Tower B, this included a laptop so occupants could enter early and pledge to change their behaviour on-the-spot. This yielded the remaining 48 entries for Tower B. This is the only time in the competition that this setup, allowing for immediate entries, was used and it was the most successful promotion method.

Week 3 has the lowest entries in both towers. This could be a result of the removal of competition posters from Wednesday through Friday. The posters had to be removed for visitors to the two towers, where the standard lobby look was reintroduced. The competition information booth was set up earlier in Week 3, on Monday and Tuesday. This could indicate that visual reminders of the competition are useful prompts during the competition.

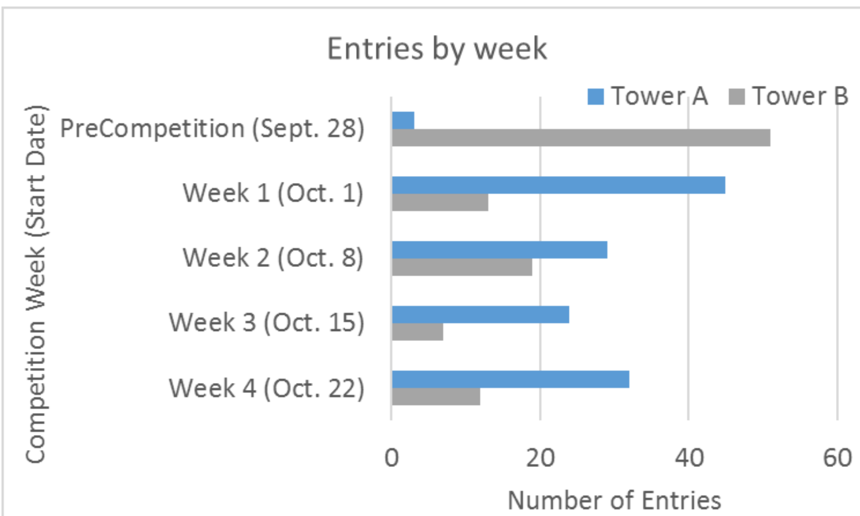


Figure 3-4: Competition entries, by week. Pre-competition entries were included with Week 1 for the purpose of incentives.

The content of the electricity reduction pledges was grouped and analyzed based on the coding of qualitative competition entries. The entries are 10.7 (s=8.4) words on average, ranging from 2 to 72 words. The shortest two entries are ‘print less’ and ‘unplug radio’.

Some entries included more than one electricity reduction behaviour change pledge, each pledge was coded individually based first on descriptive coding and second on in vivo coding techniques. The first level of coding is descriptive coding, where the code gives the topic but does not include specific content [87]. For example, the code is 'vampire', and the content is 'unplug vampire loads'. Descriptive coding is often used as a first phase for a large sample of data, and is useful in this application where multiple codes can be identified in each competition entry [88].

The top-level coded pledges are chosen as the 10 most common pledges determined using descriptive coding; they are: 'computers', 'electronics', 'lights', 'vampire loads', 'kitchen', 'communal space', 'printing', 'efficiency', 'shades', and 'other'. The average number of top-level coded pledges per entry is 1.48, with a maximum of 5 and minimum of 1.

The second iteration of coding uses the in vivo technique to give additional meaning to individual pledges when there is diversity within the simplified first coding. In vivo coding uses the actual words written in the entries to describe the data, these codes can be as short as one word or can be a longer phrase [87], [89]. For example, a pledge that is categorized as 'kitchen' and has the subcategories determined using in vivo coding, including: dishwasher, hand washing, mug use, kettle, lunch room TV, stop using Keurig pods.

3.3.1.1. Pledge Content

The building occupants indicated that they would complete a wide array of pro-environmental behaviours. These results give great insight into the available actions that occupants can complete within their offices. Results also give insight into the features of the individual tenant suites.

The top 10 electricity reduction pledges, seen in Figure 3-5, highlight behavioural changes that are widely applicable in the two office buildings.

The most common pledge was to turn off the lights. The majority of these pledges indicated they would turn off lights at the end of the day. A couple entries indicated that they would do so for short absences. The entries that note light shut offs for short absences indicates that the occupant either has a task light or works on a floor that invested in installed light switches. Access to light switches deviates from the standard base building layout provided to tenants, where shutting one light switch would mean turning off one quarter of the floor overhead lights.

Turning off computers, electronics and unplugging vampire loads were also popular pledges. Based on anecdotes from tenants, some offices never turn off computers (Tower B: Floor 15-16) where others have forced shut down procedures (Tower A: Floor 6), both gave IT updates as the reason for this behaviour. One floor (Tower B: Floor 19) ensures computers are shut off each night for security reasons.

The kitchen efficiency category includes a wide range of behavioural changes. The most popular were reusing mugs (6 pledges), efficiently using the kettle with less water or unplugging (3), and discontinuing use of coffee pods (2).

The ‘shut off communal space’ category is interesting since it shows some occupants look beyond the small items they control within their offices and take responsibility outside of their explicit domain. This is in stark contrast to anecdotes from the promotion booth, where a few occupants indicated that they had absolutely no control over energy use and therefore were not interested in participating. The communal space items included: TVs, boardroom technology, reception accent lights, lights in other people's offices, and boss's office lights.

The 'efficiency' category is almost exclusively optimizing computer electricity use (9 pledges), the remaining two concerned dimming of office lights.

Some of the most interesting pledges were the least common and were grouped into the 'other' category. There were five entries that indicated that they would leverage social pressure to reduce electricity in their offices. This is a potent energy conservation measure as previous studies have found significant energy reductions (4%) when there are peers promoting office energy reductions [77].

There were eight entrants that pledged to take the stairs between floors. In this building, the stairs are not accessible from the main floor for security reasons. Therefore, anyone pledging to use the stairs is likely doing so between floors in a multi-floor tenant suite or are taking the stairs to the gym.

Running equipment at night to take advantage of residential time-of-use rates, and completing adaptive behaviours (e.g. putting on a sweater) were each pledged three times.

Some unique pledges included: holding the elevator door to accommodate more people, use revolving doors in the lobby, work from home, hold virtual meetings and turn off excess monitors.

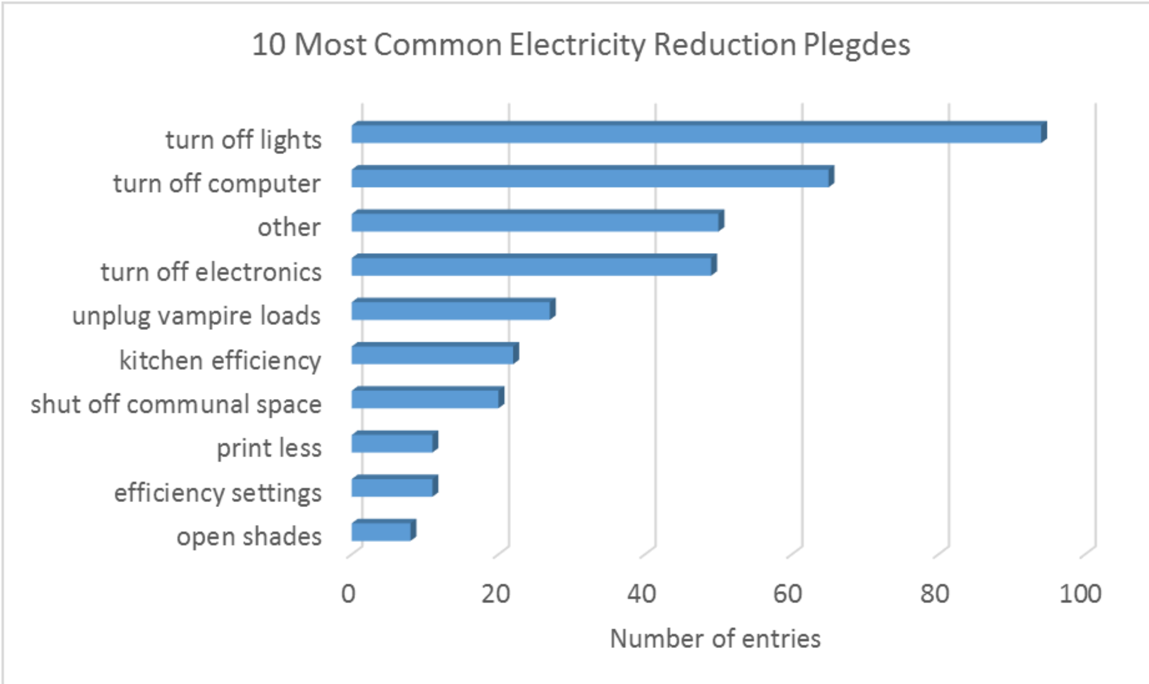


Figure 3-5: Electricity reduction behaviours

Some pledges were a little off-topic when they responded to the question “In your office, how will you reduce energy consumption?”. There were five pledges that indicated that they would take the bus or carpool to work, which would not affect building energy use. There were nine entrants that pledged a big change that may be outside the scope of the competition. For example, one entrant said they would “install blinds and shutters on [their] windows to block out the sun and reduce air conditioning loads”. Despite this being an interesting suggestion, it is unlikely that the occupant has the budget or authority within their office or the building to make such changes. In another more practical example, the entrant pledges to “install motion detecting light sensors”. It is possible that this intervention will be enacted since motion sensors are observed in two tenant suites, but it is unlikely that this change would occur during the time of the competition.

The written pledges show that occupants of the two office towers can come up with creative and impactful behaviour changes when prompted to do so. Since the written pledges were not publicly displayed there was no way to follow up to ensure the behaviour changes were completed. Previous research has shown that giving a written commitment to change is more effective than a verbal commitment and that changes are more likely to occur when the competition is ongoing, in this case, on a weekly basis [16], [31].

3.3.2. Tenant Electricity Reduction

Weekly tenant electricity reduction compared to the baseline result in 11 tenants reducing and 19 tenants increasing over the four competition weeks (Table 3-2). The combined tenant electricity use shows an increase of 2.21 MWh (a 0.68% increase) over the four weeks. This result suggests that electricity reductions are not occurring due to tenant behaviour change.

The Tower A and B total tenant electricity plus base building use shows a decrease in electricity use during the competition, resulting in 44.25 MWh less electricity use than the baseline. The baseline for the base building electricity use includes high summer demand, and is not appropriate for comparison to October electricity use which is lower.

Only one floor (Tower A: Floor 8) had electricity reductions every week of the competition. This floor holds three tenants and has an average weekday electricity use profile that is the lowest for the building and has the lowest three tenant EUIs for both buildings.

There are three tenants that have an average electricity reduction that falls below the one-sided 95% CI, in Table 3-2, and therefore have significant electricity reduction. The three tenants with significant electricity reductions are all in Tower A, they are located on floor 5b, floor 10 and floor 8, in order of significance. There are significant electricity consumption increases during the competition for 15 tenants that fall above a one-sided 95% CI (Figure 3-6).

*Table 3-2: Weekly electricity reductions during the competition, for each tenant, labelled by floor number. Reductions in electricity use are denoted with a shaded cell. The three tenants with electricity reductions determined as statistically significant are denoted with a bold font. *Two tenants' performance are not ranked due to large servers causing atypical electricity use fluctuations each week.*

	Tenant Numbered by Floor	Week 1	Week 2	Week 3	Week 4	Average [%]	Rank	95% CI reduction [%]
		Electricity Use Change [%]						
Tower A	1 - 4	-0.4	0.0	0.6	3.2	0.85	15	-1.26
	5a	1.6	0.7	3.7	1.8	1.96	21	-0.81
	5b	**-0.5**	**-6.3**	**-3.9**	**0.5**	**-2.57**	**3**	**-1.55**
	5c	1.5	0.1	5.3	3.2	2.52	22	-2.07
	6, 7 & 14	-1.6	0.1	1.2	1.4	0.27	12	-1.79
	8	**-3.0**	**-0.7**	**-3.5**	**-4.0**	**-2.79**	**2**	**-2.14**
	9	3.1	5.0	-0.7	-2.2	1.28	19	-1.76
	10	**-7.4**	**-5.8**	**0.8**	**-0.6**	**-3.29**	**1**	**-2.43**
	11	2.7	6.7	7.1	7.5	5.97	27	-2.17
Tower B	1	5.0	-4.7	0.2	-0.7	-0.04	10	-1.79
	2	3.0	1.5	2.0	-1.1	1.34	20	-2.50
	3	1.5	0.6	-1.3	1.7	0.60	14	-1.26
	4	46.6	39.5	43.0	51.7	45.18	*	-37.90
	5	-0.4	-3.1	-1.9	9.6	1.05	18	-2.01
	6	-2.0	-2.6	-2.8	3.9	-0.85	6	-1.20
	7a	1.3	2.2	2.1	-3.6	0.49	13	-1.70
	7b	7.5	4.5	0.3	2.6	3.70	26	-1.81
	8	3.9	4.0	4.4	-0.5	2.96	24	-0.94
	9	-1.2	0.2	-1.8	0.6	-0.55	8	-1.70
	10	0.3	2.3	1.4	-0.2	0.94	17	-1.42
	11	-1.5	-0.8	1.3	0.4	-0.16	9	-2.47
	12a	4.7	6.0	-10.8	-6.2	-1.56	4	-5.83
	12b	4.6	6.4	-9.2	-4.7	-0.75	7	-5.39
	13	1.2	0.8	0.6	-2.1	0.14	11	-0.78
	14	1.8	2.1	1.7	-2.2	0.86	16	-0.99
	15a	8.1	-20.4	2.0	-24.8	-8.79	*	-9.59
	15b	2.7	-2.4	7.4	3.3	2.76	23	-2.40
	16	0.1	-1.3	-3.3	0.9	-0.90	5	-1.22
	17	2.6	9.8	7.6	9.6	7.39	28	-1.59
	18	-1.5	4.3	4.3	5.5	3.17	25	-1.28

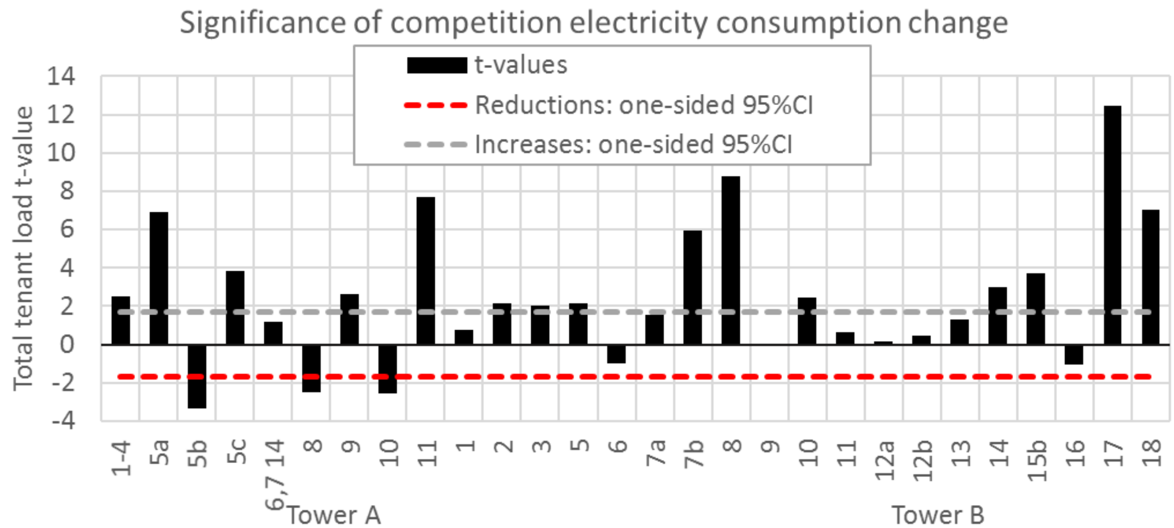


Figure 3-6: Student t-values for each tenant average electricity change over the competition month. Increases with a t-value above the corresponding one-sided 95% CI are significant, and reductions below the reductions 95% CI are significant.

