Nudging Toward Sustainability: A Pilot Study on Promoting Pro-Environmental Behavior and Reducing Carbon Emissions in a Net-Zero Carbon Building

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

As the building industry grapples with the challenges of sustainability and climate change, the role of individual behavior in resource and energy conservation practices has received less attention than technical options. This pilot study aims to address this gap by investigating the effectiveness of "nudges," or targeted information interventions, in promoting pro-environmental behavior and reducing carbon emissions in a net-zero building in Ontario, Canada. Using a carbon footprint methodology and marginal emission approach, the study looks at the interplay between human and physical factors in driving sustainable behavior. By expressing carbon emissions as a function of time and applying socio-psychological frameworks to guide effective intervention strategies, this research study contributes to the growing body of literature on sustainable building practices and carbon reduction. The study also offers insights into the potential for nudges to be used as a tool for promoting sustainable behavior and reducing carbon emissions in buildings.

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1. Introduction

The impact of climate change on the world has been substantial, both in terms of its effects and what is being done to combat it. Attaining a ‘net-zero’ carbon future in the building industry is crucial to mitigate the impacts of climate change and prospectively achieve a sustainable society and infrastructure. According to the 2018 International Living Future Institute guide report titled "Zero Carbon Certification Guide", a ‘zero-carbon’ building is defined as a structure that is developed and managed with the objective of attaining an annual carbon emissions level of zero. This implies that the operation of buildings does not contribute to the overall emission of carbon into the atmosphere. (International Living Future Institute, 2018). This concept bears resemblance to the construction principles of 'zero-energy,' 'net-zero', and green buildings, but with important differences.

According to Torcellini et al. (2006), zero-energy buildings (ZEBs) are capable of generating sufficient renewable energy to fulfil their own annual energy consumption needs, resulting in a state where they neither use nor create energy in excess. Net-Zero Energy Buildings (NEZBs) are residential or commercial buildings that have notably decreased energy loads. These buildings are designed in such a way that the remaining energy needs may be met by utilising renewable technology. According to Marszal et al. (2011), NEZBs exhibit a net-zero energy balance, whereby the amount of energy they produce equals the amount of energy they use within a given year. Finally, green buildings are purposefully designed, constructed, and operated with the intention of enhancing environmental, economic, health, and productivity outcomes in comparison to conventional structures. As discussed by Kibert (2016), there is a tendency to integrate design ideas that aim to optimise resource utilization, promote the development of healthy living and working spaces, and mitigate pollution.

Recent reports show a noticeable increase in building energy consumption, with a total increase of 135 exajoules (EJ) between 2019 and 2020, which is approximately 4% in relation to the impact of energy-related carbon emissions on the field of infrastructure. This surge represents the most substantial growth witnessed in the past decade. According to the United Nations Environment Programme (UNEP, 2022), there has been a significant rise in carbon dioxide (CO_2) emissions resulting from the operational activities of buildings. These emissions have already reached a record level of almost 10 $GtCO_2$, indicating a 5% surge compared to the figures recorded in 2020. Moreover, this current level is 2% higher than the previous peak observed in 2019. The aforementioned statistics highlight the pressing necessity for substantial measures aimed at decarbonization in order to achieve a building stock with net-zero carbon emissions by the year 2050.

In addition to recent material innovations to address sustainability concerns, human activity can impact changes in energy consumption and carbon emissions in buildings (Hong et al., 2017; Lin & Liu, 2015). However, the current state of the literature has failed to recognize the importance of socio-psychological measures taken towards low carbon targets and advancements in sustainability, leading to the importance of human behavior being unrecognized in several research studies (Juárez-Nájera, 2015; Elahi, Zhang, Lirong, Khalid, & Xu, 2021). Therefore, the literature review will focus on a promising approach to behavior change: the various interventions using green nudges designed to encourage tenants to reduce energy consumption.

1.1 Research Problem

Studies on the relationship between occupant behavior and carbon emissions have often overlooked the use of marginal emissions to recognize variations in carbon intensities over time. While green buildings are designed to be more energy efficient, there is a risk that occupants may experience what is known as the warm glow effect. In the field of behavioral economics, there exists a conceptual term that pertains to the positive emotional experience resulting from engaging in pro-social or ethical acts. Within the realm of green buildings, the notion of a ‘warm glow’ can be attributed to the perception that individuals are actively engaging in environmentally conscious behavior by merely occupying such a structure. However, this emotional state may result in a sense of contentment, thereby diminishing one's motivation to actively participate in additional energy-conservation practices (Bhutto et al., 2020; Hartmann et al., 2017; Van der Linden, 2018). This has been supported by research, such as a study conducted at the case study building that found a negative relationship between social norms and energy consumption, with energy usage through lighting and plug loads continuing to increase despite the implementation of information interventions based on social influence theory and a material cultural framework (Kawabata, 2021).

Moreover, a research study conducted by Peterson et al. (2013) illustrated these effects, wherein the authors observed a decrease in energy consumption among residents who were provided with information regarding their energy usage. Nevertheless, the decrease observed was not as substantial as initially expected, possibly because of the presence of rebound and warm-glow effects. In order to tackle this matter, it is important to take into account the utilization of carbon emissions as a means of gauging energy variations over a period of time as well as formulate efficacious approaches for fostering and maintaining energy-conserving practices among occupants. This may entail the implementation of information-based treatments that address cognitive factors as well as the provision of feedback regarding energy consumption and its environmental impacts. By taking these factors into account, it is conceivable to exert an influence on tenant behavior and mitigate carbon emissions within green buildings.

1.2 Research Objectives & Questions

The purpose of this research study is to examine the connection between socio-psychological and material factors in promoting sustainable behavior through using carbon footprint analysis as a feedback system. The study also aims to investigate the impact of tenant behavior on energy consumption in a zero-carbon building. To address these goals, the following research questions have been adopted using the green nudges:

1. Using a carbon footprint methodology, how does energy consumption in a zero-carbon building, expressed as carbon emissions, vary over time?
    - Do Marginal Emission Factors (MEFs) provide a more accurate representation of carbon intensities than Average Emission Factors (AEFs)?
    - Can hourly and seasonal MEFs provide real-time feedback on the impact of carbon emissions?
2. Are energy-saving behaviors of tenants in a zero-carbon building influenced when information interventions are introduced?
    - Do tenants in a zero-carbon building reduce energy consumption following a green nudge intervention?

Understanding individual energy practices through the use of green nudges and marginal emissions can help reduce carbon emissions from energy demand. The incorporation of marginal emissions in the carbon footprint methodology offers a mechanism for obtaining real-time feedback on the source of electricity in a zero-carbon building. This approach also enables the identification of emissions during peak and off-peak intervals, as the carbon intensities are predominantly determined by the electricity sources from the grid rather than those generated on-site (Shekarrizfard and Sotes, 2021; Siler-Evans et al., 2012). Additionally, evaluating tenant behavioral intentions with the help of green nudges will enable the development of an effective method of information intervention to promote pro-environmental behavior. Previous research on environmental behavior highlights several key areas that need to be further explored, including identifying the necessary behavioral changes to reduce environmental impacts, understanding the factors that contribute to variability in behaviors, and defining interventions that effectively encourage pro-environmental behavior.

2. Literature Review

The following section offers a comprehensive examination of the previous studies in the literature regarding energy demands and the impact of occupant behavior. This will include an overview of the concept of carbon footprint and its utilization in evaluating the environmental impacts associated with resource consumption, with a specific focus on energy usage. Additionally, the section will also explore the existing literature on the impact of pro-environmental behavior and its significance in mitigating environmental impacts. Moreover, the literature review provides a comparison between marginal and average emissions as well as a review of green nudges and their applications in addressing sustainability concerns. The section proceeds by reviewing the existing studies on the emission factors and the reasoning behind MEFs showing more time-sensitive estimations of carbon emissions than AEFs. Then a review of the applications of green nudges in addressing environmental management concerns will be undertaken.

2.1 Energy Demand and Occupant Behavior

Previous studies have confirmed that the energy demand of buildings is dependent on individuals' energy consumption practices (Gill et al., 2010; Barthelmes et al., 2016; Hong & Lin, 2013; Uddin et al., 2022; Hong et al., 2015; Li et al., 2017). Table 1 identifies various research studies that examined the behavioral influence of occupants on increasing energy demands. While more importance is placed on the importance of zero-carbon buildings, existing studies have overlooked green buildings' energy performance associated with the behavior of occupants, especially within Canada (Rouleau & Gosselin, 2020; Yan et al., 2015).