Total tenant electricity use did not decrease during the competition, but plug load electricity decreased by 437 kWh across all tenants in Tower B. This is an average reduction of 0.7% across all floors, ranging from a 6.9% reduction to a 4.1% increase in electricity use over the month of October (Figure 3-7). Most floors show large electricity use fluctuations between weeks, so the Student t-values are determined to find if plug load reductions and increases are significant and are presented in Figure 3-8. There are seven floors of 18 with significant electricity reductions, this is outside of the one-sided 95% CI for each tenant (Tower B: Floors 4, 6, 8, 9, 14, 15 and 16). There are also two floors (Tower B: Floors 3 and 18) with a significant increase in plug load consumption, above a one-sided 95% CI.

Floor 13 in Tower B includes a significant server in its plug load, resulting in a baseline electricity use that is 2.7 times higher than the next highest baseline plug load. This high baseline is paired with a low inter-week electricity change, creating a consistent plug load electricity consumption profile that is unlikely to be influenced by occupant behaviour changes.

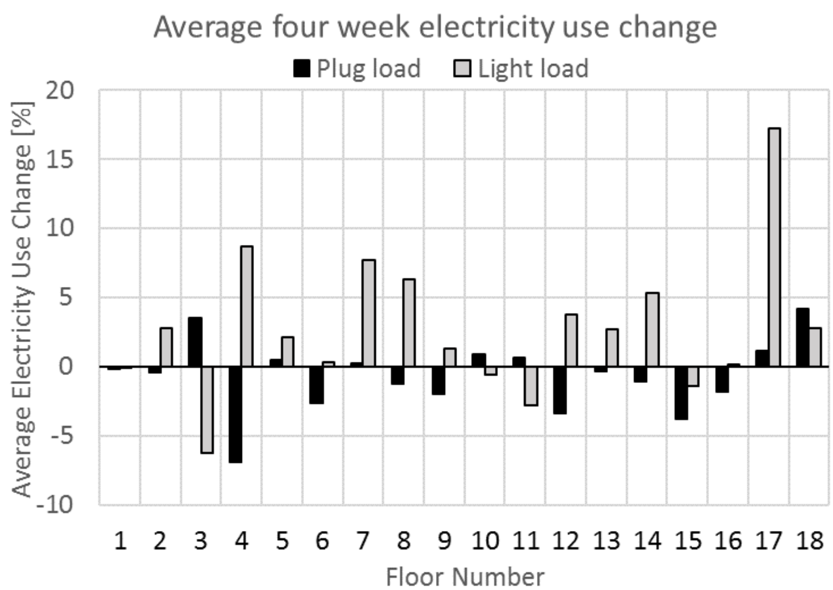


Figure 3-7: Plug load and light load electricity consumption change in Tower B. A server load is included in floor 13.

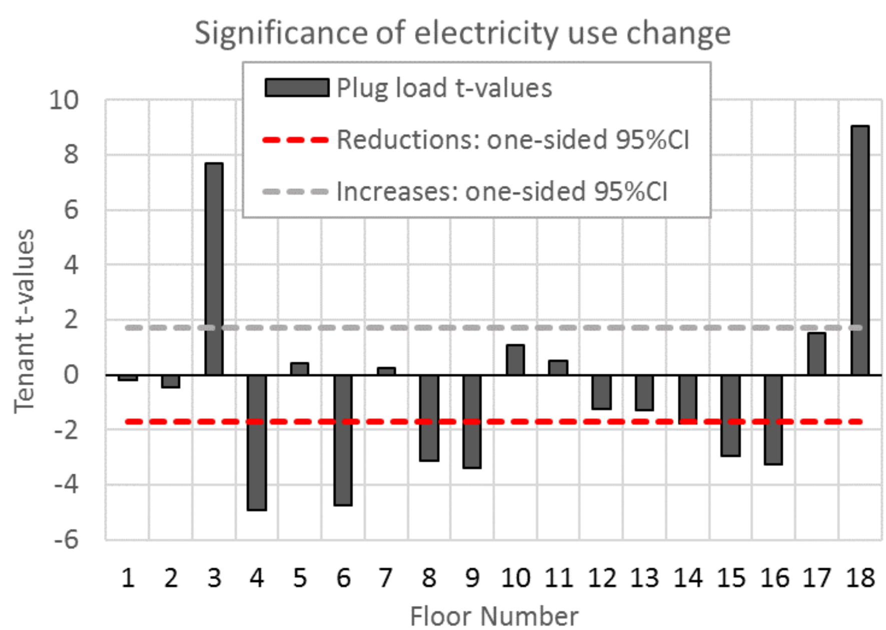


Figure 3-8: Student t-values for tenant plug load electricity change during the one-month competition

During the competition month, the light load increases by 1381 kWh in Tower B. The average increase in light electricity use is 2.8% across all floors, ranging from a 6.3%

reduction to a 17.2% increase over the month of October (Figure 3-7). There are only two floors with significant light load reductions, and 11 floors with significant increases when compared to their respective one-sided 95% CIs.

This overall and significant increase in light load could be the result of shortening daylight hours in October resulting in an increased duration of artificial lighting. The competition baseline period spans February to September and therefore includes a greater portion of summer months with longer daylight hours than October. In Figure 3-10, the weekly light loads in Tower B fluctuate with the hours of sunlight, with a coefficient of determination of 0.47. Highlighted in yellow are weeks in February and March with a comparable number of sunlight hours as the October competition weeks. The comparable weeks have similar hours of sunlight, but different sunrise times which could explain the difference in light loads between the October competition and the comparison weeks (Table 3-3). This analysis suggests that sunrise and hours of daylight could significantly increase light loads in October above the baseline consumption.

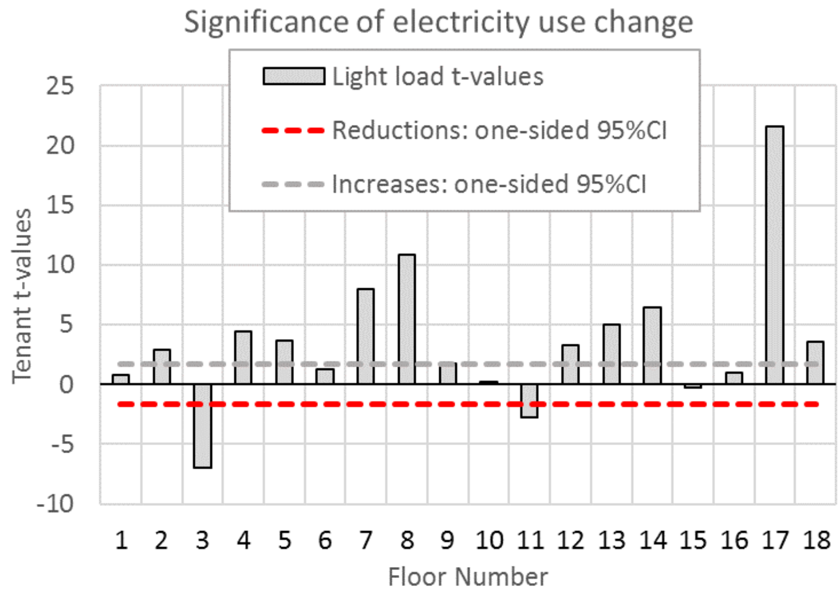


Figure 3-9: Student t-values for change in light load use during the one-month competition

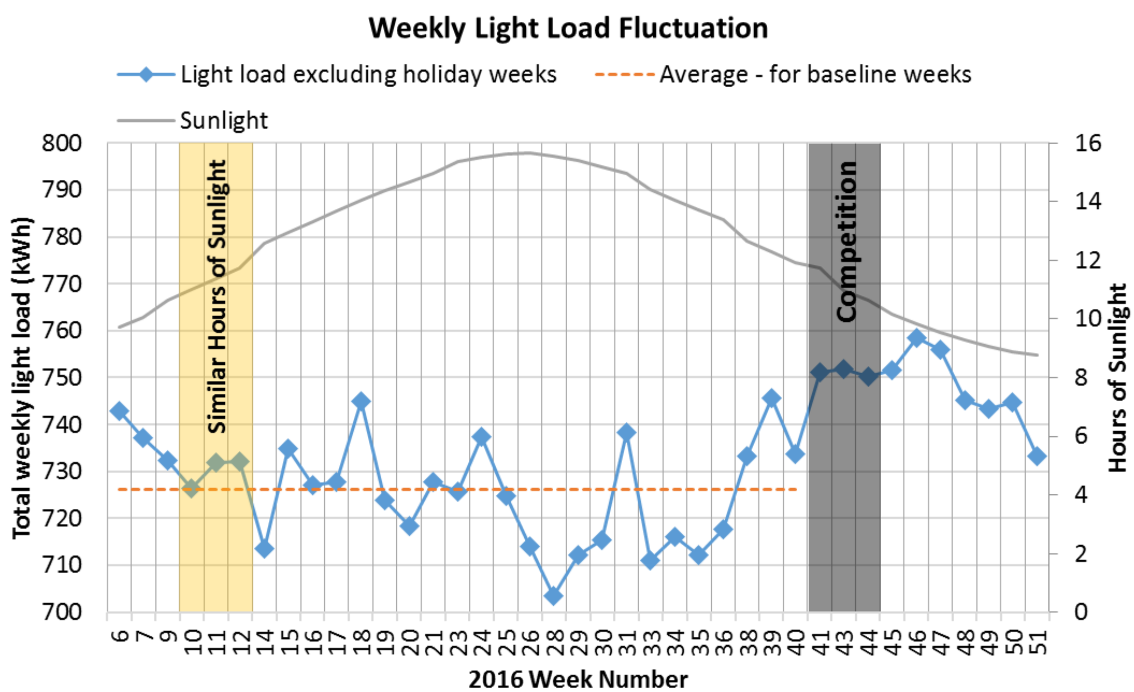


Figure 3-10: Tower B light load paired with hours of sunlight, spanning baseline, competition and post competition weeks.

Table 3-3: Sunrise and sunset times

Date	Sunrise	Sunset	Hours of Sunlight (hh:mm)
Longest Day			
20-Jun	5:14	20:54	15:40
Competition Month			
01-Oct	7	18:42	11:44
08-Oct	7:10	18:29	11:19
15-Oct	7:19	18:16	10:57
21-Oct	7:27	18:06	10:39
Similar Month			
20-Feb	6:57	17:36	10:39
27-Feb	6:45	17:46	11:00
05-Mar	6:32	17:56	11:23
12-Mar	6:20	18:05	11:45

3.4. Discussion

This study found that in-person promotion and on-the-spot behaviour change pledges are an important part of promoting an electricity conservation competition in a multi-tenant commercial building. This method is costlier than email promotion but is more likely to reach building occupants as email communication may not be forwarded from tenants to their occupants and employees. In addition, this method allows occupants to make pledges immediately without having to take further initiative to access the competition website.

Overall, participation persistence within the one-month competition is low, with only 30% of pledgers entering more than once. This result could indicate a number of things; that participants were unlikely to have persistent behaviour change after the competition, communication was poor, or that interest in electricity conservation was low. Communication with building occupants was a significant barrier and information was not passed along effectively, either occupants didn't hear of the competition at the beginning, or they did not know to enter each week. The ease of entering the competition draw was also a communication barrier, where it was either not easy enough or potential participants did not know the URL for the competition webpage. Ease of entering the competition was reduced for occupants that did not get weekly competition results emails forwarded to them and for occupants that had not collected a competition business card at the information booth.

For occupants who responded to the open-ended question with their pledge to change behaviour, many participants demonstrated a high level of electricity reduction literacy, for example many were aware of and reducing electricity consumption by unplugging vampire loads or reducing internal heat gain from appliances.

3.4.1. Effect on Electricity Use

Based on this case study, there is no verifiable reduction in total electricity use due to occupant or tenant behaviour change. The best measure of office participation is number of entries. The coefficient of determination is $R^2 = 0.079$ between competition entries and average tenant electricity change. This suggests that participation levels are not correlated to electricity use.

The lack of correlation could be in-part due to the coarse tenant electricity use data, which includes all end uses, light, plug and exceptional tenant loads.

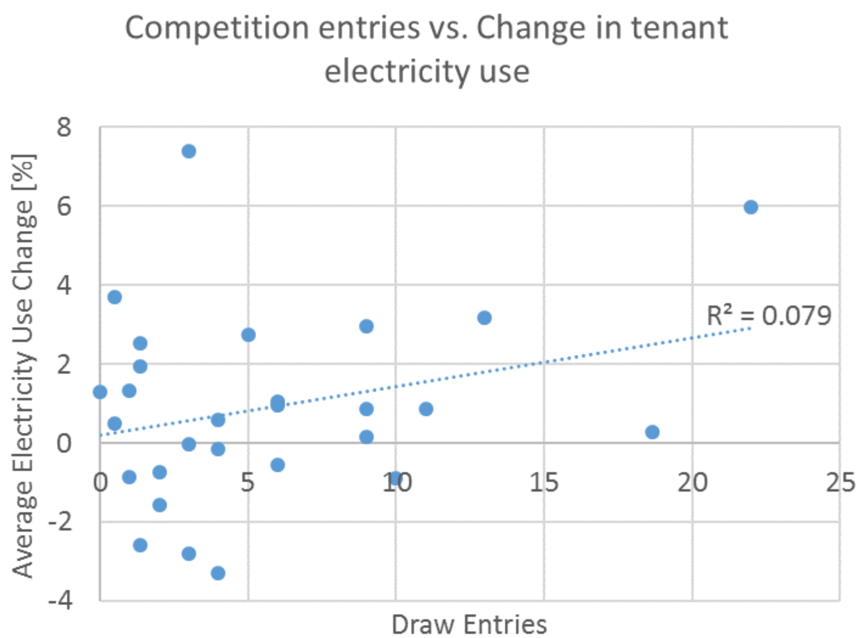


Figure 3-11: Correlation between competition participation and tenant electricity use. For multi-tenant floors, total floor entries are divided evenly by tenants (e.g. Tower B, tenants on floor 3a and 3b). For tenants on multiple floors (e.g. Tower A, tenant on floors 10 – 13) total entries are divided by number of occupied floors.

3.4.2. Plug and Light Loads

The occupant behaviour change pledges were grouped by the affected end use type, resulting in 63% of behaviour changes reducing plug loads, 29% reducing light loads and 8% affecting neither. Some of the 'turn off lights' pledges may have actually caused a reduction in plug loads instead, since task lighting is part of the plug load circuit.

The suggestion, based on behaviour change pledges, that occupants affect plug loads more that light loads is further supported by the electricity consumption results from Tower B. When plug and light loads were analyzed separately, the plug load was lower during the competition than the baseline, with significant reductions occurring in seven of 18 commercial floors. The light loads were significantly higher in October than the baseline period, but this may be the result of reduced available daylight.