Research Study	Results	Reference
Influence of individual demand on energy in UK homes	51% heat 37% electricity 11% water	(Gill et al., 2010)

Energy demand in energy-efficient houses	76% higher for intensive consumers 83% lower for less-intensive consumers	(Barthelmes et al., 2016)
Energy demand in corporate offices	89% increase with energy-intensive work culture. 50% decrease with energy-saving cultures	(Hong & Lin, 2013)
Influence of interior layouts on occupant energy-saving behaviour in buildings	Building energy performance improved by 14.9% using occupant intervention to adjust interior layouts.	(Uddin et al., 2022)
An ontology to represent energy-related occupant behavior in buildings	This study presents a novel ontology called the "DNAs" framework, which is designed to systematically represent energy-related behavior.	(Hong et al., 2015)
A framework that can identify building occupants' energy consumption characteristics and associated actions to apply energy reduction initiatives.	The findings derived from the agent-based simulation analysis demonstrate that the implementation of appropriate interventions can lead to significant energy savings.	(Li et al., 2017)

Table 1: Research studies on energy demands and influence of occupant behavior

On the one hand, technological advancements in the construction of green buildings have shown reductions in environmental impacts (Allen et al., 2015; Chegut et al., 2014; Balaban & de Oliveira, 2017). Individuals residing in zero-carbon buildings may perceive a decrease in energy expenses or a diminished environmental footprint as a result of the incorporated design elements. However, it is possible that they may knowingly modify their behavior, leading to an unintended rise in energy or resource usage compared to what would have been observed in traditional buildings. The inadvertent rise in consumption partially counteracts the expected energy and carbon emission reductions (Midden et al., 2007). In the work of Shove (2003), the author examines the relationship between contemporary notions of comfort, cleanliness, and convenience within the framework of sustainability and energy efficiency. The author argues that these concepts, while seemingly unrelated, inadvertently contribute to the escalation of energy consumption.

Furthermore, Abrahamse et al. (2005) provide multiple instances in which energy feedback and management systems implemented in sustainable buildings have resulted in users increasing their energy consumption. This phenomenon can be attributed to the discrepancy between the "net energy numbers" presented by the energy feedback and management systems, which may inaccurately indicate lower energy usage than what is actually being consumed. The observed phenomenon, known as the 'rebound effect', pertains to a situation wherein the implementation of energy-efficient and environmentally conscious design elements results in an unanticipated escalation in energy consumption or resource utilisation rather than the intended reduction. (Gillingham, Rapson, Wagner, 2020; Herring & Sorrell, 2009). This raises the common perception of green buildings as "complex socio-technical systems," as discussed by Pan (2014). Therefore, without considering socio-psychological behaviors related to energy consumption, focusing solely on technical solutions in buildings will not enable green buildings to fully address sustainability concerns. Hence, further investigations must be conducted to identify solutions to encourage sustainable behavior by individuals.

2.2 Carbon Footprint and Pro-Environmental Behavior

Sustainability has become a central issue of focus for both governmental and non-governmental organizations, and the presence of carbon emission analysis in sustainability reports provides insightful information for decision-makers in taking sustainable measures within their overall framework (Čuček, Klemeš, & Kravanja, 2012). Today, carbon emissions are closely linked to the public's understanding of climate change, as they are considered one of the key drivers accelerating global warming every year (Oppenheimer & Petsonk, 2005). Academics and environmental experts have long investigated carbon emissions and their actual impact on the environment. Wiedmann and Minx (2008) propose that accounting for carbon footprints implies the "question of quantifying and presenting emissions data for the entire life cycle of products consistently" (p. 4). The assessment of the life cycle of products has been one focus of research into carbon emissions.

The carbon footprint has emerged as a useful tool to measure the influence of climate change. The concept of carbon footprint (C.F.) is defined as "a measure of the exclusive total amount of carbon dioxide emissions that are directly and indirectly caused by an activity or are accumulated over the life stages of a product" (Wiedmann & Minx, 2008, p. 2). The understanding of carbon footprints plays a pivotal role in facilitating informed, sustainable decision-making by offering vital environmental-oriented data. The influence of consumer behavior on the variability of carbon emissions and their overall environmental impact has been widely recognized in the literature (Cerdan et al., 2009; Cor & Zwolinski, 2015). A comprehensive understanding of carbon emissions facilitates the elucidation of the importance of pro-environmental conduct in relation to the utilization of resources and energy. This, in turn, enables individuals to make more informed decisions and use more effective approaches to mitigate the environmental consequences of their energy consumption.

According to the Intergovernmental Panel on Climate Change's (IPCC) 1996 guidelines, greenhouse gas (GHG) inventories were introduced to identify and calculate the GHG emissions within the environment and translate the emissions into universal terms of CO_2 equivalence. Through this methodological guideline, the framework has been segregated in terms of the entity for which the emissions can be recorded, either through a city, a corporation, or even a product scale. Additionally, by utilizing the carbon footprint concept, direct and indirect greenhouse gas emissions can be reported, providing a full picture of the emissions across an entity and the potential environmental impact (Samara et al., 2022). The literature review section 2.1 will provide a more detailed explanation of the calculation methodology and the concepts utilized in developing a carbon footprint framework. Additionally, Section 3.3 will elaborate on the methodology employed.

Marginal emissions and average emissions are two distinct measures used to quantify carbon emissions. Marginal emissions pertain to the emissions linked to the additional system load caused by a certain activity or process during a specific hour (Marginal Emissions Factors for the U.S. Electricity System, n.d.). In contrast, average emissions pertain to the collective emissions produced within a designated timeframe, usually calculated as an annual average. Akbarnezhad and Xiao (2017) conducted a study that demonstrates how the two metrics offer distinct viewpoints on carbon emissions and can be employed to assess the environmental impacts of various activities or sectors.

Moreover, it is imperative to comprehend the correlation between marginal emissions and average emissions in order to effectively evaluate the environmental implications of particular activities. When evaluating the environmental impacts of operations, it is important to take marginal emissions rates into account instead of only relying on annual average emissions factors. According to Sun et al. (2019), through the utilization of marginal emissions rates, it becomes feasible to ascertain whether the avoided emissions linked to a certain activity, such as the production of photovoltaic (PV) electricity, exhibit a disproportionate magnitude during various seasons and times of the day (Marginal emissions factors for the U.S. electricity system, n.d.; Virupaksha et al., 2019). Hence, this methodology facilitates a greater understanding of the sustainable benefits associated with solar energy power generation, empowering policymakers and academics to discern the most appropriate times for optimizing emission reductions.

The proposed research approach is anticipated to serve as a valuable instrument for augmenting eco-based innovations. Comparative analysis can be employed to evaluate predictable energy patterns. Furthermore, the implementation of annual quantifiable assessments of carbon emissions will serve as a foundation for the accurate and effective incorporation of strategic planning for carbon management (Alvarez et al., 2014). Incorporating such an initiative into procurement protocols would guarantee efficient and enduring decision-making processes while also affirming the value of sustainable practices in mitigating emissions.

Furthermore, past studies have confirmed the influence of pro-environmental behaviors on reducing environmental impacts (Steg & Vlek, 2009; Brick et al., 2017). Steg & Vlek (2009, p. 309) defines pro-environmental behavior as "behavior that harms the environment as little as possible or even benefits the environment". Although numerous studies have mainly focused on the estimation and breakdown of carbon emissions at an individual or organizational level (Li, Tan, & Rackes, 2015; Gómez, Cadarso, and Monsalve, 2016; Yoshino, 2018; Ozawa-Meida et al., 2013), minimal attention has been paid to the influence of occupant behaviors to reduce individual carbon emissions.

2.3 Carbon Footprint

The evaluation of marginal emissions has been identified as a major factor in assessing the impact of alterations to carbon emissions from electricity generation. According to the Independent Electricity System Operator (IESO), in the province of Ontario, the primary sources of electricity are nuclear and hydropower, which contribute 53.7% and 25.9%, respectively, thereby reducing the reliance on natural gas-fired generation (IESO, 2022). However, nuclear power plants are not capable of rapidly adjusting to changes in electricity demand. In these situations, natural gas power plants are often utilized to respond to demand changes and are therefore considered to be on the "margin" (Total Atmospheric Fund (TAF), 2021). While green buildings may tout their use of fully renewable energy sources, demand for energy from occupants during peak hours is often met with natural gas as a marginal source (Byrd & Leardini, 2011; Siler-Evans et al., 2012). Further research is necessary to examine the sources of electricity used in green buildings during both peak and off-peak hours.

Emission factors are estimates of how much of a particular type of pollutant a particular activity releases into the atmosphere, such as burning a gallon of gasoline (US Environmental Protection Agency, n.d.). In the context of quantifying carbon emissions from energy sources in buildings, average emission factors (AEFs) calculate the average amount of carbon pollution produced per kilowatt-hour of electricity (kWh) consumed and are commonly used to quantify pre-historic and current emissions. They can be expressed on an annual or hourly basis (Shekarrizfard & Sotes, 2021; Mancarella & Chicco, 2009; TAF, 2021). Marginal Emission Factors (MEFs), on the other hand, estimate the changes in carbon emissions per kWh resulting from an actual or proposed consumption of electricity, taking into account the generating source of the electricity. Like AEFs, MEFs can also be expressed for different time periods, such as an annual, seasonal, or hourly basis, as well as on an on-peak or off-peak basis (Shekarrizfard & Sotes, 2021; Siler-Evans et al., 2012).