The combination of behaviour change pledges and plug load electricity reductions suggests that tenants and occupants in commercial buildings have greatest control over the tenant plug load end use.

3.5. Conclusions

This study implemented a one-month electricity reduction competition between commercial floors in two office buildings. The five greatest-reducing commercial floors were published weekly to foster competition and participation from tenants and occupants. Simultaneously, there was a weekly prize draw for building occupants who pledged to complete specific behaviour changes during the competition.

During the competition, there were 236 occupant behaviour change draw entries, covering popular office energy reducing behaviours from turning off computers to printing less often. The majority of behaviours pledged by occupants would result in reduced plug load electricity consumption. It is recommended that future studies target specific plug load reducing behaviours, since occupants may have greater control over this end use compared with light loads.

When analyzing total tenant electricity reductions across both Tower A and B, the one-month electricity reduction competition did not result in electricity reductions. Of 28 tenants, significant tenant electricity reductions were observed in only three tenants, where 15 tenants had significant increases in electricity use.

The 18 floors in Tower B were analyzed for significant electricity use changes in plug and light load end uses, separately. Plug load electricity was observed to significantly reduce on seven and increase on two commercial floors. Light load electricity significantly reduced for only two floors and increased on 11 floors. These results could indicate that tenants and occupants have greater control over plug load end use compared with light loads, and that external factors increased light load electricity consumption during the competition.

This study found tenant representatives to be a significant barrier to communication and promotion of the electricity reduction competition. For future competitions in a multi-tenant commercial building, it is recommended to have tenant representatives pledge to participate and making it mandatory for participating representatives to forward competition emails to their office occupants. By securing the tenant representatives' pledge to forward emails, two experimental groups can be formed to determine the effect of tenant representatives' participation on electricity use. Alternatively, in buildings without full tenant participation, it is recommended to promote an energy reduction competition with information booths where occupants are signed up in-person, and therefore not requiring information from tenant representatives.

4. Post-Submetering Electricity Measurement

4.1. Introduction

Implementing submetering in a commercial building is complex and must allocate electricity costs to tenants based on a fluctuating electricity price schedule [90]. In a multi-tenant commercial building, existing tenants can complicate the submetering implementation process by resisting installation, especially if existing lease contracts do not have provisions for submetered billing or the financial responsibility for installation is unclear.

In a commercial building setting, the implementation of submetering can result in energy savings ranging anywhere from 1% to 20% [90]–[92]. Submetering data can help both building operators and tenants reduce electricity through identifying inefficiencies, choosing appropriate equipment upgrades, and altering day-to-day activities. Since the new submeters were installed and used to create feedback only on tenant electricity use, any reductions to electricity consumption will be a result of tenants reducing their consumption and not changes to base building operations. The submetering data and feedback is used by tenants within their leased suites to incentivise any reductions in electricity consumption.

This chapter includes two key methods for measuring the effect of submetering on electricity use. Tenants were aware of the implementation of submetering only one month following installation; therefore, the baseline of submetered tenant electricity use is not adequately large to compare before and after tenant awareness of submetering. Once tenants are aware of submetering their electricity consumption behaviour has potentially been altered. The lack of an ideal baseline results in the choice of two alternate baselines that conform to measurement and verification best practices. The benefits and limitations to each alternate analysis method is discussed with their respective results.

The hypothesis is that submetering will lead to modest electricity reductions over the first 15 months post-submetering implementation. This hypothesis is based on the long-term effect of incremental changes within commercial tenant suites. Another building in the property managers' portfolio shows the long-term effects of submetering, where they successfully reduced electricity consumption by 10%, through a combination of tenant and base building changes.

4.2. Methodology

This section details the development of two methods for comparing tenant electricity use from before and after submetering, each with its own pros and cons.

This measurement and verification (M&V) reporting process follows the steps and recommendations as the SaveOnEnergy retrofit program, the *International Performance Measurement and Verification Protocol* and the OPA's *Conservation First* guideline [93]–[95]. These standardized methodologies are used to prove energy savings following the implementation of submetering as an energy conservation measure, incentivized by the SaveOnEnergy program.

4.2.1. Data Collection

The minimum data collection period following the implementation of submetering is six months [94]. This section assesses 15 months of hourly electricity interval data, from January 2016 to March 2017, inclusive. The data collected includes the tenant load that was submetered and does not include vacant spaces, to conform to the guidelines [93].

4.2.2. Electricity Consumption

The implementation of submetering was expected to result in a reduction in tenant controlled electricity use, for all tenant electricity end uses.

Comparing electricity use before and after submetering has some challenges. Electricity use data from before submetering implementation combines tenant loads with base building loads which include HVAC equipment and chillers that are weather dependant.

To avoid the challenges of comparing to pre-submetering years, tenant loads can be compared with the submetered tenant consumption recorded during the first few months following submetering. The first few months following submetering implementation were expected to have similar consumption patterns to pre-submetering because tenants were unlikely to have made immediate and significant changes to their electricity use within this short time period. Tenant representatives were only informed of the submetering implementation in February, starting at the beginning of the month for the highly-involved tenant focus group, with the disclosure of submetering to all tenants on February 29, 2016. Following the disclosure of the submetering implementation, tenants were given electricity use feedback through the online dashboard starting on March 22, 2016. For the majority of tenants, they did not receive an electricity bill for a one-year period, where electricity use was charged as a line item in their lease. For a select few tenants with significant projected cost increases due to electricity use, they were given the option of monthly bills starting in February. Since the majority of tenants do not have any electricity feedback or financial responsibility during February and March, this two-month time period is the best approximation of a pre-submetering baseline.

Both the comparison between before and after submetering (Method 1) and between early submetering months and later submetering months (Method 2) conform to the SaveOnEnergy M&V program [93].

4.2.2.1. Method 1: Before and After Submetering

Method 1 compares like months and has the most complete baseline data set by choosing a full year, 2015, as the comparison to the submetered 2016 data. Since tenant submetering data is not available for 2015, one data set for electricity consumption in Tower A and B must be used for comparison purposes. The total electricity consumption for Tower A and B includes tenant loads plus base building loads, including air conditioning and ventilation loads.

Method 1 follows the guidelines for Option B of the IPMVP and the SaveOnEnergy retrofit program [93], [94]. The guidelines require a full year of monthly electricity use prior to submetering to be compared with a minimum of four months of post-submetering data [94].

4.2.2.2. 2015 Electricity Adjustment

Between 2015 and 2016 the base building electricity consumption was assumed to be equivalent as there were no building upgrades that affected electricity consumption during this period.

Two new tenants moved into Tower A and B at the start of 2016, the associated increase in electricity use must be accounted for when comparing 2016 with 2015 data.

Equation (9) is used to determine the effect of the new tenants' electricity use on total tenant electricity. The average monthly fraction of new tenant electricity is determined as $\Delta_{occupancy}$=0.019396 of total building electricity use. This fraction is used to adjust the 2015 monthly electricity use in Equation (10), increasing it for better comparison with 2016.

$$\Delta_{occupancy} = \frac{1}{12}\sum_{i=1}^{12}\frac{NewTenant1_i + NewTenant2_i}{AllTenants_i - (NewTenant1_i + NewTenant2_i)} \qquad \text{Equation (9)}$$

$$E2015_{i,\ Adjusted\ for\ occupancy} = E2015_i * (1 + \Delta_{occupancy}) \qquad \text{Equation (10)}$$

where i is month number, $NewTenant1_i$ and $NewTenant2_i$ are the monthly electricity use in kWh for the two new tenants in 2016, $AllTenants_i$ is the monthly electricity use in kWh combined for all tenants in 2016, $\Delta_{occupancy}$ is the fraction of electricity use from new 2016 tenants, $E2015_i$ is the 2015 monthly electricity use for the whole building in kWh, $E2015_{i,\ Adjusted\ for\ occupancy}$ is the 2015 monthly electricity use in kWh for the whole building at 2016 occupancy rates.

4.2.2.3. Adjusting for Weather Conditions

The 2015 adjustment for weather conditions is built upon the 2015 building electricity use that is already adjusted for occupancy changes. Changes in outdoor temperature affects how much cooling electricity is consumed by the base building in Tower A and B. The cooling degree day (CDD) method is applied to 2015 monthly electricity use to approximate the effect of outdoor air temperature on building electricity consumption. By approximating the effect of cooling degree days, the electricity consumption trends between years can be more accurately compared. In Tower A and B, heating energy comes from natural gas and therefore is not analyzed.

Balance Point Temperature

Before determining the monthly CDDs, a balance point temperature (a.k.a. base temperature) for the combined Tower A and B must be determined. The balance point temperature is the point above which CDDs are counted. The traditional method of calculation uses 18.3°C for all applications in North America and 15.5°C in the United Kingdom [86], [96], [97].

The more accurate variable base degree day method determines a balance point temperature for the specific case building [86]. This balance point temperature is the point at which the building's heat gains equal its heat losses [86], [98]. A balance point temperature lower than in the traditional calculation method was expected due to the size and function of Tower A and B. Tower A and B have high internal heat gains from occupants, lights, office plug loads and server rooms. Tower A and B have highly compact rectangular floor plates, this shape reduces heat loss to the exterior [99]. The building envelope is highly glazed with double-pane tinted windows, this increases solar heat gains and increases cooling loads [99]. Tower A and B are large and complex buildings, so determining a balance point temperature by measuring each source of heat loss and heat gain in the complex is impractical and therefore the balance point temperature must be estimated.

There are two common methods to estimate the buildings' balance point temperature using only electricity consumption and outdoor air temperature, the performance line and energy signature methods [97].

To estimate the buildings' balance point temperature using the performance line method, the coefficient of determination is assessed between CDDs and building electricity use. The CDDs are calculated for different balance point temperatures and the highest resulting coefficient determines the most appropriate balance point [97].

For Tower A and B, the monthly CDDs are determined for each balance point temperature at 0.5°C intervals from 4.5°C - 14.5°C, and compared with 2015 monthly electricity use. Both CDDs and monthly electricity use are divided by number of days in the month for more accurate monthly comparison. The balance point temperature that best approximates a linear relationship between CDDs and electricity use is 9°C (Table 4-1).

Table 4-1: Determining CDD balance temperature of 9°C using the coefficient of determination. This table is a subset of balance temperatures, the full data set was checked at 0.5°C intervals from 4.5 to 14.5 °C.

	2015 Total building electricity use	[CDD/day]						
		Balance Temperature [°C]						
Month	[MWh/day]	6.5	7.5	8.5	9	9.5	10.5	11.5
Jan	24.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Feb	25.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mar	25.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Apr	25.7	2.5	2.1	1.7	1.5	1.4	1.1	0.9
May	26.7	9.8	8.8	8.0	7.5	7.1	6.3	5.5
Jun	29.0	11.0	10.1	9.1	8.6	8.1	7.2	6.3
Jul	29.8	14.6	13.6	12.6	12.1	11.6	10.6	9.6
Aug	29.5	13.4	12.4	11.4	10.9	10.4	9.4	8.5
Sep	29.6	11.6	10.6	9.6	9.1	8.7	7.7	6.8
Oct	25.7	2.5	2.0	1.6	1.4	1.2	0.9	0.6
Nov	25.9	1.6	1.2	0.9	0.8	0.7	0.5	0.4
Dec	24.3	0.3	0.2	0.1	0.1	0.1	0.1	0.1
Coefficient of Determination (R^2)		0.8988	0.9021	0.9027	0.9035	0.9025	0.9008	0.8980

The energy signature method was used to check the balance point temperature that was estimated with the performance line method. The energy signature method plots the energy use against temperature to find the balance point temperature at which the temperature independent base load occurs [97]. For total building energy use, including the heating and cooling loads, the plot will look like Figure 4-1. With sufficient data points the balance point temperature can be estimated directly for the plot [100].

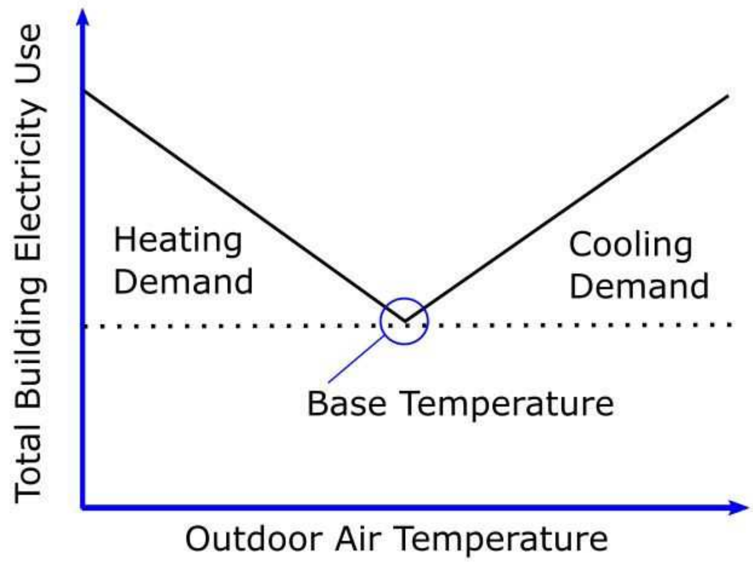


Figure 4-1: Theoretical trend in temperature dependant electricity consumption [97]

For Tower A and B, the energy signature plot will only include electricity consumption and therefore will only capture the temperature independent load and the cooling load. Theoretically, this will present at a plot with a slope of zero for all outdoor temperatures below the balance point, and an increasing linear curve above the balance point.

In Figure 4-2 the monthly electricity use is plotted against the average of the daily mean outdoor air temperatures, for both 2015 and 2016. A piecewise function is plotted to simplify the expression, each function is the linear regression for temperatures above and below the 9°C balance point temperature [101]. Where the piecewise functions meet there is a discrepancy of only 1.01 MWh/day, this is a relatively small discrepancy considering there is a gap in data points near the balance point temperature. The resulting piecewise function for the energy signature plot is reasonable for a balance point temperature of 9°C, therefore confirming the estimate from the performance line method.

The shape of the piecewise function, with a near zero slope below the balance point and a positive slope above, indicates that heating related electricity use does not significantly affect the total electricity use below 9°C. If the heating electricity use was significant, including only fans and pumps and not the heat energy source, it would present in the graph as a negative slope.

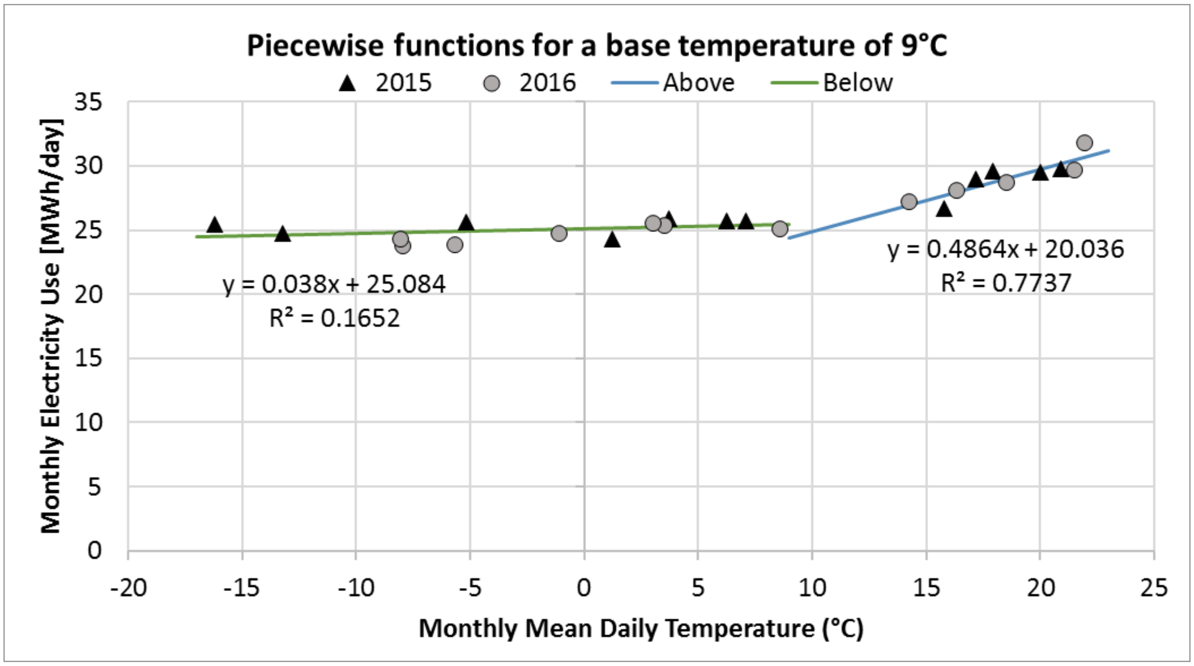


Figure 4-2: Trend in 2015 and 2016 electricity consumption

CDD Calculation

For the calculation of CDDs there were two available methods, the mean temperature method and the integration method. The mean temperature method calculates the CDDs for each day using the mean temperature and takes a summation for each month. This method does not account for large fluctuations during the day that may affect building electricity use.

The integration method is chosen since it calculates CDDs from all available data, theoretically it could use an infinite number of temperature recordings. Since the outdoor air temperature is recorded hourly, the CDD calculation takes the form of Equation (11); the CDDs are divided by days to normalize across months. To calculate CDDs, n is number of days per month, j is hours in a day, t_j is recorded outdoor air temperature, t_b is the balance point temperature,

$$\frac{CDD}{day} = \frac{1}{n} * \sum_{i=1}^{n} \left(\sum_{j=1}^{24} MAX\{t_j - t_b, 0°\mathrm{C}\} * \frac{1}{24} \right). \tag{11}$$

Equation (11)

Electricity Adjustment With CDD

A linear regression of 2015 CDDs and electricity use was determined for the balance temperature of 9°C (Figure 4-3) in order to determine the expected electricity use based on the CDDs. This allows for the adjustment of 2015 electricity use based on the observed CDDs from 2016, allowing for weather adjusted comparisons between the two years. The correlation between 2015 electricity use and CDD is strong, with a coefficient of determination of 0.9035. This strong correlation includes months with zero CDD, which typically create scatter [98].

Looking at 2016 electricity use, in Figure 4-3, the monthly CDDs are strongly correlated with base building electricity use (R^2=0.9485), but not correlated with aggregated tenant electricity use. In Figure 4-3 the linear regression for 2016 has a lower y-intercept and greater slope than the linear regression for 2015; this suggests that electricity reductions have occurred in the 2016 base load.

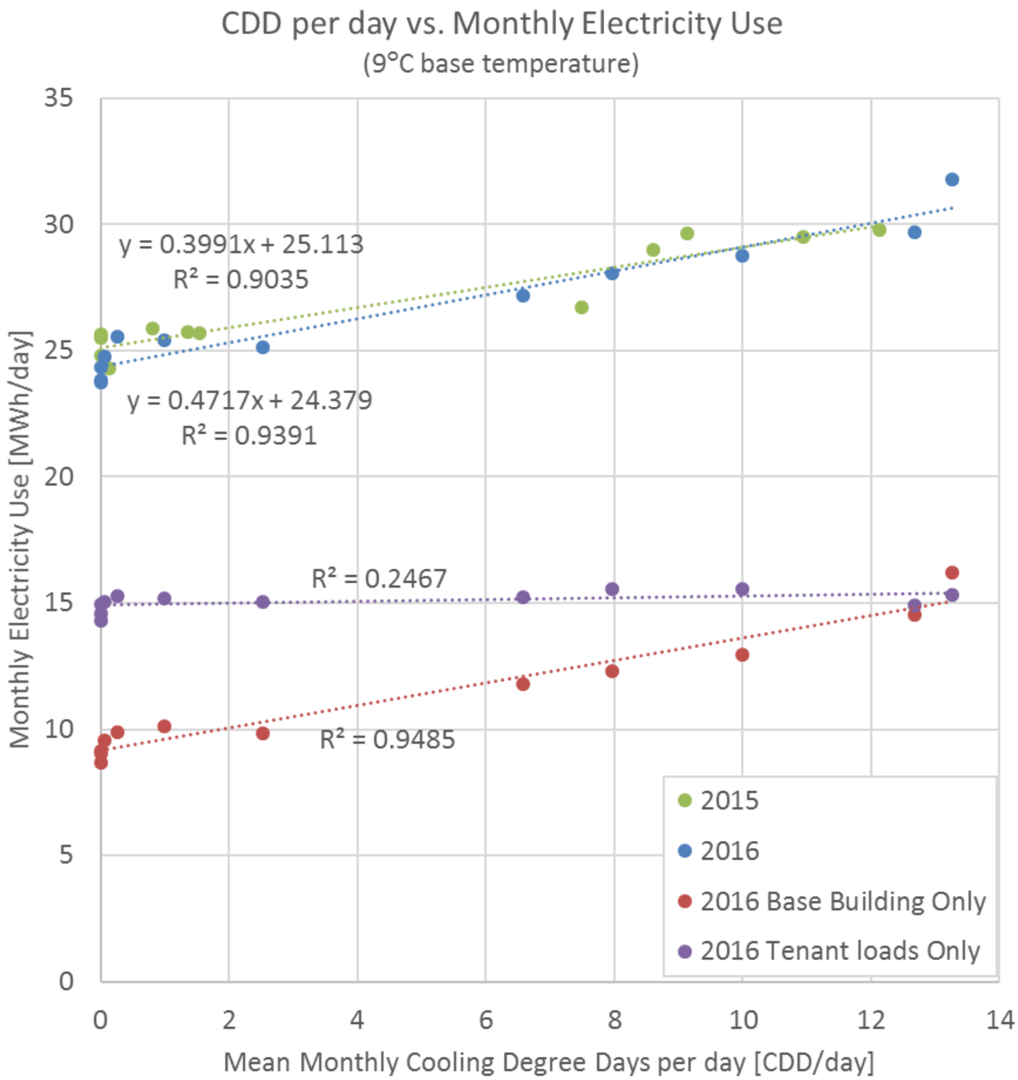


Figure 4-3: Linear regression of CDD

Using the 2015 linear regression, the resulting 2015 electricity adjustment is Equation (12), where monthly 2016 CDDs are inputs. In this equation, the number of days per month are accounted for and the proportion of weekdays and weekends in each month is assumed to be similar.

$$E_{2015\, weather\, adjusted,\ i}\left[\frac{MWh}{day}\right] = 0.3991 * \frac{CDD\ 2016_i}{days_i} + 25.113 \qquad \text{Equation (12)}$$

$$E_{year}\left[\frac{MWh}{day}\right] = \frac{\sum month\ total\ electricity\ [MWh]}{Days\ in\ a\ year}$$ Equation (13)

Equation (12) is used to adjust the monthly electricity use from 2015 with CDDs from 2016 for each month *i*. The cooling degree day method has more uncertainty during months that fluctuate above and below the balance point temperature [96]. Therefore, the adjustment is applied for all months with a monthly CDD per day greater than 1.0, this is equivalent to a month with a mean temperature of 10°C. This exclusion of months with 1.0 CDD per day or less excludes months that are less affected by cooling loads and have more uncertainty. The resulting adjusted months are from May to October. For comparing the full year electricity use Equation (13) is used.

Limitations of CDD Method

When only the outdoor air temperature is available, the best approximation of weather effects on building electricity use is the degree day method, but this method has many limitations [97], [100].

The greatest limitation is determining the balance point temperature for the building since the heat gain and loss can be complex and is difficult to directly measure [97], [98]. The building shape will significantly affect building heat flow and therefore will affect the choice of balance point temperature [99]. The degree day method is less accurate in commercial applications, when compared to small residential, in part due to complex and unevenly distributed internal heat gains [99]. In non-steady state cases, the balance point temperature will not be constant throughout the year, this case applies to Tower A and B because in a commercial application the building is only occupied with full internal heat gains during work hours, fluctuating weekly or seasonally [96], [98]. In a study by Valor, Meneu and Caselles [100], a significant reduction in electricity use is observed in August due to employee holidays, not due to a relationship with degree days.

The temperature used in the degree day method is based on only the sensible heat that creates conduction through the building envelope, this ignores humidity, wind speed and solar radiation. In the highly glazed Tower A and B, the effects of solar radiation will be significant. The combination of air temperature and solar radiation on a building results in either a net heat gain or loss that will take a period of time to affect the building. The time period that weather conditions affect the building is based on its materials, it is called the building's thermal response time (or thermal inertia) [96], [99]. Therefore, temperature and incident solar radiation conditions within the thermal response time will affect instantaneous electricity consumption. To express this effect in a temperature, the "effective temperature" is a weighted calculation of previous thermal conditions [96]. The effective temperature is less variable than the recorded temperature, especially for large buildings like Tower A and B. This effect can result in higher electricity use during a heat wave spanning multiple days resulting in an elevated effective temperature, than would be predicted using the instantaneous recorded temperature to calculate CDDs.

The cooling and heating equipment efficiencies and characteristics can affect the accuracy of the degree day method, especially if determining a linear electricity use adjustment [99]. The chiller electricity use is not linearly related to outdoor air temperature since the equipment coefficient of performance is not linearly related between full and part load [96]. In addition, cooling equipment with limited power can result in a temperature where the maximum cooling power is attained, above this temperature the electricity use could remain constant [100].

4.2.2.4. Method 2: Post-Submetering Baseline

This method uses electricity consumption data for tenant controlled loads, including plug, light and exceptional loads, and excluding the base building component. Here, the baseline energy use is created using February and March 2016 monthly data. This baseline is compared to energy use in later months after tenants have energy use feedback and are more likely to control their behaviour. The baseline excludes January since two tenants were in the process of moving in and do not have representative electricity use.

Weather conditions do not significantly affect the submetered tenant electricity use, with no relationship between total tenant electricity and CDDs (see Figure 4-3). For a select few tenants, their exceptional load was affected by outdoor air temperature due to the use of chillers to cool large servers. The tenant electricity use can be indirectly influenced by external conditions as the result of seasonal work hours, vacation time and daylight levels.

The baselines were calculated for Tower A and B combined using the monthly electricity consumption for total tenant use and for individual end uses with Equation (14) and the monthly percent change was calculated with Equation (15).

$$Baseline_a = 0.5\left(\frac{E_{Feb\ 2016,a}}{29days} + \frac{E_{Mar\ 2016,a}}{31\ days}\right) \qquad \text{Equation (14)}$$

$$Baseline_{Total\ Tenant} = 15.01\ MWh/day$$

$$Baseline_{Tenant\ Plug\ \&\ Light} = 9.17\ MWh/day$$

$$Baseline_{Tenant\ Exceptional} = 5.84\ MWh/day$$

$$\Delta E_{month-i,a}[\%] = \left(\frac{E_{month-i,a}}{days_{month-i}} - Baseline\right) / \ Baseline \qquad \text{Equation (15)}$$

where a is each load type, either the total tenant load, tenant plug and light load or the tenant exceptional load, $E_{Feb\ 2016,a}$ and $E_{Mar\ 2016,a}$ are the electricity use in MWh for February and March for each load type, $Baseline$ is the reference electricity use in MWh/day for each load type, $\Delta E_{month-i,a}$ is the percent change for month i relative the baseline for each load type, $E_{month-i,a}$ is the monthly electricity use in MWh for each load type.

CUSUM Analysis

To check if consumption patterns are changing, the mean monthly electricity use over time, a cumulative sum (CUSUM) is assessed [102]. The CUSUM is applied to the tenant plug and light loads using Equation (16). The tenant plug and light loads baseline mean, μ, is the equal to the previously defined baseline $Baseline_{Tenant\ Plug\ \&\ Light} = 9.17\ MWh/day$ [103]. The resulting positive and negative slope in the CUSUM plot (Figure 4-7) indicates increasing and decreasing electricity consumption, respectively

[104]. A V-mask is applied to the data to check for an out of control change to the mean, which indicates a significant change has occurred following the baseline period [105]. With the tabulated V-mask, S_{hi} and S_{lo} are each a measure isolating the shifts to the mean electricity use, either upwards or downwards, respectively; they are calculated in Equation (17) and Equation (18). The reference value, $k = \sigma/4$, sets the threshold for detectable changes in the mean at half a standard deviation and $h = 3\sigma$ sets the outer limits. If the calculated S_{hi} or S_{lo} falls outside of the boundary h, then the CUSUM is deemed to have significantly changed [105].

$$CUSUM_i = \sum_{j=1}^{i}(x_j - \mu) \qquad \text{Equation (16)}$$

$$S_{hi,(i)} = \max(0, S_{hi,(i-1)} + x_i - \mu - k) \qquad \text{Equation (17)}$$

$$S_{lo,(i)} = \max(0, S_{lo,(i-1)} - x_i + \mu - k) \qquad \text{Equation (18)}$$

where i is the currently calculated month, j refers to preceding months, x_i is the calculated month electricity use, x_j is the preceding months electricity use in MWh/day.

4.3. Results

The following section assesses the impact of submetering using multiple electricity measurement methodologies.

4.3.1. Comparison to Historical Use

Monthly electricity consumption is available for the combined Tower A and B dating back to 2007 and is plotted in

Figure 4-4. Electricity use has significantly reduced since 2007, largely due to base building equipment upgrades. The analysis in all following sections applies normalization to better compare between years.

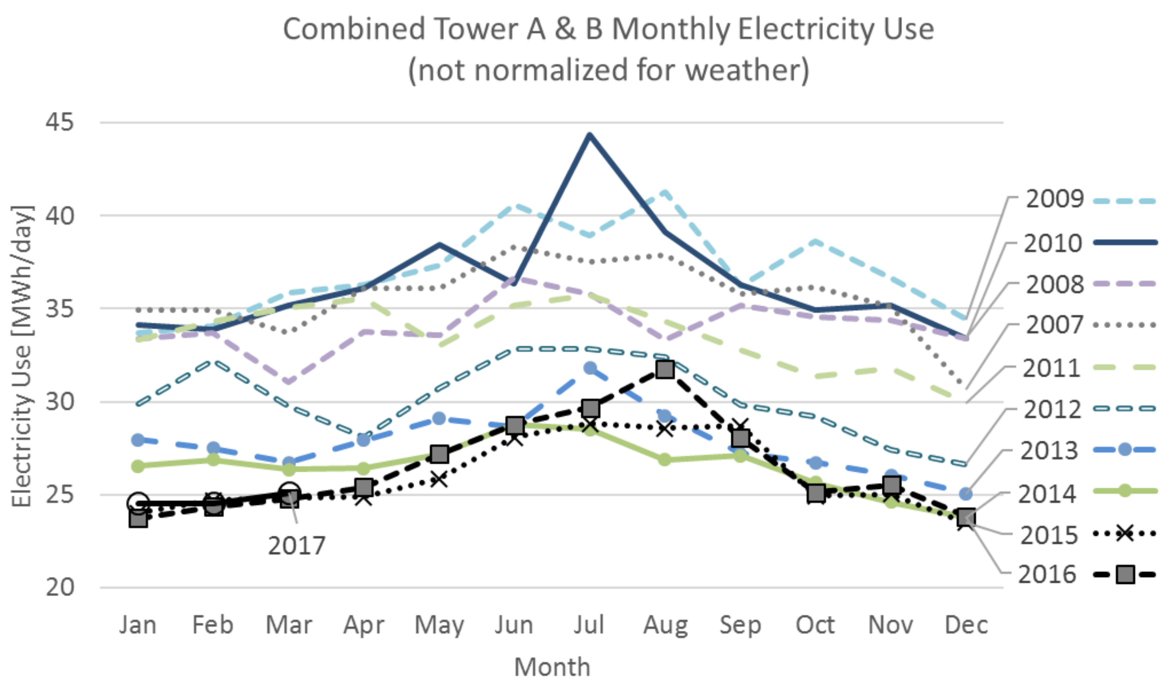


Figure 4-4: Historic electricity use

4.3.2. Method 1: Comparing Between Years

Total building electricity consumption decreased by 1.68% between 2015 and 2016 and by 2.27% between partial 2015 and 2017. Overall, this results in a 2.0% reduction in electricity use over the 15 months following submetering. The monthly changes in electricity consumption are presented in Figure 4-5, indicating that electricity reductions are persistent throughout most of 2016.