While AEFs provide a more general overview of emissions and are commonly used by policymakers (Dacunto et al., 2013), MEFs are more accurate in measuring emissions from specific periods or activities because they account for short-scale, localized emissions, which AEFs do not consider (Manzo & Salling, 2016). In order to validate the higher level of accuracy of MEFs in relation to AEFs, it is important to recognise the variability of emission intensity over the course of a day and across different seasons. The utilisation of shorter time intervals, such as hourly measurements, offers a more comprehensive understanding of potential prospects for reducing emissions. To address this claim, the quantitative part of our study will use empirical methods to test the accuracy of using MEFs to estimate carbon emissions over time while also answering question 1.1.

Furthermore, MEFs also allow for the consideration of regional differences in the analysis of emissions from specific industries and activities, enabling the tailoring of environmental policies to best suit local conditions and providing flexibility when applied to wider policy decisions and programs (Thind et al., 2017). One example (figure 1) of the differences between MEFs and AEFs can be seen in the evaluation of the potential CO_2 reductions from installing LED retrofit lights in a building, as demonstrated by TAF (2021, p.12). In this case, it is assumed that the installation of LEDs would result in an increase in natural gas consumption for heating during the winter due to higher energy demand, and a decrease in electricity consumption for cooling during the summer. When converting the electricity consumption units to carbon emissions, using AEFs shows that the installation of LEDs would increase carbon emissions, while MEFs provide a more accurate estimation showing that the installation would actually reduce carbon emissions based on the timing of energy use. This highlights the importance of using the most accurate emission factors available to properly assess the environmental impact of different energy sources and technologies.

Example

Lighting retrofits illustrate the importance of using MEFs to estimate the impact of changes in electricity consumption. Installing more energy efficient lights will have an impact on heating and cooling systems. Since inefficient lights produce a lot of waste heat, upgrading to LEDs can increase heating energy-use during the winter and reduce cooling energy-use in the summer. Using Ontario's current AEF, energy efficient lighting upgrades will result in a net increase in carbon emissions. But, using the Annual MEF will show that the actual impact of lighting retrofits is a net reduction in carbon emissions, even when accounting for the increased heating demand.

The review of a feasibility study provided the following results:

- Savings from change in lighting: 94,249 kWh/year
- Increase in natural gas consumption for heating: 6,116 m^3/year
- Reduction in electricity consumption for cooling: 2,495 kWh/year

Carbon reductions = A - B + C

A: Reductions in lighting emissions with efficient bulbs

B: Increase in emissions due more heating needed in winter

C: Reduction in emissions due less energy needed for cooling in the summer

If we just use the AEF (31), the project will result in an increase of 8.62 TCO_2e/year:

(94,249 kWh/year x 31gCO_2e/kWh x 0.000001) - (6,116 m^3/year x 0.001899 tCO_2eq/m^3) + (2,495 kWh/year x 31gCO_2e/kWh x 0.000001) = - 8.62 TCO_2eq/year (increase in carbon emissions)

But, if we use Annual MEF (123), the project will result in a reduction of 0.29 TCO_2e/year:

(94,249 kWh/year x 123gCO_2e/kWh x 0.000001) - (6,116 m^3/year x 0.001899 tCO_2eq/m^3) + (2,495 kWh/year x 123gCO_2e/kWh x 0.000001) = 0.29 TCO_2eq/year (decrease in carbon emissions)

Figure 1: Calculation example using MEFs and AEFs. Retrieved from (TAF, 2021, p. 12.)

The value of MEFs is found to be higher than AEFs due to the changes in carbon emissions caused by changes in electricity generation sources as a function of time. Unlike AEFs, MEFs express the incremental source as a primary factor that is added to meet the demand at that specific time. This enables estimations of carbon intensities to have a higher rate of accuracy in the case of MEFs in contrast to AEFs (TAF, 2021). Moreover, research findings from previous studies have concluded that the use of MEFs was found to be more consistent in the estimation of CO_2 savings than AEFs. When assessing the environmental impact of wind-power generation projects in the UK, using MEFs within the framework of environmental impact assessments (EIA) was found to be more accurate and precise in contrast to AEFs (Thomson et al., 2014). Additionally, within the context of electricity outputs sourced from national grids, studies conducted in England, Wales, and California have shown the inconsistencies and underestimations of CO_2 savings when AEFs are integrated within their estimations (Bettle et al., 2006; Hawkes, 2010). Therefore, it can be observed that the use of marginal emissions within a carbon footprint methodological approach can enable the provision of real-time feedback on the impact of electricity sources used in green buildings in a more consistent and accurate manner than conventional AEF approaches.

2.4 Concept of Nudges

Through a better understanding of human behavior in both its rational and irrational dimensions, it becomes possible to take more effective action to modify behavior as we wish. The concept of 'nudge, which was initially developed by Thaler (1994), proposes a unique approach to taking behavioral actions through the integration of gentle encouragements based on advanced knowledge in the decision-making process. Sunstein (2015) analyzes the ethical foundation underlying the concept of nudge theory, which is commonly referred to as 'libertarian paternalism.' The term in question presents itself as an oxymoron, as libertarian ideology advocates for unrestricted individual freedom, but paternalism entails providing direction or imposing limitations purportedly for the individual's benefit. The general norm perceives positive behavioral action through cost modifications, which tend to deviate society through activating their cognitive norms to believe and adapt to the change. The application of nudging contests is simple, low-cost, and immensely effective in driving new behavioral change. Therefore, the benefits of nudges have been observed notably due to their remarkable power of altering behaviors through cost-effective actions. On the other hand, the concept of nudges has been subject to criticism, notably with regards to its effectiveness, particularly in ethical contexts, and its capacity to maintain long-term impacts in altering behavioral patterns.

Sunstein (2015) examines the ethical implications associated with nudges, arguing that they have the ability to hinder autonomy and weaken the capacity for independent decision-making. The paper delves into the ethical considerations pertaining to the practice of 'nudging.' The author claims that nudges, through the discreet manipulation of option context or presentation, possess the ability to discreetly steer individuals towards specific decisions, all while evading their conscious awareness of the exerted impact. The criticism presented in this context is the potential degradation of individual autonomy. The concept of nudges naturally implies that decision-makers may not possess complete information or awareness regarding the effects that are at play. The absence of transparency can be perceived as a manipulative tactic that has the ability to diminish individuals' autonomy in making well-informed and autonomous judgments. Additionally, the author admits the aforementioned difficulties while simultaneously positing that the majority of decisions we make occur within the confines of a pre-established choice architecture. However, from an ethical standpoint, this raises concerns regarding the delineation between beneficial guidance and manipulative intervention.

Hertwig and Grüne-Yanoff (2017) examine a limitation of nudges, namely their limited efficacy in inducing enduring modifications in behavior. Although nudges have the ability to impact immediate decision-making, they generally do not effectively enable individuals to autonomously make better choices over an extended period of time. As a proposed resolution, the authors recommend the implementation of "boosts," which are treatments specifically tailored to augment individuals' proficiency and consistent efficacy. The aforementioned research demonstrates that although nudges have demonstrated efficacy in behavior modification, it is imperative to address substantial ethical and efficacy considerations. It is apparent that the impacts of nudges are not always enduring, highlighting the necessity for alternate approaches to achieve sustained behavioral modification. Additionally, ongoing reminders are pivotal to maintaining the effectiveness of nudges in fostering long-term behavioral changes that align with sustainable action plans.

Nudge, as an expression of behavioral intervention, has recently gained recognition for its importance in policy and business-oriented decision-making processes. In economic terms, nudges are conceptually defined as the change in the individual’s decision environment that impacts society's behavior without the need for their choices or economic incentives to be affected (Thaler and Sunstein 2009, p. 367). Therefore, nudges project the enhancement of an individual’s welfare without tackling their respective externalities. Camerer et al. (2003, p. 1212) elaborate further on the benefits of a well-structured nudge towards individuals who make errors in their decision-making process while prohibiting any consequences for those who are fully rational. Hence, it is perceived that nudges can be utilized as a form of behavioral solution to an existing behavioral problem. The concept of nudges is classified as either self-focused or green nudges, depending on the overall decision-making process in the individual’s respective environment. Both classifications are categorized under pure and moral nudges. To differentiate between the approach of nudging from an individual’s welfare perspective and a nudge that minimizes environmental impact, literature studies define the latter as a "green nudge" (Planas, 2013; Bühren & Daskalakis, 2020; Akbulut-Yuksel & Boulatoff, 2021; Mélon, 2020).