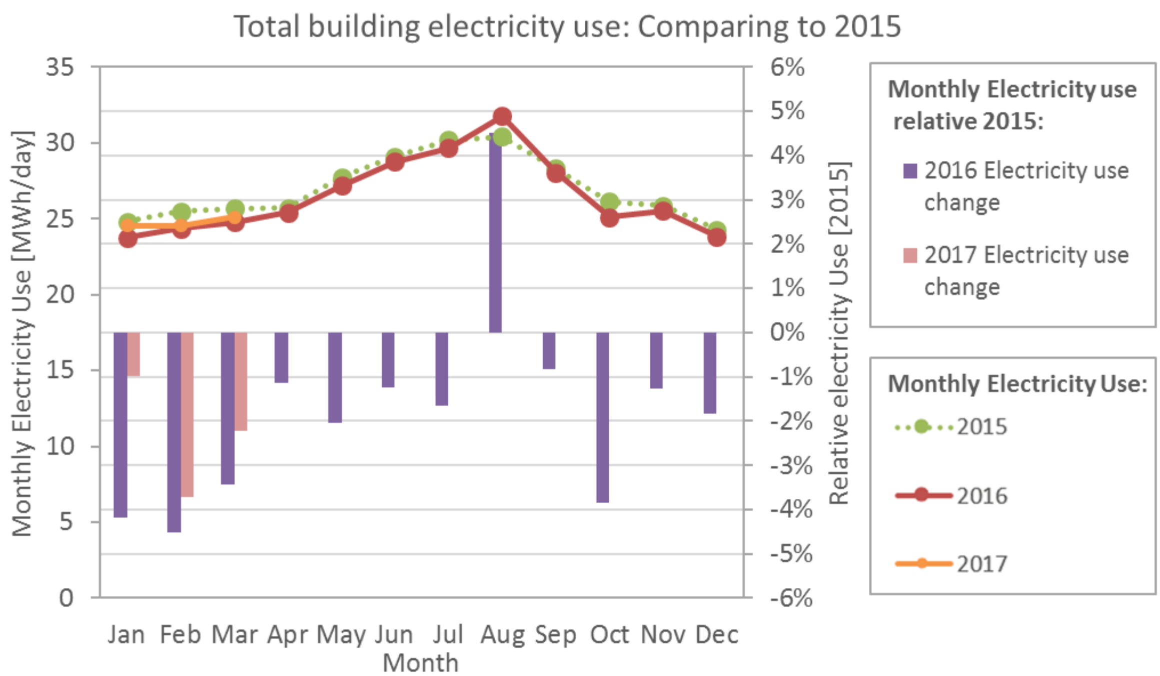


Figure 4-5: Comparing 2016-2017 electricity use to the 2015 base year that is adjusted for weather conditions with the CDD method

4.3.3. Method 2: Compare Between Months

These results compared the baseline, determined as the first two typical months following submetering, February and March 2016, to the following monthly electricity use. The result is an average of 0.1% decrease in total tenant electricity over the following 12 months (Apr-2016 to Mar-2017), seen in Figure 4-6.

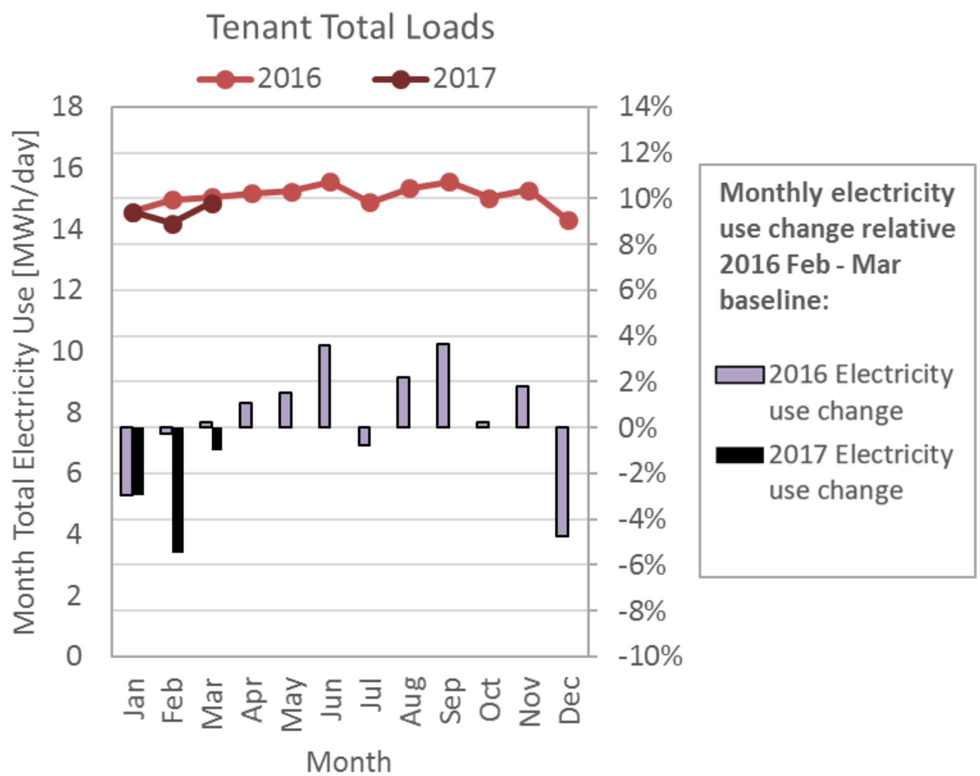


Figure 4-6: Total tenant loads, compared to the February – March baseline

Tenant plug and light loads and exceptional loads were compared separately to their respective baselines, resulting in a 3.0% reduction and a 4.5% increase, respectively, over the following 12 months.

The difference in electricity performance between end uses indicates the need for further analysis, therefore, monthly data is presented in Figure 4-8. The tenant plug and light loads show consistent reductions in electricity during summer months, this is most pronounced in July and August. Lower summer electricity consumption could be the result of employee vacations or shorter hours, opposed to electricity reductions due to submetering.

To determine if the reductions in tenant plug and light loads are significant and not just a seasonal change the CUSUM plot and V-mask was assessed. The pattern in S_{lo} (Table 4-2), the isolated downward shift to the mean, shows that the mean electricity use began a decreasing trend, six months after the submetering implementation in January 2016. The downward trend is considered significant because the values of S_{lo} falls outside the V-mask outer limit, h=0.80, indicated as shaded cells in Table 4-2. This continuous decreasing pattern is also observed in the CUSUM plot in Figure 4-7.

Table 4-2: Tenant plug and light load 2016, CUSUM and V-mask. Shaded cells indicate downwards shifts to the mean that are greater than the outer limit h and therefore are considered significant.

	Tenant Plug & light x_i [MWh/day]	Increase in mean	S_{hi}	Decrease in Mean	S_{lo}	CUSUM [MWh/day]
Jan	8.89	-0.34	0.00	0.21	0.00	-0.28
Feb	9.19	-0.05	0.00	-0.09	0.00	-0.26
Mar	9.15	-0.09	0.00	-0.05	0.00	-0.28
Apr	9.16	-0.07	0.00	-0.06	0.00	-0.28
May	8.94	-0.30	0.00	0.16	0.16	-0.51
Jun	8.96	-0.27	0.00	0.14	0.30	-0.72
Jul	8.37	-0.86	0.00	0.73	1.03	-1.51
Aug	8.73	-0.50	0.00	0.37	1.40	-1.95
Sep	8.94	-0.30	0.00	0.17	1.57	-2.18
Oct	8.79	-0.45	0.00	0.31	1.88	-2.56
Nov	9.34	0.11	0.11	-0.24	1.64	-2.39
Dec	8.57	-0.67	0.00	0.54	2.17	-2.99
Jan	8.90	-0.33	0.00	0.20	2.37	-3.25
Feb	8.74	-0.50	0.00	0.36	2.74	-3.68
Mar	9.27	0.03	0.03	-0.16	2.57	-3.59
k	0.07	h	0.80			
μ	9.17	σ	0.27			

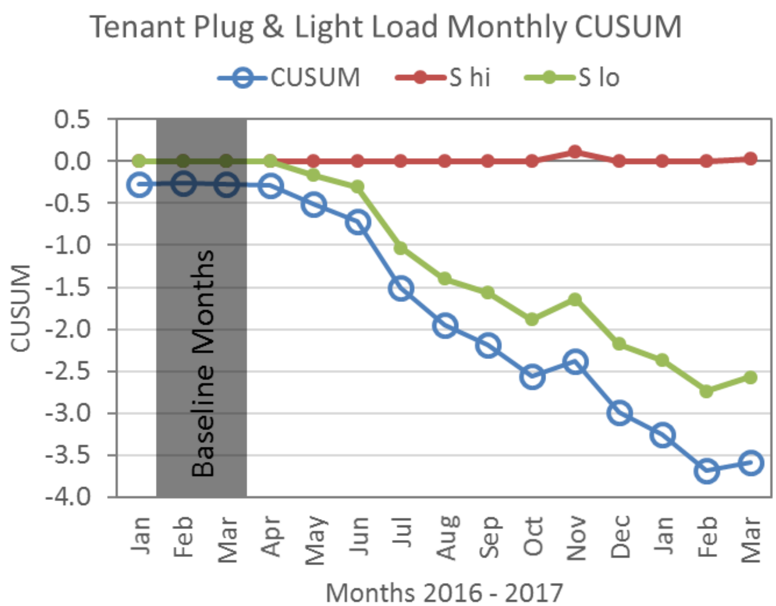


Figure 4-7: Plotted CUSUM results

The tenant exceptional loads, including servers and their dedicated chillers, show significant increases in electricity consumption outside of winter months (Figure 4-8). This indicates that exceptional loads are outdoor temperature-dependant; therefore, the February-March baseline is not appropriate when looking at year-long trends. To avoid the seasonal variation, the percent change between 2016 and 2017 exceptional loads was compared between like months, resulting in a 3.7% reduction over three months. This is a significant reduction in exceptional loads, and is likely the result of submetering.

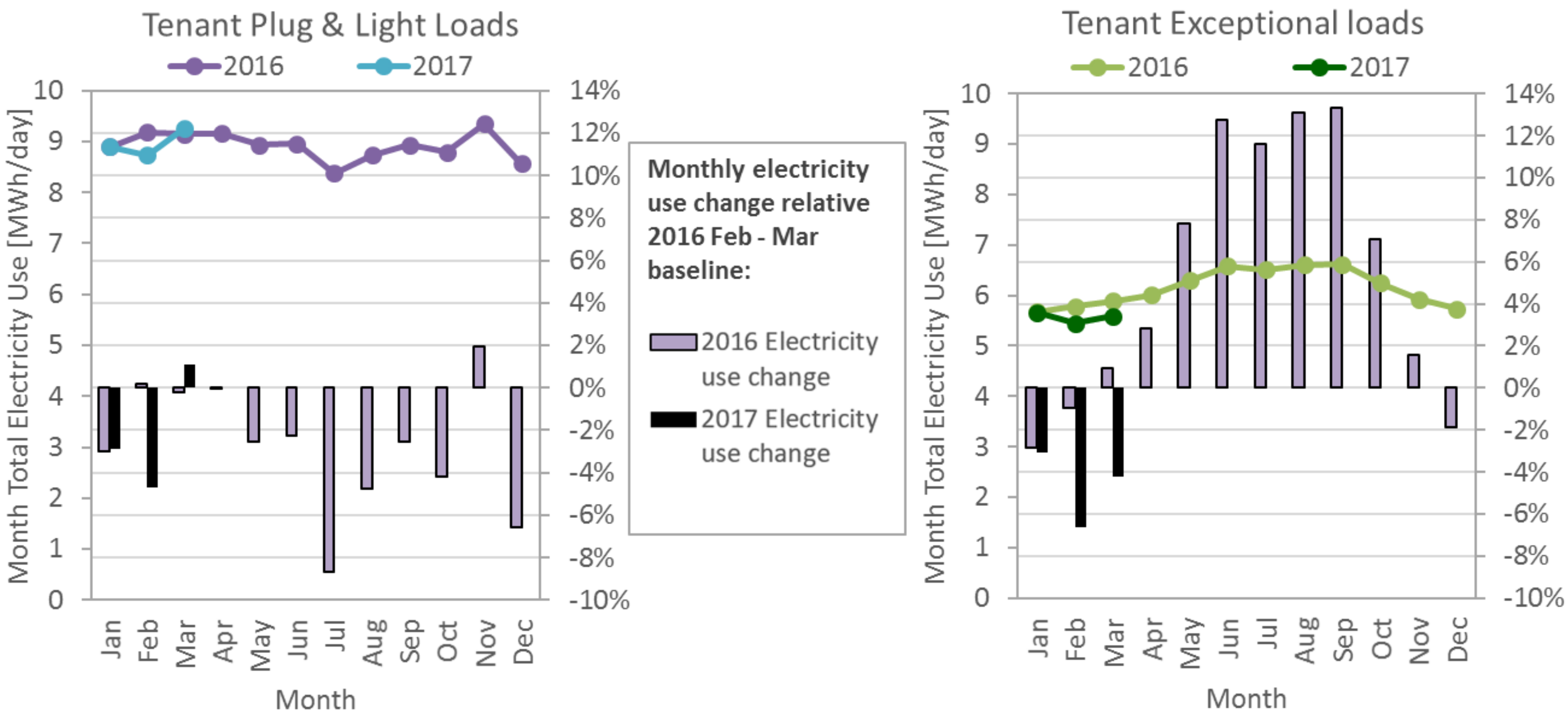


Figure 4-8: Electricity performance by tenant end use, compared to the February – March baseline

The final analysis compares like months between 2016 and 2017, separating tenant electricity use between buildings and each end use. The tenant plug load in Tower B shows consistent reductions for each month in 2017 (Table 4-3). Tower B has greater electricity reductions than Tower A, this is especially pronounced in the exceptional loads.

Table 4-3: Compare end uses between like months. January 2016 had lower than normal loads due to two new tenants in Tower B.

	Percent change: 2016-2017 Like months				
	Tower A		Tower B		
Month	Plug & light	Exceptional	Light	Plug	Exceptional
Jan	1%	5%	-1%	-3%	-2%
Feb	-1%	0%	-8%	-7%	-8%
Mar	5%	2%	2%	-2%	-8%

4.4. Discussion & Conclusion

The effect of submetering on tenant electricity use was analyzed by comparing total building electricity consumption between years and comparing tenant electricity consumption post-submetering to a baseline.

The comparison between years suggests a reduction of 2.0% in electricity consumption in the 15 months following submetering, compared to the 2015 building baseline year. The electricity reductions cannot be fully attributed to tenant electricity use changes without uncertainty due to the inclusion of the base building component. The advantage of comparing years captures seasonal variations in tenant electricity consumption, this relates to seasonal businesses and employee holiday schedule and the tenant exceptional load which is partially weather dependant.

The comparison of total tenant electricity use to the post-submetering baseline yields a reduction of 0.1%, but is not representative of actual consumption changes due to the inclusion of weather dependant tenant exceptional loads. When isolating the weather dependant tenant exceptional load, the winter baseline results in an apparent load increase of 4.5% over the 12 months following the baseline. An appropriate representation of exceptional load changes is the comparison of like-months between 2016 and 2017, yielding an electricity reduction of 3.7% over three months. This inter-year comparison is limited by the three-month period and therefore is not generalizable to the whole year.

The post-submetering baseline is most appropriate for assessing changes in tenant plug and light load, which does not significantly vary with external weather conditions or seasons. The main limitation of this method is the relatively short, two-month, baseline data set. The resulting plug and light load reduction of 3.0% is observed over 12 months, when compared with the post-submetering baseline. In addition, the tenant plug and light loads are on a decreasing trend according to a CUSUM analysis, this decline in consumption is significant starting six months after submetering was implemented.

Due to the limitations of each submetering analysis method, the results of three metrics must be used in combination to suggest the influence of submetering on tenant electricity consumption, estimating electricity reductions between 2.0%, 3.0% and 3.7%.

The best measurement of tenant electricity change is the post-submetering baseline for tenant plug and light loads indicating a reduction of 3.0% over 12 months. This metric isolates the tenant typical office use, including plug and light loads. The metrics comparing like-months between years, for total building electricity reductions and the isolated exceptional load, support and validate the 3.0% tenant plug and light electricity reduction. The total building electricity use year-over-year gives an overview of the building, indicating that electricity reductions are occurring (2.0% reduction). Comparing tenant exceptional load between months in 2016 and 2017 (3.7% reduction), fills the analysis gap created by only analyzing tenant plug and light load, which excludes exceptional load from high-users who are the most financially motivated to conserve electricity.

In conclusion, this study suggests that the total tenant electricity consumption has declined 3.0% and is continuing on a declining trend due to the implementation of submetering. The suggestion that submetering has influenced tenant electricity use is based on the observation that total building electricity consumption has declined since 2015, that the tenant plug and light loads have declined and continue to decline since the debut of submetering and that the tenant exceptional load has reduced when comparing the first three months of 2016 and 2017.

5. Discussion

This section discusses the lessons learned throughout this thesis and recommendations, with a focus on the commercial multi-tenant setting. Recommendations for electricity use metrics and level of submetering were informed and influenced by the lessons learned and anecdotes from tenants and occupants.

5.1. Lessons Learned

Throughout the case study there was one main lesson that was learned and reinforced at every step, that multi-tenant commercial buildings respond differently to top-down behavioural interventions than single-tenant or owner-occupied buildings. When the property management plans and introduces new services, the key tenant representatives are consulted in a focus group to ensure new services are useful and will be embraced by tenants. Despite tenant consultation, new initiatives from the property management team may not be fully effective or taken advantage of, due to varied participation levels of tenant representatives.

Many factors affect tenant representative participation; the following factors were determined from tenant anecdotes from those who chose to participate in in-person meetings with researchers. Some tenant representatives were very active with respect to promoting energy awareness and learning about services that were provided to them from property management. Other tenant representatives were very busy and did not engage in activities or with emails unless required, as their status as a tenant representative is only a small aspect of their responsibilities. Some tenant representatives felt motivated by submetering to attain cost savings benefits that are directly measured and rewarded within their company, whereas others do not interact with finances at all. There was one tenant who had hired a third-party to act as their tenant representative, in this case there is no incentive for the third party to participate in building initiatives and it is unknown how many tenant representatives are in this position. Due to these competing interests, the role of leadership and varying job descriptions, the tenant representative can be a significant barrier to communication to all occupants and tenants within a multi-tenant commercial building.

The tenant representatives were the greatest barrier to the promotion of the electricity reduction competition. This was not particularly surprising as a competition could be seen in a negative light, as ineffective when compared to the costs of electricity, unnecessary or even as a distraction to working employees.

The implementation of submetering directly affected all tenants and was mandatory for all tenants to acknowledge. Submetering was received positively by most tenants, since the system is fairer and provides accurate electricity use and carbon footprint feedback. A number of the five high-users did not want the new system because it came with higher bills after years of other tenants subsidising their high use.

To help with the transition to submetered billing, tenants were offered tools to reduce energy consumption through an energy dashboard and informal energy audit. Very few tenant representatives logged into the energy dashboard more than once but a select few continue to check their electricity consumption and contact property management with further inquiries. Of the 43 tenants, 26 met for an introduction to the dashboard, of these tenants 19 participated in the informal energy audit that was paired with a set of suggested energy reduction strategies customized to their suite. Anecdotes from these tenant-researcher meetings are informative and are summarized in Appendix A. Many anecdotes indicate that tenant representatives are interested in electricity conservation, but interest does not mean they have any impact on electricity use, where determining the level of long-term commitment and the varying level of control of each tenant representative is a challenge. Business structure within tenant suites, as well as business policies and rules that span many business locations can act to facilitate or undermine an individual tenant representative's intent to conserve electricity.

Based on anecdotes from tenants, the high users were the most likely to be actively tracking their electricity consumption, where both the high users and other tenants were engaged with improving the efficiency of their workplaces.

The ability to engage full tenant participation could increase electricity reductions from both implemented energy reduction strategies in the case study towers.

5.2. Metrics Recommendations

Commercial building performance metrics can span many topics, from energy use, operating costs, sustainability, comfort and worker productivity [106]. In this case study, the performance metrics of interest concern electricity use, electricity costs and some measure of environmental impact.

Currently there is no unified set of performance metrics included in energy dashboards to assist in reducing energy consumption [107]. The lack of consistency in metric utilization results in difficult comparisons between building electricity use, this can occur even within the same property management portfolio. Choosing one standard set of metrics is useful for assessing the performance of behavioural interventions and to gauge if results are repeatable.

Existing recommendations on performance metrics look at usability for operations managers, but do not go further to address tenant or occupant focused metrics [107], [108]. In addition, existing recommendations have a varying level of input data, some look solely at electricity data and building footprint, where others require detailed information on number of occupants and even workplace sick leave policies [108], [109]

The report by Barley et al. [108] outlines over 40 detailed building performance metrics and their most appropriate presentation form and units. Each of these metrics is useful, but a subset must be chosen and additional metrics or presentation methods must be selected for each of the stakeholders in this multi-tenant commercial building. The chosen metrics must be simple and have applicability to many situations or buildings in order to facilitate easy comparisons over long-term data sets [106], [109]. Fowler, Solana and Spees [109] determined 15 selection criteria to guide the optimal choice of performance metrics in order to maximize the ease, usefulness and quality of data. Metrics should be relevant to their target audience and inform energy conservation measures that are actionable in the commercial building context.

Recommendations on the most useful electricity presentation metrics are determined based on existing metrics, recommended selection criteria and through informal interactions with building management, tenant representatives and individual occupants. The metrics recommendations are summarized in Table 5-1.

Table 5-1: Summary of metric recommendations

Operations Managers			
Metrics	Load Type	Interval	Purpose
Demand [kW] + Irregularities [Y/N] + Irregularities notification system	Individually metered base building equipment and systems	Smallest available (e.g. 15-minute)	Error checking and resolution
Consumption[1] [kWh] + Cost[1] [$]	Total building	Yearly + Monthly	Predicting yearly costs and trends. Goal setting.
Consumption[2] [kWh]	Total tenant load	Monthly	Monitor submetering progress
ENERGY STAR[3] [rating]	Total building load	Yearly	Determine relative energy performance
Typical tenant yearly consumption per ft^2 [kWh/ft^2]	Aggregated individual tenant load, excluding outliers	Yearly	Billing estimates for new tenants
Tenant consumption[2] [kWh] + Cost[2] [$]	All individual tenant loads	Yearly	Billing tenants
Tenants			
Metrics	Load Type	Interval	Purpose

Tenant consumption[2] [kWh] + Cost[2] [$]	Individual tenant load	Yearly + Monthly	Budgeting costs
Consumption + Cost trends [% up or down]	Individual tenant load	Yearly + Monthly	Budgeting and goal setting
EUI for all tenants [kWh/ ft^2]	All individual tenant loads	Monthly	Comparison to others
Environmental impact [equivalent CO_2 emissions]	Individual tenant load + Portion of base building	Monthly	Environmental reporting
Occupant error reports	Tenant load	Manually entered	Error checking and resolution
Occupants			
Metrics	Load Type	Interval	Purpose
Comparison to past demand [% up or down]	Individual tenant load	Smallest available (e.g. 15-minute)	Reminder to conserve
Comparison to other tenants [equivalent CO_2 emissions/ ft^2]	Individual tenant load + Portion of base building	Monthly	Motivation with an environmental focus
[1][108] [2]'Functional Area' subset defined as the area occupied by tenants [108] [3][110]			

5.2.1. Building Operations Management

The operations managers of Tower A and B will be the most interested in overall building performance. Since submetering was introduced recently, it is recommended that the effect of submetering on tenant and building electricity use is presented over the years following implementation. The quantitative effect of submetering can encourage the continuation of submetering in Tower A and B. The continuation of submetering is currently planned to include a new submeter installed for each new commercial tenant, increasing data granularity over time. The results of submetering in Tower A and B also influences the decision for other commercial office towers considering submetering implementation. This could influence building managers within the same company, and competitors within the same region.

The total building performance and data trends in costs and consumption are useful for predicting electricity costs at the building level from year-to-year. Trends in yearly electricity consumption, paired with the rising rate of electricity prices, can be used to create electricity reduction goals that will mitigate these rising costs. It is in the building management's best interest to mitigate rising electricity costs, since the base building electricity cost is passed onto tenants, without their control over the consumption, based on floor area. Proof of historic low electricity costs will help keep the overall leasing prices competitive in the commercial real-estate market. Electricity demand trends are excluded from the recommended metrics, because the total building demand information has less utility than consumption when considering building level efficiency interventions [109].

Electricity reduction goals from the building managers mostly affect the base building load, which accounts for 44% and 41% of Tower A and B total end use. Reports on specific base building equipment and zones, e.g. for chillers and lobby lighting, are useful for error checking. These detailed reports can find equipment that is not powering down or has higher than average use, creating an actionable list of equipment needing inspection. The base building component is the greatest electricity end use controlled by one entity in both Tower A and B, this gives the building managers the greatest ability to affect electricity consumption.

The building management's conservation goals can go beyond base building electricity consumption to affect tenant use. There is currently a movement towards LED base building lights in tenant spaces. This upgrade is controlled by the building managers and it affects the lighting end use, accounting for 12% of electricity end use in Tower B. In addition, the building management operate energy awareness campaigns to influence the tenants to reduce their electricity use.

An important metric for the building management is the electricity use for a typical tenant. This is important for marketing floor space to prospective tenants who may not know their own electricity demand and consumption patterns. Use of recognized energy metrics, specifically ENERGY STAR, can also assist in marketing and judging energy performance in a commercial office building.

The building management need a combination of granular data over short intervals for error checking, monthly data to determine rising or falling trends in electricity use, and yearly results to use for the yearly billing of tenants.

5.2.2. Tenant

The tenants are most interested in their office suite electricity use, not the performance of the whole building, so their specific data is required. The main concern for tenants is the billing information. They receive bills once per year, but interim feedback on electricity consumption is important so the yearly bill is not an unwelcome surprise. Therefore, tenants need monthly feedback on both the electricity consumption and the costs.

In order to show their change in electricity use over time, there should be comparisons between months, and between months from previous years. These two comparisons are useful since a short-term increase could be the result of the business function where one business quarter is more active than others. In this case, visualizing like-months across years will show this trend is temporary and will not discourage tenant electricity reduction goals.

Comparing to other tenants in the same building could also benefit tenants. If a tenant has completed their electricity conservation goals and still has higher electricity use than other tenants in the building, this may motivate them to look for additional electricity saving opportunities in their suite. In this case, comparing to others acts as a benchmark for what is possible for electricity reduction and could inspire some competition between tenants.

Another useful metric for tenants is a carbon footprint report. Some tenants have been ordering equivalent CO_2 emission reports before the implementation of submetering, part of a sustainable business policy. By framing electricity use as equivalent CO_2 emissions, the focus shifts from costs to impact on the environment, thus creating an intrinsic motivation to reduce electricity consumption.

The tenant representative is most interested in monthly data, and often has control over equipment upgrades and business practices that will encourage savings over the long term.

5.2.3. Occupant

The individual occupant within a tenant space has control over their immediate environment and can choose to perform many small energy efficient behaviours throughout their day. The occupants can also manually error check their suite, through the reporting of inefficiencies to their managers, such as a light that won't shut off or a shared printer that fails to enter sleep mode. During the informal energy audits, many inefficiencies were noted by office occupants, but a channel to report them was only available to tenant representatives and only available for property management controlled items.

In order to harness the power of the occupants, presenting real-time electricity consumption data can be useful as it acts as a reminder to complete energy efficient behaviours. Presenting real-time data over the course of the day can be paired with a typical day's electricity use, to quickly show how the office is performing compared to normal. Getting this real-time data to the occupants can be completed through an online energy dashboard, that could act as the homepage for office computers. This method of delivering data could result in multiple views per day per occupant, increasing the chances of behaviour change, in occupants that are already motivated and have knowledge on how to reduce electricity consumption. This method is preferred to emails, as emails often go unopened, and it is preferred to a dedicated office display that presents the data, since a screen consumes electricity and goes against the core values of the intended message.

Comparing the occupant’s office to other tenant suites in the building and compared to past use can reinforce the importance of the individual occupant’s small behaviour changes, especially if the office is performing well. In addition, presenting the carbon footprint of the office can give the individual occupant reason to participate in changing to more energy efficient behaviour, since the cost of electricity is not a motivating factor.

5.3. Submetering Recommendations

Before installing submetering in a commercial building, property management must first ensure that lease agreements permit the use of metering data for the purpose of customized tenant utility billing. When recommending the ideal granularity of submetering data in a multi-tenant commercial building, the initial cost of submetering is weighed against the potential benefits of the highest available level of metering.

In a multi-tenant commercial building, the initial costs can be prohibitive because high quality meters must be used, that are reliable and certified, in order to use the collected data for fair billing. Working hours must be dedicated after installation to educating tenants and addressing concerns with the new billing strategy. The more complex and nuanced billing scheme can result in long term increased building management costs due to working hours dedicated to determining each tenants’ yearly utility bill. Submetering with higher granularity would result in more ongoing working hours used to process the data or would hiring specialists that can apply machine learning techniques to automatically process detailed electricity consumption data.