Sunstein (2015) draws attention to several criticisms directed at the oxymoronic term. Critics contend that the concept of 'libertarian paternalism,' particularly when implemented through self-focused pure nudges, has the potential to compromise personal autonomy by modifying individuals' actions without their explicit agreement or awareness. These subconscious alterations manifest due to subtle influences in 'choice architecture"—the manner in which decisions are framed and presented. For instance, the strategic positioning of nutritious food alternatives at the level of consumers' line of sight within grocery shops serves as a subtle influence that steers individuals towards making healthier selections. However, this practice has been subject to criticism as it may potentially affect individuals' decisions on a subconscious level, leading to concerns about the infringement on personal autonomy. Additionally, the author also argues that, notwithstanding the presence of ethical issues, choice architecture is an inherent and unavoidable component of the decision-making process. The author posits that rather than completely avoiding nudges, it is more important to prioritize their competent implementation, which upholds and advances individual autonomy whenever feasible.

Moral nudges use a similar approach, but with the addition of a reward for doing the right thing, triggering the individual’s psychological reactions. In other words, the method of approach encourages behavior that benefits the one being nudged (Bhattacharya & Dugar, 2022). The most common and effective approach to using a moral nudge is through social proof. For instance, "compared to your neighbors with similar-sized houses, you consume far more energy" (Allcott 2011). Therefore, moral nudges are perceived to be the dominant and most effective approach to initiating new behavioral actions due to their ability to trigger a psychological response in the individual being nudged (Capraro et al., 2019).

2.5 Green Nudges

The application of nudging has gained traction in the field of environmental policy and management, as it has been shown to influence people's actions towards reducing negative externalities in resource consumption and waste disposal (Schubert, 2017; Carlsson et al., 2021; Wensing et al., 2020; Boruchowicz, 2021). Nudging is perceived as a behavioral solution to modern economic issues involving negative externalities. Green nudging differs from self-focused nudging in that it relies on the cognitive norms and moral concerns of the individual to steer them away from choices that result in negative externalities (Wensing et al., 2020), rather than addressing decision-making errors as self-focused nudges do.

Green nudges are generally preferred over self-focused nudges because they are not based on paternalism, which involves making decisions on behalf of others and restricting their freedom and responsibility to act in their own self-interest (Sugden, 2018; Planas, 2013). In addition, several studies have implemented green nudges as a form of information intervention to persuade consumers and influence their purchasing decisions. Boruchowicz (2021) identified two types of green nudges: pure and moral. Pure green nudges include default options, the provision and simplification of information, changes to the physical environment, and reminders. Moral green nudges, on the other hand, include interpersonal motivation and social comparisons, moral suasion, and goal setting and commitment.

Green nudges are effective in simplifying information and influencing decision-making processes (Caplin & Dean, 2015). For example, Stadelmann and Schubert (2018) found that the use of labels to illustrate financial and forecast-based information on energy-efficiency savings led to increased sales of energy-efficient appliances. Tienfenbeck et al. (2016) used real-time feedback on energy consumption in the form of an animation to convince users to reduce their shower times, resulting in a 22% reduction. Wallander, Ferraro, and Higgins (2017) found that reminders with encouraging notes sent to registered volunteers whose contracts were about to end increased the likelihood that they would extend their contracts. Gosnell, List, and Metcalfe (2020) used personalized reminders with individualized goals to encourage pilots to fly more efficiently for fuel conservation. Over a nine-month period, this resulted in fuel savings of up to 10%. In summary, research has shown that green nudges can be an effective, low-cost method of information intervention that promotes pro-environmental behavior due to their simplicity and effectiveness in delivering information.

3. Methods

In the pursuit of understanding how occupants can be motivated to adopt sustainable energy practices, it is important to employ a research methodology that goes beyond statistical analyses based solely on occupant behavior and energy consumption data. Recognizing the limitations of such an approach in unraveling the intricate behavioral mechanisms at play, researchers have turned to the explanatory sequential mixed methods design to shed light on the relationship between structural and socio-psychological factors and energy practices in green buildings.

In order to comprehensively examine the factors that influence occupants' adoption of sustainable energy practices, this study employs a research approach that incorporates both quantitative and qualitative assessments. These assessments are utilized to analyze energy consumption patterns, specifically in relation to carbon emissions, as well as to investigate occupant behavior. The study employs an explanatory sequential mixed-methods methodology to examine the correlation between structural and socio-psychological elements and energy practices in green buildings. The first research question, together with its subsequent questions (1.1 and 1.2), will focus on quantitative evaluations pertaining to energy consumption and the trendlines of carbon emissions. Section 3.2 offers a comprehensive examination of the methodologies employed for calculating carbon footprints, specifically in accordance with the greenhouse gas (GHG) corporate accounting and reporting standard. Furthermore, in Section 4, a comprehensive analysis will be conducted to examine the quantitative assessments pertaining to tenants' lighting and plug load utilization, as well as the overall building performance. The second question and succeeding question 2.1 will focus on the qualitative evaluations of the thesis report using the concept of green nudges. These assessments will examine the behavioral intentions of tenants in relation to their prospective adoption of pro-environmental behavior. This evaluation will be conducted through the implementation of biweekly information interventions. Section 5 of the report will provide a more comprehensive analysis of the qualitative assessments by employing a three-phase methodology that includes focus group recruiting, nudging, and follow-up.

3.1 Research Site

In this study, we examine evolv1, a noteworthy example of a net-positive energy, zero-carbon building, which was established in 2018 and holds the distinction of being Canada's first certified zero-carbon design office building under the Canada Green Building Council’s certification system (Canada Green Building Council, 2020). This building is a remarkable illustration of high-performance green infrastructure, recognized by the Leadership in Energy and Environmental Design (LEED) certification system. LEED is a well-established certification that uses a category rating point system to evaluate and acknowledge the sustainability and environmental features of buildings. The ratings awarded range from certified to silver, gold, and platinum, with evolv1 achieving LEED platinum certification (Turner et al., 2008, p. 7; Canada Green Building Council 2020).

The zero-carbon building, near a university in southern Ontario, served as the venue for this research. Occupying three floors, the building accommodates various entities, including universities, corporations, and an environmental non-profit organization (Canada Green Building Council, 2020). Spanning approximately 110,000 square feet (10,000 m2), this remarkable structure received the prestigious LEED Platinum Certification, underscoring its sustainability credentials (Canada Green Building Council, 2020). Its construction was successfully finalized in 2018, marking its entry into the realm of environmentally conscious buildings (Canada Green Building Council, 2020).

Furthermore, the zero-carbon building has been thoroughly designed to minimize energy consumption by integrating various innovative features (Canada Green Building Council, 2020).

Triple-glazed windows work in conjunction with a highly efficient building envelope to ensure the best possible insulation and thermal performance. Additionally, a solar wall facilitates ventilation with pre-heated air, reducing energy demand (Canada Green Building Council, 2020). In the atrium, two adjacent elevators and a central staircase with glass railings take center stage. East and west side stairs flank the structure, providing additional access points (Canada Green Building Council, 2020). The zero-carbon building also uses renewable energy sources, with solar panels on the roof and carport as well as a geothermal system that harnesses on-site renewable energy (Canada Green Building Council, 2020). To monitor energy consumption and indoor temperatures, sensors and meters have been installed throughout the building (Canada Green Building Council, 2020).

The zero-carbon building serves as an exemplar of sustainable building practices in Canada. It offers an opportunity to explore the energy behaviors of occupants within a green building setting. By conducting research within this environmentally conscious structure, the study aims to understand the relationship between structural and socio-psychological factors and energy practices. Through the exploration of occupant behaviors, motivations, and interactions within the context of this exceptional research site, valuable insights and actionable recommendations can be gleaned to foster energy-efficient practices.

To address the main research questions of this study, the following methodological approaches will be used. To accurately estimate carbon emissions, guidelines were followed in alignment with the greenhouse gas (GHG) protocol corporate accounting and reporting standard, which will be employed in calculating carbon emissions (WBCSD, 2004). The values for the corresponding emissions factors are obtained from the ‘A Clear View of Ontario’s Emissions’

2021 edition report by the TAF, which develops these values sourced from the IESO or the National Inventory Report (TAF, 2021).

3.2 Sequential Explanatory Mixed Methods

In accordance with Creswell and Creswell (2018), the present study uses an explanatory sequential mixed methods design to methodically investigate our research questions. Mixed-methods research is a complete strategy for conducting research that integrates qualitative and quantitative data collection and analysis methodologies. The utilization of this specific methodology allows for the examination of our research inquiries from multiple angles, leveraging the benefits of each to achieve a full understanding of the complex phenomena under investigation (Creswell & Creswell, 2018; O'Leary, 2010).

The research questions can be classified into two primary categories: quantitative and qualitative. The quantitative component of our research, which includes questions 1, 1.1, and 1.2, relates to the measurement of energy consumption, the assessment of carbon emissions, and the evaluation of statistical trendlines. The main emphasis is on the performance of tenants and buildings. In contrast, our qualitative questions, namely questions 2 and 2.1, revolve around assessing the efficacy of utilizing information interventions as a means of influencing tenant behavior, drawing upon the theoretical framework of nudges.

The integration of mixed approaches allows for a seamless connection between the two unique components of our research. This methodology not only aligns with our research approach but also efficiently tackles our research questions. This facilitates the examination of the potential impacts of both physical and human factors on changes in occupants' behavior, thereby offering valuable insights into the manner in which these elements influence energy use. Furthermore, this enables us to explore the fundamental factors and mechanisms behind energy conservation actions, encompassing theoretical and empirical ramifications.

The purpose of the quantitative analysis in this study is to examine the relationship between energy consumption by the tenants and carbon emissions over time. To address question 1 and its subsequent questions, energy consumption data will be collected from 2019 onward and analyzed using a carbon footprint approach, which expresses the data in terms of kilograms of carbon dioxide equivalent ($kgCO_2e$). The study will also use both marginal emission factors (MEFs) and average emission factors (AEFs) as indicators to compare the relative carbon intensities. Both MEFs and AEFs will be compared on an annual and hourly basis for comparative purposes. MEFs are particularly useful for understanding the carbon impact of energy consumption on an hourly and seasonal basis and can provide real-time feedback on the impact of carbon emissions. The results of the analysis will be presented through trend analysis using statistical regression models and will aim to provide a more comprehensive understanding of energy consumption patterns and their carbon impact.

The qualitative component of our research study fulfills an entirely distinct yet complementary role to the quantitative analysis. Using detailed data from the quantitative phase, the qualitative investigation is designed to figure out the best times to deliver information interventions to tenants with the objective of encouraging them to adopt more sustainable energy behaviors. When considering question 2 and its subsequent question, 2.1, we explore the topic of behavioral change in relation to sustainable energy consumption. The aim of this study is to evaluate the efficacy of information interventions based on the principles of nudges in promoting pro-environmental behavior among the occupants of the building.

Through a qualitative analysis of the effects of these interventions, our objective is to offer meaningful insights into the optimal conditions and methods for maximizing the effectiveness of these nudges. The comprehension of the concept of nudges is based on an empirical understanding of energy usage trends and their associated carbon emissions, which are derived from quantitative analysis. The qualitative phase of our research plays a vital role in our study, enabling us to convert insights derived from data into practical initiatives aimed at fostering the adoption of sustainable energy habits among tenants.

3.3 Carbon Footprint Calculation

In order to address the carbon footprint calculations, the standards were adhered to in accordance with the GHG Protocol Corporate Accounting and Reporting Standard, a comprehensive resource that offers detailed information on the computation of carbon footprints **(**WBCSD, 2004).

$$GHG\ Emissions = Activity\ Data * Emission\ Factor * Global\ Warming\ Potential\ (GWP)$$

Eq. 1

Equation 1- Carbon Footprint Calculation

There exist two fundamental categories of data required in the computation of CO_2-related emissions: activity data and emission factors (see Eq. 1). Activity data may encompass measurements of emissions generated by various activities, whether they are produced directly or indirectly, such as the quantity of gasoline or paper utilized. Emission factors are employed to convert activity data into CO_2 emissions. Emission factors are tailored to a particular source and quantified in terms of carbon dioxide emissions per unit of measurement. Furthermore, the concept of global warming potential (GWP) pertains to the extent to which a particular greenhouse gas contributes to global warming compared to carbon dioxide (WBCSD, 2004). The GWP of carbon dioxide (CO_2) has been designated as **1** (IPCC, 2007). Upon acquiring the activity data and emission factor, the values are multiplied together, resulting in the expression of greenhouse gas (GHG) emissions in kilograms of carbon dioxide equivalence (kgCO_2e).

4. Quantitative Study

4.1 Tenant Locations and Electricity Meters

The study focuses on evaluating the consumption of electricity in tenant areas of the green office building. Tenant areas refer to the spaces leased and occupied by organizations, with the exclusion of common areas such as the atrium, corridors, and washrooms. Five tenants, designated as Tenant A, Tenant B, Tenant C, Tenant D, and Tenant E, were investigated and their corresponding areas monitored (Kawabata, 2021; Z. Zhu, 2020).

Tenant A, a private cooperation in which the tenant areas are segregated into non-office and office spaces. Tenant plug loads and lighting consumption in both areas were monitored using electricity meters. Two out of the four meters were designated to record data from the non-office space, while the other two meters collected data from the office area. Additionally, Tenant A's office area also contained a shared bar space and a cafeteria.

Tenant B, a multi-party innovation hub, contained two electricity meters to monitor plug loads and lighting electricity consumptions, respectively. Tenant B's allocated space also included a shared kitchen used by both Tenant B and Tenant C. However, the electricity usage data from the kitchen area was included with the office area electricity data of Tenant B, and no allocation was made to Tenant C.

Tenant C, a university group, had tenant areas shared for researchers and a dedicated classroom utilized for teachings and group event purposes. The two electricity meters were operated to record the joint office areas and classroom, through which one measures the plug loads, and the other measured lighting consumption.

Tenant D, also a private cooperation, included four electricity meters employed in recording their electricity consumption. The tenant areas were distributed into three parts: a dedicated office area on the east side, an office area on the west side, and a server panel room. The meters were segregated to measure consumption from plug loads in the east and west office spaces, as well as the server panel room. Another meter monitored the lighting usage in all the areas combined.

Tenant E is a small research unit operating within a large national corporation. The rationale for its location in the building is to ensure proximity to the pool of talent accessible at the university. Two meters were placed throughout the office area to measure the levels of lighting and plug load consumption.

In sum, there are a total of fourteen electricity meters utilized in the monitoring of lighting and plug load usage, respectively, by Tenant A, B, C, D, and E. The sample for the analysis of electricity usage within the case study building includes occupants from Tenant A, Tenant B, Tenant C, Tenant D, and Tenant E. The quantitative analysis uses tenant lighting and plug load data from January 2019 to December 2022, collected within the tenant areas. Table 2 summarizes the electricity meters used for data collection in the tenant areas.

Meter	Tenant Name	Type of Usage	Energy Type	Space (m^2)
1	A	Non-office area	Lighting	**3886**
2	A	Office area	Plug loads	
3	A	Office area	Plug loads	
4	A	Non-office area	Lighting	
5	B	Office area and shared kitchen	Lighting	**590**
6	B	Office area and shared kitchen	Plug loads	
7	C	Office area and classroom	Lighting	**230**
8	C	Office area and classroom	Plug loads	
9	D	Office area and server room	Lighting	**1220**
10	D	Server room	Plug loads	
11	D	Office area on the east side	Plug loads	
12	D	Office area on the west side	Plug loads	
13	E	Office area	Lighting	**100**
14	E	Office area	Plug loads	

Table 2: Electricity meters employed for data collection in designated tenant areas

4.1.1 Data Collection

An electricity-based submetering system, along with electricity meters within the green office building were installed to monitor electricity consumption patterns in an effective manner. As part of the submetering system, the 14 meters were strategically positioned to measure respective plug loads and lighting data within the designated tenant areas. The monitored data from these respective meters were dispatched wirelessly to the online CircuitMeter platform, provided by CircuitMeter Inc. (Figure 2). The online platform functions as a central database hub for the electricity data, making it both convenient and accessible for researchers to assess and evaluate in their study.

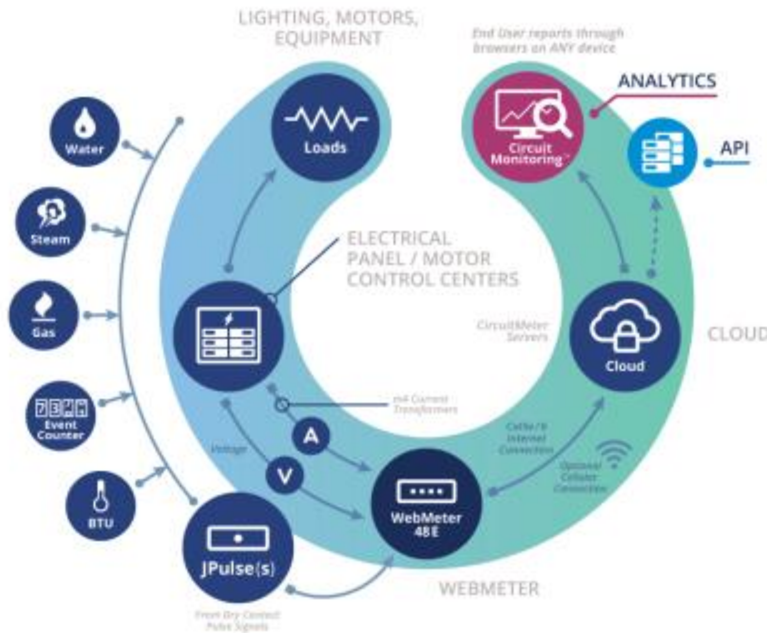


Figure 2: Summarized image of the energy submetering system, CircuitMeter, obtained from Kawabata (2021).