In this case study, the property managers paid for the initial submeter installation, but future tenants will be required to purchase one meter for each of their new suites. The cost of one meter is relatively small compared to operating and leasing costs for an incoming tenant, but there has been pushback from prospective tenants. Prospective tenants that are aware of their own high electrical demand may be discouraged from moving to a submetered building simply because they can be subsidized by other tenants in a multi-tenant bulkmetered building. The upfront costs of submetering result in the desire to limit the number of installed submeters.

Insights from granular submetering data can inform the adoption of energy efficient measures within tenant suites. Greater granularity can give insights into specific behaviours within offices, for instance, if electricity data determines that personal printer use is low in an office, then the tenant can make an informed decision to transition towards shared services. Such a high level of metering, on every electrical outlet or on every office may result in too much information to be distilled easily and automatically without professional or researcher analysis. Such a high level of metering could yield privacy issues, where detailed occupancy schedules for each worker could be inferred by the data. Based on the limited number of energy dashboard logins from tenant representatives, the collected electricity use data may never be seen or used by the representatives, who have the greatest power to make informed conservation decisions.

In a multi-tenant building, electricity feedback is useful for estimating cost benefits of energy conservation measures, but, due to lack of tenant representative participation, the benefits of highly granular submetered data may go unrealized. Due to the high variability in electricity use between tenants, the use of submetering is recommended to ensure fair billing. More specifically, one electricity submeter per tenant is recommended, in the case that the property management is providing the upfront installation cost.

5.4. Future Work

This case study highlights some important issues for future studies that plan to analyze the role of occupant behaviour on commercial electricity consumption.

This case study looked at the full behaviour system in two multi-tenant buildings, including the property management, tenants and occupants and the interactions between all three groups. Future work could isolate the impact of either occupant behaviour change or tenant behaviour change through the design of the study.

To isolate occupant behaviour change, the property managers must not make any changes to the building systems and the tenants must not make any changes, including workplace policy and environmental messaging. One option to achieve these criteria is implementing an occupant behaviour change strategy within one company, where a top-down intervention can be made to minimize any confounding factors from tenants or property managers.

To isolate tenant behaviour change, there should be communication between researchers and tenants, where behaviour change messaging from researchers should not be seen by occupants. Tenant behaviour change should be assessed in either a submetered multi-tenant building or in a single occupancy building. If there are any changes to building systems by property management, the utility data should remove the effect of upgrades and researchers should work with tenants to determine if the changes are influenced by tenants.

Further research into the effect of occupant and tenant behaviour on building electricity use can help determine new methods to increase the electricity savings from behaviour change. This case study identified many system failures that limit the impact of occupant and tenant behaviour change, including: communication barriers, the dissemination of information, and infrequent utility billing. For some occupants and tenants, the combination of barriers can result in the perception that they have little to no impact on electricity use, whereas others still feel that they can make an impact. This difference in perception between individuals indicates that there are numerous mental models in the workplace that pertain to electricity reduction and pro-environmental behaviour change. Determining if these mental models affect behaviour change and determining how to change these mental models will be important steps in future research on electricity reduction.

Another important research avenue is determining the appropriate use and interpretation of electricity demand profiles. This case study determined the electricity demand profiles for the tenants in Tower A and Tower B, and suggests that the existing

ASHRAE schedules could be updated to better reflect current electricity use patterns by reducing mid-day demand and including confidence bounds. Future work should consider if updates to the ASHRAE schedules are required by focusing on two main purposes of the existing profiles. More conservative estimates of electricity demand are useful in the design and selection of building systems that must service commercial tenants in the case of extreme electricity demand, where many or all tenants are high users. In other applications, such as modelling electricity demand to prove compliance with minimum energy performance, the most accurate electricity demand data is ideal and should be standardized. An updated commercial electricity demand profile, or set of profiles, will be useful as energy efficiency and building energy modelling predictions becomes a greater focus in new construction and retrofits.

6. Conclusion

This thesis involved the collection of 15 months of submetered electricity consumption data from two commercial office towers in Eastern Ontario, including 43 commercial tenants across 32 submetered floors. The first year of collected electricity use data was analyzed to determine if typical electricity patterns exist and compare tenant electricity consumption to prior studies and typical consumption estimates.

During the recorded period, a one-month electricity consumption intervention in October 2016 was implemented to promote energy conservation to commercial tenants and occupants. The intervention was an electricity reduction competition between commercial floors in the two office buildings, paired with an incentivised environmental behaviour change pledge. In October, the five greatest-reducing commercial floors were published weekly to foster competition and participation from tenants and occupants.

The implementation of submetering at the beginning of January 2016 was assessed for its impact on tenant electricity consumption. Submetered electricity billing was introduced to tenants early 2016, with estimates on how the billing change would affect individual tenant operating costs. Due to tenant awareness of submetering shortly after installation, there was no ideal baseline of submetered tenant electricity consumption. The resulting analysis focused on two available methods to illuminate the effect of submetering on tenant electricity consumption.

6.1. Summary of Results

The results from the one-year data collection period showed that there is no unified typical tenant electricity profile. Between commercial floors, tenant electricity demand shows a large range in demand between tenants, but a relatively tight IQR. The average tenant electricity demand profile is similar in shape to the estimates from ASHRAE, but the case buildings display much lower demand during working hours, spanning from 9:00 to 17:00 [50], [61]. Only two commercial floors, have a higher peak electricity demand when analyzed over one year, than estimated by ASHRAE. Over the year, the tenant peak loads are concentrated outside of summer months and are out of phase with the building peak loads which occur in late June. The building-wide peak electricity consumption is found to be driven more by base building loads, specifically air conditioning, than by coincident tenant loads.

After the promotion and implementation of the one-month competition to reduce tenant electricity consumption, there was an overall increase in weekly tenant electricity use. Of 28 observed tenants, significant tenant electricity reductions occurred in three tenant suites and 15 tenants had significant increases in total tenant electricity use.

The effect of the electricity reduction competition is analyzed with more granular data in Tower B, where tenant plug loads and light loads are assessed separately. The results of the disaggregated plug load on 18 commercial floors found significant reductions on seven floors and increases on two commercial floors. Concurrently, light load electricity significantly reduced on only two floors and increased on 11 floors. In Tower B, the increases to light load electricity outpace all decreases in plug load electricity, likely due to the decreased availability of natural light in October.

The electricity data during the competition is paired with pledges to change behaviour to reduce office electricity consumption. The majority of behaviours pledged by occupants would result in reduced plug load electricity consumption. The pledges paired with the significant reduction in plug load electricity on seven of 18 commercial floors could indicate that occupants have greater control over office plug load than total tenant load.

The impact of submetering on tenant electricity consumption was analyzed over the first 15 months following submetering. This data was compared to like-months from the previous year using the total building electricity consumption and to a baseline created from two months of early tenant submetering data.

This study suggests that the total tenant electricity consumption has declined and is continuing on a declining trend due to the implementation of submetering. The best metric indicating this trend, compared tenant plug and light electricity use to the post-submetering baseline yielding a 3.0% electricity reduction over 12 months. In addition, the tenant plug and light loads are on a decreasing trend according to a CUSUM analysis; this decline in consumption began six months after submetering was implemented.

This resulting electricity reduction is supported by comparing total building electricity between years, which found a reduction of 2.0% in electricity consumption over 15 months, when compared to the 2015 building baseline year. The total building electricity reductions cannot be fully attributed to tenant electricity use changes as fluctuations in the base building electricity component are included. To further support electricity reductions, the tenant exceptional load was determined as reducing by 3.7% between 2016 and 2017.

6.2. Research Contributions

This thesis adds to the growing body of research within multi-tenant commercial buildings that aim to typify electricity demand based on a business work week and yearly fluctuations in business operations. New research on business electricity use is required as business culture evolves over time. Prevalent office trends that affect electricity use include: working lunches, flexible work hours, overtime hours, working from home, technological changes, efficient equipment adoption and choosing on-site servers. Each trend can affect business electricity consumption unequally across difference tenants and business sectors. Contributions include:

- Created an hourly demand profile with confidence bounds for building energy modellers
- Determined load diversity across multiple commercial tenants
- Determined that ASHRAE overestimates electricity demand during occupied time periods
- Found that tenant exceptional loads are significant in a modern multi-tenant commercial context.

The electricity reduction interventions contribute to research by implementing an electricity reduction competition and through the implementation of submetered billing. The use of an electricity reduction competition is a research contribution to the property management field as there are no documented gamification studies launched by property managers in a multi-tenant commercial building. Measuring the effect of tenant electricity feedback on electricity consumption is a contribution to research because it isolates the reductions due to tenant behaviour change. Isolating tenant behaviour change excludes changes to the base building operations, which typically account for a significant portion energy reductions. Contributions include:

- Determined barriers to implementing an energy reduction competition in a multi-tenant commercial building
- Found that occupants have more control over plug load end use than light loads
- Concluded that tenant submetered billing results in reduced electricity consumption that begins six months after implementation.

This thesis contributes to the knowledge on commercial electricity use through the access to tenant representatives to track their interest and reception to the electricity reduction interventions. Tenant contact and insights can help understand the original electricity consumption patterns as well as the measures used to reduce electricity consumption and the resulting electricity consumption trends.

6.3. Recommendations and Lessons Learned

In a multi-tenant commercial building, there are some unique challenges that are not observed in owner-occupied commercial buildings or in the residential sector. All initiatives to reduce electricity use in a multi-tenant commercial building that are enacted by the property manager are beholden to the participation of individual tenant representatives. This study found that the tenant representatives can be a significant barrier to communication with all occupants and tenants within a multi-tenant commercial building.

The lessons learned through data analysis and the level of participation from tenant representatives informs the recommendations for the ideal submetering granularity in a multi-tenant commercial building. Due to the high variability in electricity use between tenants, it is recommended, at minimum, the use of submetering on each tenant separately to ensure fair billing. From a researcher perspective, submetering tenant servers, tenant light load and tenant plug load end uses separately is recommended to provide granular data, where higher granularity results in better understanding and more accurate approximations of occupant behaviour. In a multi-tenant building, granular electricity use data could be useful for estimating benefits of energy conservation measures, but due to lack of tenant representative participation, the benefits to granular data may go unrealized. Therefore, the authors recommend one electricity submeter per tenant, especially in the case that the property management is providing the upfront installation cost.

Recommendations for future work include a long-term analysis of the effect of tenant submetering on electricity consumption. The 15-month post-submetering observation period is relatively short when considering the one-year commercial electricity billing period which can result is delayed responses to submetering implementation. In addition, many tenants received a reduction in costs due to submetering, which may not encourage immediate reductions in electricity use. Furthermore, submetering may have the greatest effect on tenants that choose to move into a submetered building, as they may be inherently low consumers and may plan their suite fit-up based on financial responsibility for their electricity use.

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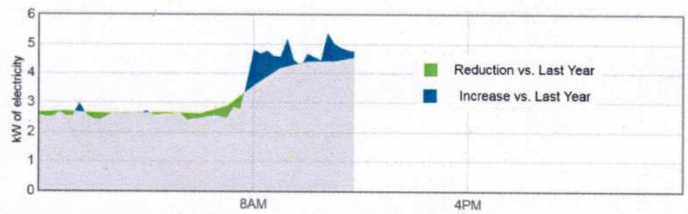
Appendix A. Energy Dashboard Introduction Handout

RealSuiteData is a web-based platform that provides tenants with quick, relevant, and informative data on energy use and greenhouse gas (GHG) emissions for their occupied spaces.

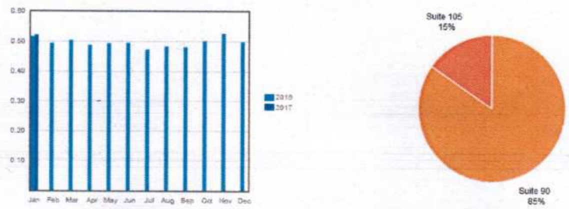
Dashboard:

View in-suite electricity use in real-time to see how you're performing vs. last year.



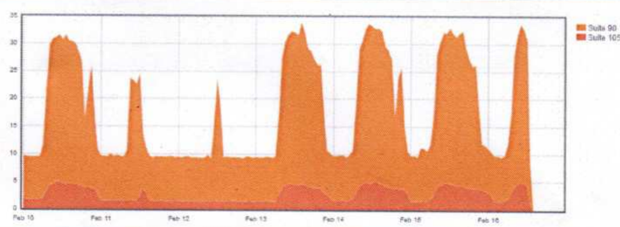
Past Use:

View historical monthly consumption and allocated electricity use by suite.



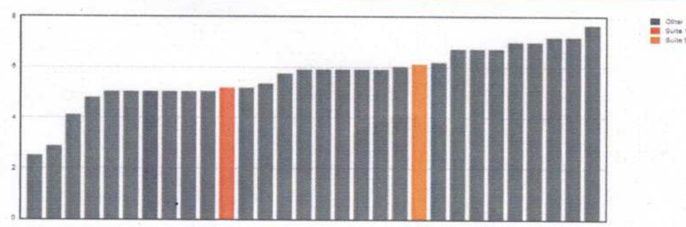
Hourly Profile:

Understand the hourly consumption profile for electricity use in your suite(s).



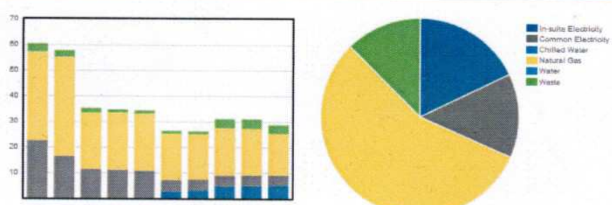
Compare to Others:

Compare your electricity use per square foot to other building tenants.



Carbon Footprint:

Download GHG emission reports including all utilities (elec, gas, water, waste).



Budget Tracking:

Compare actual electricity costs vs. budget on a monthly basis.

Appendix B. Initial Meeting Handouts

The following handouts are stripped of property management logos and associated images

Office Energy Reduction

March 2016

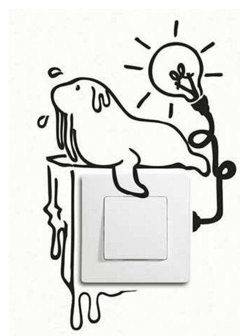
Quick Implementation Strategies

Target Energy Use during unoccupied hours

- Ensure lights are off at the end of the day
- Turn off any equipment not needed during nights and weekends
- If computers are left on for IT updates, consider turning off over weekends

Office Reminders

- Simple messages can go a long way
- Carbontrust.com has free printable stickers and posters
- Remind people that screen savers do not save energy

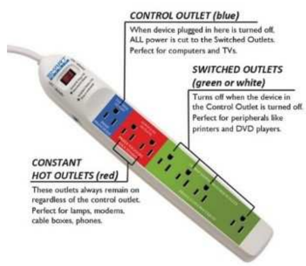


Examples from: http://www.hu2.com/decals/eco-reminders/

Automate shut-down - Power bars

- On/off master switch power bar (approx. $40)
  - These are ideal for manually switching off many loads at once which have vampire or standby power. (e.g. TV with speakers and other associated loads)
- Timer set power bars (approx. $20-30)

    - Ideal for larger equipment with standby loads that can automatically shut off at the end of the day/week (e.g. large printers, coffee pots, microwaves, etc.)
- Current-sensing Smart power bars (approx. $40-70)
    - One plug is the 'control'
    - If a monitor is plugged into the control plug, when it goes into standby mode the reduction in power tells the power bar to turn off other plugs (e.g. task lighting, personal heater, etc.). Some plugs will be always on (e.g. computer, phone charger)



Current sensing power bar

Power strip with on/off switches

(Shown: Safemore Smart bar)

Long Term Energy Planning Strategies

These strategies act as guidelines when making large and inevitable changes in the office.