4.1.2 Data Analysis

The analysis of the baseline of tenant electricity usage is focused solely on the data retrieved from the designated tenant areas. Common areas, such as washrooms and corridors, were excluded from the analysis. The rationale behind the removal is that tenants would not have control over the electricity usage within the common areas, as they are available for usage by other occupants who may not be tenants, for instance, visitors. Therefore, for an effective model representation of the baselines of tenant electricity usage only, consumptions relating to plug loads and lighting within the tenant spaces were taken into consideration.

The analysis of the monitored electricity data from 14 meters, including both lighting and plug loads, is carried out on an hourly and seasonal basis. In alignment with the carbon footprint calculation described in section 3.1, the documented electricity consumption measured in kWh, serving as the activity data, is converted to $kgCO_2e$ using the emission factors reported for each hour and season. Therefore, to address research questions 1 and 1.1, tables 3-5 illustrate the hourly and seasonal values for MEF and AEF respectively, which were sourced from TAF (2021). In addition, it should be noted that the emission factors report obtained from TAF (2021) only referred to the 2021 edition. Consequently, the emission factors from the year 2020 were employed in order to forecast the emissions for the year 2022. The emissions factors for the year 2022 were estimated by extrapolating from the emission factors recorded in the directly prior year, 2020, due to the unavailability of the most current TAF emission factors report.

Hourly MEFs (gCO_2e/kWh)		
Hour	**2020**	**2019**
1	103	99
2	98	98
3	93	94
4	94	96
5	99	100
6	103	109
7	109	124
8	118	132
9	125	136
10	128	139
11	133	138
12	132	138
13	133	139
14	134	139
15	131	139
16	134	139
17	136	145
18	137	151
19	138	150
20	139	149
21	138	143
22	130	137
23	124	124
24	112	110

Table 3: Hourly MEF values for the year 2019 and 2020 retrieved from (TAF, 2021, p.15)

Hourly AEFs (gCO_2e/kWh)		
Hour	**2020**	**2019**
1	14	15
2	13	14
3	14	14
4	16	16
5	19	19
6	23	22
7	26	26
8	28	30
9	31	32
10	34	34
11	36	35
12	38	36
13	39	37
14	41	37
15	42	38
16	43	38
17	43	40
18	43	41
19	42	41
20	40	39
21	36	36
22	30	31
23	23	23
24	17	17

Table 4: Hourly AEF values for the year 2019 and 2020 retrieved from (TAF, 2021, p.11).

2020 Seasonal MEFs (gCO_2e/kWh)				
Hour	**Winter**	**Spring**	**Summer**	**Fall**
1	109	57	153	91
2	102	53	152	84
3	102	49	140	82
4	101	49	147	79
5	104	56	149	86
6	108	58	153	94
7	108	62	161	105
8	114	73	174	112
9	116	81	187	117
10	119	88	191	115
11	121	93	199	117
12	114	95	201	116
13	115	99	198	120
14	118	99	199	119
15	110	95	203	115
16	115	98	206	118
17	112	107	208	118
18	111	108	204	125
19	123	102	200	127
20	115	112	199	130
21	120	104	199	128
22	119	91	196	116
23	113	84	187	111
24	108	66	170	102
Seasonal Average	**113**	**84**	**184**	**110**

Table 5: Seasonal hourly MEF values retrieved from (TAF, 2021, p.19).

4.2 Tenant Lighting and Plug Load Emissions

To determine the carbon emission intensities at various scales (annual, seasonal, and hourly), equations 2-7 will be utilized to assess the carbon emissions associated with both tenant lighting and plug loads, respectively. In order to assess the accuracy of carbon intensity estimations, equations 2-3 will be employed to evaluate the yearly hourly emissions, taking into account the application of both MEFs and AEFs, respectively. To quantify the carbon emissions, the hourly emission factor values presented in tables 3 and 4 will be incorporated. Moreover, to assess the annual seasonality, equation 4 is utilized, utilizing the seasonal average MEF values as presented in table 5. Additionally, in order to conduct a comparison analysis of the distinct seasons at an hourly level, equation 5 will be substituted for equation 4. This substitution will include utilizing the hourly seasonal MEF values provided in table 5. Finally, to compare the emissions of individual tenants on an hourly basis, equation 6 will be employed, utilizing the seasonal hourly MEF values provided in table 5.

Furthermore, taking into account that tenant's spaces are occupied in unequal dimensions (as shown in table 2), the emissions recorded on an hourly and seasonal basis are modified to account for the square footage allocated to each tenant. Therefore, equation 7 is provided to calculate the tenant lighting and plug load emissions respectively, accounting for marginal emissions, both on an hourly and seasonal basis. By applying this adjustment, the technical approach ensures an appropriate comparison of emission with consideration of space variations amongst the tenants in the case study building.

Equation 2 – Annual hourly electricity emissions using marginal Emission Factors (Table 3)

$$kgCO_2e = \frac{Annual\ Electricity\ data\ (kWh) * Hourly\ MEFs\ (\frac{gCO_2e}{kWh})}{1000}$$

Eq. 2

Equation 3 – Annual hourly electricity emissions using average emission factors (Table 4)

$$kgCO_2e = \frac{Annual\ Electricity\ data\ (kWh) * Hourly\ AEFs\ (\frac{gCO_2e}{kWh})}{1000}$$

Eq. 3

Equation 4 – Seasonal electricity emissions using seasonal average marginal emission factors (Table 5)

$$kgCO_2e = \frac{Seasonal\ Electricity\ data\ (kWh) * Seasonal\ Average\ MEFs\ (\frac{gCO_2e}{kWh})}{1000}$$

Eq. 4

Equation 5 – Seasonal electricity emissions using seasonal hourly marginal emission factors (Table 5)

$$kgCO_2e = \frac{Seasonal\ Electricity\ data\ (kWh) * Seasonal\ Hourly\ MEFs\ (\frac{gCO_2e}{kWh})}{1000}$$

Eq. 5

Equation 6 –Tenant hourly electricity emissions using seasonal hourly marginal emission factors (Table 5)

$$kgCO_2e = \frac{Individual\ Tenant\ Electricity\ data\ (kWh) * Seasonal\ Hourly\ MEFs\ (\frac{gCO_2e}{kWh})}{1000}$$

Eq. 6

Equation 7 – Tenant emissions with respect to the dimensional space

$$\frac{kgCO_2e}{m^2} = \frac{Tenant\ emissions\ (kgCO_2e)}{Tenant\ Area\ (m^2)}$$

Eq. 7

4.3 Case Study Building Parameters

This section provides a comprehensive analysis of the overall performance distribution of the case study building in terms of energy consumption throughout the calendar year 2022. The main aim of this analysis is to determine the specific time period, specifically the season, in which further measures need to be implemented to reduce carbon emissions. Our objective is to develop a standardized framework for promoting environmentally friendly behavior by analyzing the building's solar generation and total energy consumption.

4.3.1 Data Collection

For the analysis of the case study building’s performance, the CircuitMeter submetering platform is utilized for the collection of electricity data on the building’s solar generation, imports, and exports. The energy consumption is collected on a monthly basis over the course of the year 2022.

4.3.2 Data Analysis

For further understanding of the electricity data recorded by PV generation, import, and export meters in the case study building, calculations will be exercised to outline the building's overall self-consumption and total consumption. Equation 8 will be used to calculate the self-consumption, which includes the summation of all PV generation meters and deducting the overall exports. Additionally, equation 9 will be utilized to determine the total consumption of the building, which includes both the total PV generation and imports while subtracting the exports.

Furthermore, to gain a general understanding of the building's energy performance, equation 10 will be used to convert the imported electricity data into marginal carbon emissions using the seasonal hourly MEF values provided in table 5. The conversion will aid in better understanding the environmental impact with respect to carbon emissions across the different seasons.

Equation 8 – Self consumption of the case study building

$$Self\ Consumption\ (kWh) = \sum PV\ Generation - Exports$$

Eq. 8

Equation 9 – Total consumption of the case study building

$$Total\ Consumption\ (kWh) = \left(\sum PV\ Generation + Imports\right) - Exports$$

Eq. 9

Equation 10 – Monthly emission imports of the case study building (Table 5)

$$kgCO_2e = \frac{Imports\ (kWh) * Seasonal\ Hourly\ MEFs\ (\frac{gCO_2e}{kWh})}{1000}$$

Eq. 10

5. Qualitative Study

The qualitative aspect of the study aims to investigate the effectiveness of using nudges in the form of bi-weekly flyers to promote pro-environmental behaviors among tenants of Evolv1. The experimental design for this study has been adapted from Kawabata (2022), with the inclusion of the research study to be conducted through four phases: focus group recruitment phase, nudging phase, and follow-up phase. The following section will extensively discuss how the performance of the case study building will be utilized in correlating the analysis made in understanding tenant behavioral patterns of electricity usage.

5.1 Focus Group Recruitment Phase

During the focus group recruitment phase, the primary objective was to engage with all tenants in the green office building to solicit their valuable insights regarding potential behavioral strategies that could be integrated into the subsequent phase, the nudging phase. In order to ensure confidentiality and privacy requirements within the zero-carbon building, our methodology was disseminated through a general invitation, affording interested tenants the opportunity to partake in the focus group phase.

Tenants who responded to the invitation were then invited to take part in pre- and post-intervention focus group meetings. These meetings served as an opportunity for acquiring firsthand feedback from tenants, particularly on effective energy-saving behavioral techniques pertaining to both lighting and plug load usage. Therefore, direct engagement with tenants through open and insightful discussions cultivates a comprehensive understanding of their unique experiences and perspectives, thereby creating a set of tailored information interventions to be presented in a meticulous and responsive manner.

5.2 Nudging Phase

The nudging phase is carried out over a span of six weeks (table 6), starting with the distribution of biweekly flyers. Table 7 also illustrates the timeline on which the nudging phase has taken place. At the onset of the first week, an announcement flyer is circulated amongst the tenants residing in the green office building, outlining the justifications behind our pursuit of sustainable action through promoting pro-environmental behavior. A QR-code is attached alongside the flyer, which directs users to another unique flyer tailored to contain a compilation of effective behavioral strategies. These strategies are constructed in accordance with the feedback gathered during the focus group recruitment phase. Figures 3 and 4 illustrate the flyers employed during the first two weeks of the nudging phase.

Figure 3: Announcement Flyer

Week No.	Timeline
1	**7th April – 14th April**
2	**14th April – 21st April**
3	**21st of April – 28th April**
4	**28th April – 5th May**
5	**5th May – 12th May**
6	**12th May – 19th May**

Table 6: 6-week nudging phase timeline

Week	Phase	Description
1	Pre-nudging phase and the start of the nudging phase	Tenant lighting and plug load electricity consumptions were monitored and recorded.
2		
3	Initiation of the nudging phase	Announcement & behavioral strategy flyers were distributed. Electricity performances amongst tenants were compared to week 1-2
4		
5	Nudging Phase and the start of the follow-up phase	Behavioral strategy flyers were distributed once again. Electricity performances amongst tenants were compared to week 3-4
6		

Table 7: 6-week nudging phase breakdown

Figure 4: Behavioral strategy flyer

Furthermore, at the end of the second week, monitored electricity data pertaining to both tenant lighting and plug loads was recorded and compared to the two-week data collected during the pre-treatment phase. The analysis serves as a preliminary point to illustrate the initial relative percentage of electricity savings achieved during the two weeks of the nudging phase. Subsequently, a second flyer was circulated amongst tenants, detailing the comparison of tenant performances and showcasing the progress made. Moreover, the behavioral strategy flyer was circulated as a reminder for tenants to continually adopt the energy-saving practices within the zero-carbon building.

As the six-week nudging phase period came to an end, the electricity data was monitored and recorded once again to serve as a comparative analysis of the previous two weeks. The analysis aims to elucidate the relative percentage savings of electricity from both tenant lighting and plug loads, respectively. Additionally, weather conditions corresponding to each day of the week during both the pre- and post-nudging phases were documented. The documentation serves as a focal point to emphasise sustainable action to be taken during cloudy days with less sunlight, as well as supporting the impact of structural and socio-psychological factors on tenant behavior.

5.2.1 Data Analysis

During the first two weeks of the 6-week nudging phase, the electricity consumption of both tenant lighting and plug loads, respectively, across all tenants was carefully monitored and recorded. After the distribution of both the announcement and behavioral strategy flyers in weeks 3 and 4, the electricity consumption of tenants was assessed. To measure the progress made based on the information interventions provided, equation 11 will be used to compare the energy consumptions between weeks 1-2 and weeks 3-4. This equation will enable a comparative analysis to be conducted to measure the percentage of electricity savings. Additionally, weather conditions corresponding to each of the days during the four weeks were recorded.

Equation 11 – percentage electricity savings in weeks 3-4

$$\%\boldsymbol{Electricity\ Savings} = \frac{[\sum \boldsymbol{tenant\ electricity\ in\ weeks\ 1-2}] - [\sum \boldsymbol{tenant\ electricity\ in\ weeks\ 3-4}]}{[\sum \boldsymbol{Sum\ of\ tenant\ electricity\ consumptions\ in\ weeks\ 3-4}]} * \mathbf{100}$$

Eq. 11

Moreover, prior to the commencement of week 5, the percentage electricity savings sourced from equation 9 were included with the attachment of the behavioral strategy flyer. Both the flyer, as well as the percentage energy savings, were circulated once again to the tenant representatives to serve as a reminder and as an additional nudge. By the end of week 6, electricity data collected during weeks 3-4 will be compared with week's 5-6 to calculate the percentage electricity savings using equation 12 Therefore, by assessing the energy consumption across the various weeks of the nudging phase, the influence of the information interventions, as well as the tenant's dedication to energy-saving practices can be assessed.

Equation 12 - percentage electricity savings in weeks 5-6

$$\%\textit{Electricity Savings} = \frac{[\sum \textit{tenant electricity in weeks } 3-4]-[\sum \textit{tenant electricity in weeks } 5-6]}{\sum \textit{tenant electricity consumptions in weeks } 3-4} * 100$$

Eq. 12

5.3 Follow-up Phase

The follow-up phase essentially involves a final meeting with the tenants who have participated in the focus group recruitment phase. The meeting functions as a dynamic platform to assimilate constructive feedback on the potency of the flyers and the behavioral strategies used in promoting sustainable action within the zero-carbon building. Additionally, the follow-up phase enables key drivers of behavioral change to be identified, thereby providing insights and recommendations for future actions, particularly during periods of less sunlight, for instance, the seasons of fall and winter.

During the follow-up meeting, tenants are invited to discuss their experiences and provide feedback on the efficacy of the interventions carried out during the nudging phase. Their observations and perspectives on the impact of the information interventions are influential in evaluating the relative success of our efforts to promote pro-environmental behavior. By assessing the tenant’s experiences, presumptive suggestions can be deduced for future actions, refining our approach towards optimizing energy-saving behaviors in the building. Additionally, to illustrate the progress achieved, tenant lighting and plug load electricity data over the final two weeks of the nudging phase was also showcased as performance comparisons amongst the tenants through percentage savings in consumption.

6. Results and Discussions

6.1 Tenant Lighting and Plug loads.

This section aims at delving deeper into question 1, as well as its subsequent questions pertaining to the utilization of marginal and average emissions for estimating CO_2 intensities in sustainable buildings. The inclusion of emission factors is of utmost importance as they serve as a fundamental component in the measurement of the environmental impacts associated with energy usage in buildings. There exist two primary approaches employed in the estimation of emissions contributions: average emission factors and marginal emission factors. The practical demonstration of emission contributions from tenants on an annual, seasonal, and individual level was presented in *section 6.1* of the results. The sections were dissected to illustrate the emissions resulting from tenants' usage, utilizing both marginal emission factors and average emission factors.

In order to investigate the first research question, the study utilized a carbon footprint methodology to examine the energy consumption patterns within the zero-carbon building. The comparative analysis presented in *section 6.1.1* examines the emissions from tenant lighting and plug load, utilizing both marginal and average emission factors, on an annual basis. In *section 6.1.2,* an examination is conducted on the seasonal fluctuation of emissions on a yearly basis. The emissions data provided by TAF's report lacks average seasonal emission factors for comparison with marginal seasonal emission factors. Therefore, the published results solely demonstrate the annual fluctuations in emissions by season, using marginal emissions. The rationale behind employing this approach is rooted in the need for accurate representation. Assigning marginal emission components to average data would not adequately showcase the accuracy of carbon intensity estimation.

Section 6.1.3 delves into the examination of tenant performances in relation to energy fluctuations over time, focusing on the justification for utilizing marginal emissions as a reliable measure. This section specifically explores the impact of tenant lighting and plug load emissions on a seasonal and hourly basis. This will facilitate our comprehension of the tenant's consumption patterns across different seasons. Furthermore, this section also offers clarification regarding how fluctuations in carbon emissions on an hourly and seasonal basis can serve as immediate indicators of environmental impact.

6.1.1 Annual Tenant Lighting and Plug Load Emissions.

Figure 5 showcases the annual total of tenant lighting emissions by hour for the years 2019, 2020, and 2022. The horizontal axis represents the hour of the day, while the vertical axis corresponds to the calculated electricity emissions using equation 2. The utilization of MEFs obtained in table 3 enables the conversion of the annual hourly electricity data recorded into marginal emissions.