Equipment

- Consider energy efficiency when upgrading copiers, refrigerators, coffee machines, etc.
- Look for Energy Star labels

Lighting Retrofit and Design

- During the next renovation consider high efficiency LED lighting
- Focus on a lighting strategy with ample task lighting and lower ambient light so it may service individual needs and respond to occupancy changes
- Incorporate daylight in lighting design. This can be done with light sensors to turn off lights near windows, or manually.

Computers

- Schedule IT updates so that computers can be turned off at night
- Consider laptops due to their low energy usage for mobile workers

Energy Use Observations

Example Tenant - Tower B floor number 15 **March 2016**

After initial energy use analysis, Example Tenant's energy use on a square footage basis is lower than the average consumption.

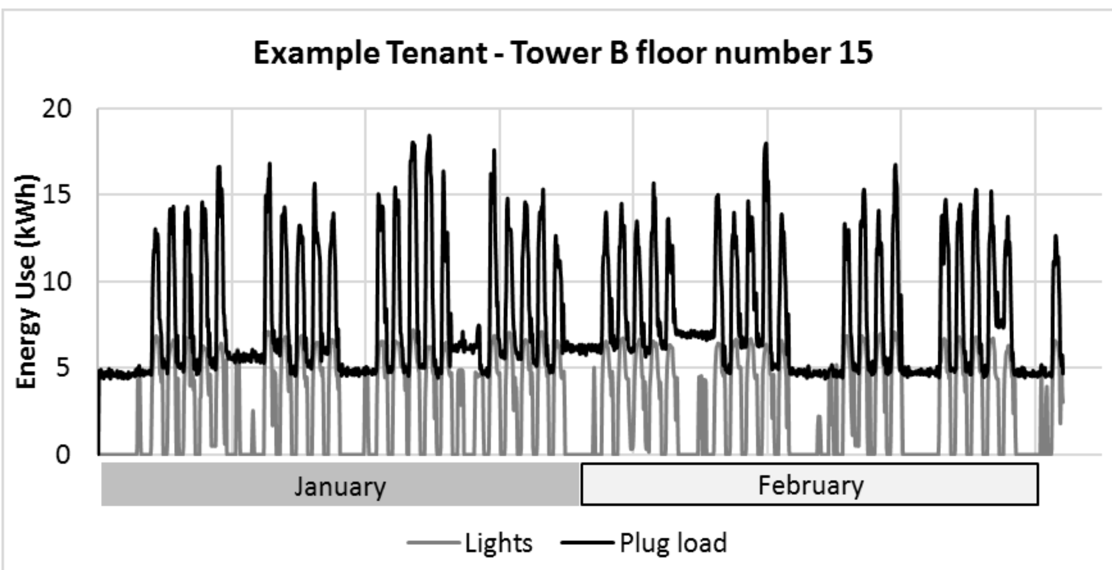
Observations

	January	**February**
Total Use (kWh)	21576	20332
Daytime AVG (9am-5pm)	46.6	45.9
Nighttime AVG (8pm-6am)	21.4	22.1

Energy Saving Opportunities

Unoccupied hours

Night and weekend use accounts for 46% of the total load. Night loads are 50% of the average daytime use.



Appendix C. Example Tenant Informal Energy Audit

Walk Through Results

Example Tenant: Tower B Floor 15

April 2016

Following site investigation and my observations, summarized below are the most effective interventions for consideration. These measures target large energy uses such as lighting and base loads during unoccupied hours.

Best Interventions

- Light decommissioning – in any over lit spaces, especially small offices with multiple lights
- Investigate 24/7 server room power use
- Turn off training room electronics
- Unplug and power down machinery with standby power when out of the office
- Consider a daytime cleaning trial, to save on lighting energy use at night

Server Room

- Investigate cooling set point, some servers can operate optimally at higher temperatures

Standby Power Intervention

- Printer – HP LaserJet M4345mfp
    - Power: in use 830, in sleep 16 W.
    - Saves 6.9 kWh a month with night and weekend shut off

- Printer – HP LaserJet 4200/4300
    - Power: in use 580 W, in sleep 21 W.
    - Saves 9.1 kWh a month with night and weekend shut off
- Printer – HP LaserJet 5200
    - Power: in use 550 W, in sleep 7 W.
    - Saves 3.0 kWh a month with night and weekend shut off
- Printer – Canon Imagerunner
    - Power: in use 1473 W, in sleep 1 W.
    - Very efficient machines, adjust time for sleep settings
- Average Computer
    - Draws 15 W while in sleep/hibernate mode
    - Turn off 1 computer over nights and weekends saves 6.48 kWh per month ($7.50/year)
- Laptops
    - Use much less power than a computer
    - In use they consume between 15 – 45 W, opposed to a computer at 120 W
    - Draws between 0.5 - 5 W in sleep mode depending on model

Occupant Engagement Options

- Office reminder for computer shut downs at night
- Office reminder to switch off unused lights
- Encourage task lighting for desks, requiring less overhead light

March 29th Visit: To Further Investigate Tenant Questions

Coffee Machines

- Flavia – uses 6.1 W in sleep mode and negligible power to start up
    - Saves 2.64 kWh a month with night & weekend shut off
- IQ2000 – used 33.7 W in sleep mode and 1187 W during a 5 minute start up
    - Start up uses 98.9 Wh, turning off over one night saves 404.4 Wh. Therefore unplugging at night and weekends is worth it.
    - Saves 14.6 kWh a month with night & weekend shut off
- Timer power bar: Return on investment for an $18 bar from Lowes
    - IQ2000 machine would save $16.95 a year taking 1.06 years to pay off
    - Flavia machine would save $3.07 a year taking 5.87 years to pay off

March 30th Visit: To Further Investigate Tenant Questions

Power Draw

- Newco coffee – switched off, 0 W. Standby 0.6 W. Power up 1170 W for under 1 min.
    - Power surge is 3.2 Wh, power saved over one night 7.2 Wh
    - Unplugging or switching off saves 259 Wh per month (nights & weekends)
- Small Microwave – standby 1.4 W. no power up surge
    - Unplugging saves 605 Wh per month (nights & weekends)
- Big Microwave – standby 1.7 W. no power up surge
    - Unplugging saves 734 Wh per month (nights & weekends)
- Printer – HP 4250 – switched off, 0 W. Standby 16 W. Sleep 10.8 W. Power up 1000 W for 5 seconds.
    - Start-up uses 1.39 Wh, switching off or unpulg over one night saves 130 Wh. Therefore unplugging at night and weekends offsets the start-up power use.
    - Saves 4.67 kWh a month switching off night and weekends
    - Switching from 30 min sleep to 15 min sleep saves 52 Wh per month (Assume goes to sleep twice a day. Once after initial power on, and once after a print job.)
    - Switch to 15 min sleep mode: Menu -> Configure Device -> System Setup -> Sleep Delay
- Timer power bar payback: for 18$ bar
    - 21 years for the Big microwave
    - Small microwave and Newco coffee is longer
- Current sensing power bar: WOODS 6 plug bar from home hardware ($40)
    - Not including shut down over lunch breaks/out of office
    - HP 4250 saves $5.43 per year, 7.3 year payback

*Energy saving assumptions: nights are from 7pm – 7am, weekends are Saturday & Sunday, a month has 4 weeks and 4 weekends.

*Energy cost assumptions: average energy price is 9.7 cents/kWh, based on [management company's] energy use projections for 2016.

Appendix D. Anecdotes from Tenant Representatives

The following table includes select office anecdotes from the 26 in-person tenant meetings and a subset of 19 that also completed informal office energy audits. Identifying information and shorthand notes are kept with the record of meeting dates.

In most cases it is the more environmentally conscious tenant representatives that give more time and specific responses to questions on energy efficiency in the office.

A reoccurring theme across all offices is the excessive lighting, as the base building lights were designed conservatively. Therefore, in many spaces the tenants were specifically asked about if they would consider reducing lighting.

Office Context	Anecdote
Lawyers, multi-floor large office	Computers should never be turned off because the billable hours are so high, the billable hours wasted waiting for a computer to start is not worth it. Some people do not want to exit their files, so that they are open in the exact same place in the morning. Others want remote access.
Lawyers (same office as above)	There is the belief that turning a computer on and off reduces the lifespan of the machine more that leaving it on. Specifically, that the computer will break when trying to boot.
Lawyers (same office as above)	Despite being resistant to making employee behavioural changes, they are very willing to look at office level change if there is a feasible return on investment (ROI). They were keen on a large upfront investment on LED lighting until it was proven to have no feasible ROI.
Lawyers (same office as above)	The younger lawyer turns off his computer at night.

	This office invested in light switches in meeting rooms but most are all turned on despite the area being empty. In our meeting room, the lights were off and it was still very bright with natural light.
Engineering office with significant equipment loads including a metered ‘exceptional’ load	This company isn't autonomous, they have a buyer for the company that chooses and maintains copiers for all of North America. This results in little tenant control and an apathetic view of energy conservation in the office. There are a number of over bright spaces that the tenant representatives agreed were wasteful. For example, a break room with large windows, excessive overhead lighting plus accent lighting throughout. They do not want to decommission extra lights as people are reported to complain about any changes in the office.
Efficient Office	This office has removed excessive base building lighting in the past due to employees with headaches due to the high light level. Now this office is removing excessive lights in personal offices when there is a new person moving into a space. This is planned to get around individuals’ resistance to change.
Office	This office has light switches in personal offices; many employees keep them off. Employees turn off coffee machines at 5pm and run the dishwasher daily. Reception has TV and LED lights that are always on.
Efficient Office	This office has a forced shutdown for computers every weekend (for update reasons). Servers are virtualizing therefore there are fewer of them and their energy use is declining.
Office	Very energy efficient lighting with high level of control (best in building).

	This office has a home sized Keurig machine. They acknowledge that these machines are not good for the environment but they need them since people want an individual coffee immediately. No one wants to wait for a coffee pot to brew.
Multiple offices	Representatives often say they want light switches and controls. When informed that this is not the property managers responsibility, but the individual tenant responsibility, they seem to lose interest in getting switches.
Cultural Office (more orderly and disciplined than a typical office)	Excellent routine behaviour that includes shutting off everything in the office in the evening. Every single light, printer, computer, monitor, breakroom appliance is shut off at night. This office is also over lit, they have added lights to offices, very unusual compared with other tenants, but they do work nights. These lights do not have switches so they are part of the base building system. Here the building's automated light system is not welcome, at night the base building lights will shut off every two hours, so anyone in the office must manually switch on at minimum one quarter of the floor's lights every two hours.
Efficient Office	This office has a high level of lighting control where most spaces have a switch and everything is turned off at night. One exception is some specialty lighting in the lobby which is on 24/7. This lighting used to act as a frame for a medium sized TV but now is fully covered by a larger TV. The staff don't know how to unplug it so it has stayed on since the last renovation. It was clearly indicated as a problem by staff but there is no plan to remove it. This

	is likely because it requires a visit from a professional to pull the wall panel apart.
Office	A lack of knowledge of lighting fixtures can result is wasteful practices. Accent lighting in this lobby was installed but the wrong halogen lights were used, so the lights were burning out as frequently as once a week. Instead of investigating the problem they continued to buy more of the wrong light that was overloaded. Through proper installation channels the LED equivalent is now provided by the building for free, so this problem was easily remedied.
Office	One office representative does not turn off their computer nor do they know if anyone in their office turns off computers. They suspect they are not allowed to turn them off. They also indicate that there have been technical issues since the computers never update, a direct result of not being shut off. It seems a simple solution to promote turning off computers to reduce electricity use and reduce technical issues, but to our knowledge this problem has not been investigated further.
Bank	This representative shows interest in conservation, but says there is an issue with many independent sub-groups from the same company on their floor that lack coordination. Due to this lack of coordination they do not feel they have control over energy use and have not made any changes, nor have they involved the sub-groups.
Office, Tech company	This office is not interested in efficiency or an energy dashboard at all. This office is solely represented by a facilities manager that is contracted and not part of the office. This facilities manager is very busy and indicates that they do not have additional time to think about energy reductions. During the visit of this office there are no staff that are direct employees of the company present, but many TVs and all the lights are on anyways.

Office	This office representative is interested in energy reductions, unfortunately, interesting office politics prevent any actions. The contact person is a facilities manager, their boss is the ideal person to contact but is not practical to contact because of interpersonal issues in this office. We met outside of the tenant suite. They shut off computers at night but many people forget. They have light switches but things are very often left on, or someone will go through in the morning and switch on every light, even in the boardroom when there are no meetings. This facilities manager finds this situation very frustrating and they wish they could make a difference, but it is not possible.
Efficient Office, small	This office representative cares greatly about energy efficiency. During the tour of the office it is clear that everyone except one employee tries to reduce energy. A number of employees noted behavioural changes they make to reduce energy. A number of employees jokingly noted I should spend all my time in just one office, where the one high-consuming occupant was out to lunch with the TV on. The office representative even went into their space to shut this TV off. There is clearly pressure to conform to environmentally responsible behaviour. This office used to have a Keurig but removed it for environmental reasons. (At the time of office visits, they had the lowest energy use per square foot)
Efficient Office, small	Another very environmentally conscious tenant. One employee leaves his lights and TV on and others note this. When it was discovered that a tablet docking station draws power when not in use it was decided to leave it unplugged. They seemed offended that a charger without even a little LED light on it would secretly draw power. As a result of meeting, this office also installed timed power bars to shut off equipment on weekends and evenings.
Efficient Office	This office representative has been trialling turning off the breakroom TV to see if anyone notices, and they are considering

	removing it entirely. Removing this TV saves money on cable/satellite and energy so they feel motivated to test this.
Bank, Large Office	This office does not care, since all changes come from the head office and this tenant representative just follows the company changes. I offered to check energy use of appliances, since the office at least has control of turning things off. They said not to bother, there could be someone in on the weekend to print things and they would have to figure out how to turn things on. Breakroom appliances are even plugged into a prominently placed power bar that already has switch on it, this office has the easiest set up to turn things off, but they are not receptive. Personal printers are all being thrown away since that's what the head office has planned, fully functional personal printers are getting tossed for bigger central Ricoh machines.
Engineering, Efficient Office	This tenant representative is very eco conscious and receptive. All offices and meeting spaces are on motion sensor lighting. Everyone has task lighting; she says personal task lighting is always all switched off by the time she leaves at the end of the day. They turn off all coffee makers when not in use. This office had a commercial Keurig machine but it leaked, so she brought in a smaller model from home since her husband hated the machine (for environmental reasons), it is complete with reusable cups. Two other proprietary coffee machines are within the office (Nescafé and another brand). Employees bring their own cups, one of 3 proprietary cups. Everyone seems to have their own preference based on their home behaviour.

	The majority of offices in the two building have pod style single cup coffee machines, but none had more than two proprietary brands in one place, and no other offices had the reusable cups. Attitudes towards these machines seem to be a good indicator of office wide environmental attitudes and practices.