The emission distribution illustrated in the graph demonstrates a pattern of emissions increasing at the start of the day, approaching a peak at around noon. For the year 2019, the peak emissions were recorded at 750 $kgCO_2e$, followed by 542 $kgCO_2e$ in 2022, and finally 400 $kgCO_2e$ in 2020. Additionally, the marginal emissions remain steady throughout the day, and eventually decrease as the day ends. Therefore, the year 2019 produced the highest marginal emissions, followed by 2022, and 2020.

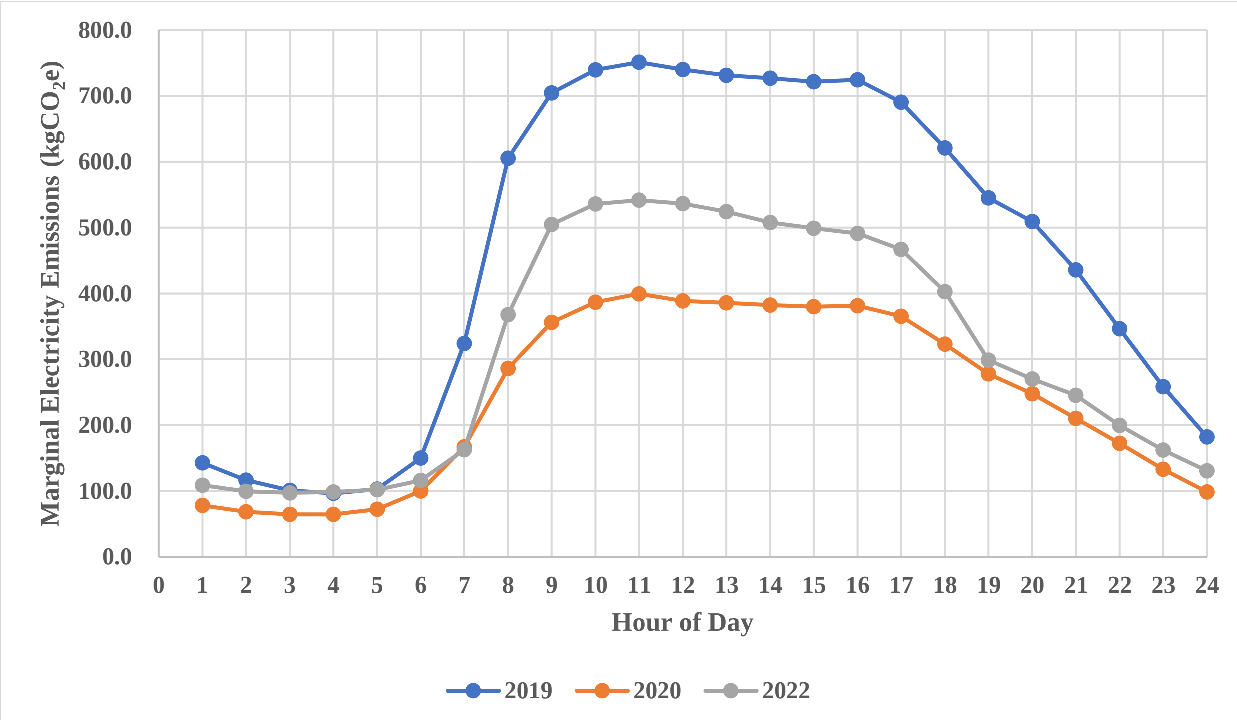


Figure 5: Total hourly tenant lighting marginal emissions, 2019, 2020, 2022

Moreover, figure 6 showcases the hourly aggregate electricity emissions derived from plug loads used by tenants, spanning the years 2019, 2020 and 2022. In order to measure the number of emissions produced by electricity, we utilized equation 2, which incorporates the use of MEFs provided in table 3. The x-axis of the graph shows the hours of the day, while the y-axis corresponds to the calculated marginal emissions of plug load electricity. According to figure 7, it becomes apparent that the utilization of electricity for tenant plug loads exhibits a noticeable pattern over the course of the day. The data indicates a consistent increase in electricity usage during the early hours of the day, followed by a relatively steady emission pattern throughout the remainder of the day. As the day progresses, there is a gradual decrease in the emission of electricity.

The analysis also considers the distinction of comparing emissions from tenant plug loads with emissions from tenant lighting. In terms of emissions, it is observed that the year 2019 exhibited the largest emissions for both tenant plug loads and lighting. Subsequently, the year 2022 emerged as the second-highest contributor, while the year 2020 ranked third in both categories. Nevertheless, it is imperative to acknowledge that the emission production linked to plug load consumption exhibits a considerably higher magnitude, approximately twice as much as that of lighting usage. In the year 2019, the emissions resulting from tenant plug load activities reached their highest level, amounting to 1.44 TCO_2e. Concurrently, the emissions attributed to lighting were measured at 0.750 TCO_2e.

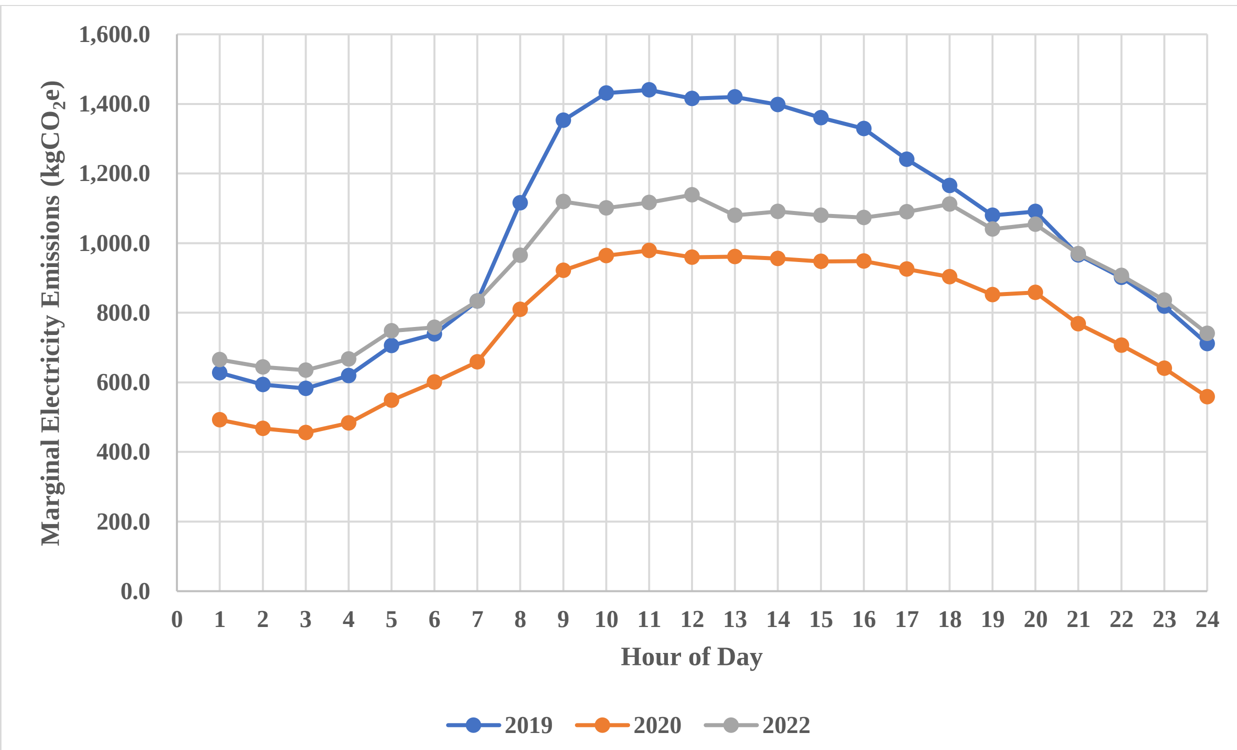


Figure 6: Total of tenant plug loads marginal emissions from the year 2019-2022

Moreover, figure 7 provided below depicts the cumulative yearly average emissions of tenant lighting, calculated using equation 6 to convert electricity data into average emissions by employing the AEFs provided in table 4. The graph illustrates a comparable emission distribution pattern to the preceding graph, wherein emissions exhibit an initial increase at the onset of the day and subsequently decline gradually as the day unfolds. The graph illustrates a gradual rise and fall in emissions rather than a consistent distribution of emissions during peak hours. Furthermore, when analyzing the electricity data used for converting emissions, it is observed that the average emissions yield lower estimations of emissions compared to the marginal emissions.

For the year 2019, the mean emissions from tenant lighting reached a maximum of 262 $kgCO_2e$. This was followed by a value of 145 $kgCO_2e$ in 2022 and a further decrease to 120 $kgCO_2e$ in 2020. The aforementioned values demonstrate a reduced level of emissions in contrast to the marginal emissions documented in the previous figure. However, it is noteworthy that both graphs prominently depict the year 2019 as exhibiting the most substantial emission output, subsequently followed by the years 2022 and 2020.

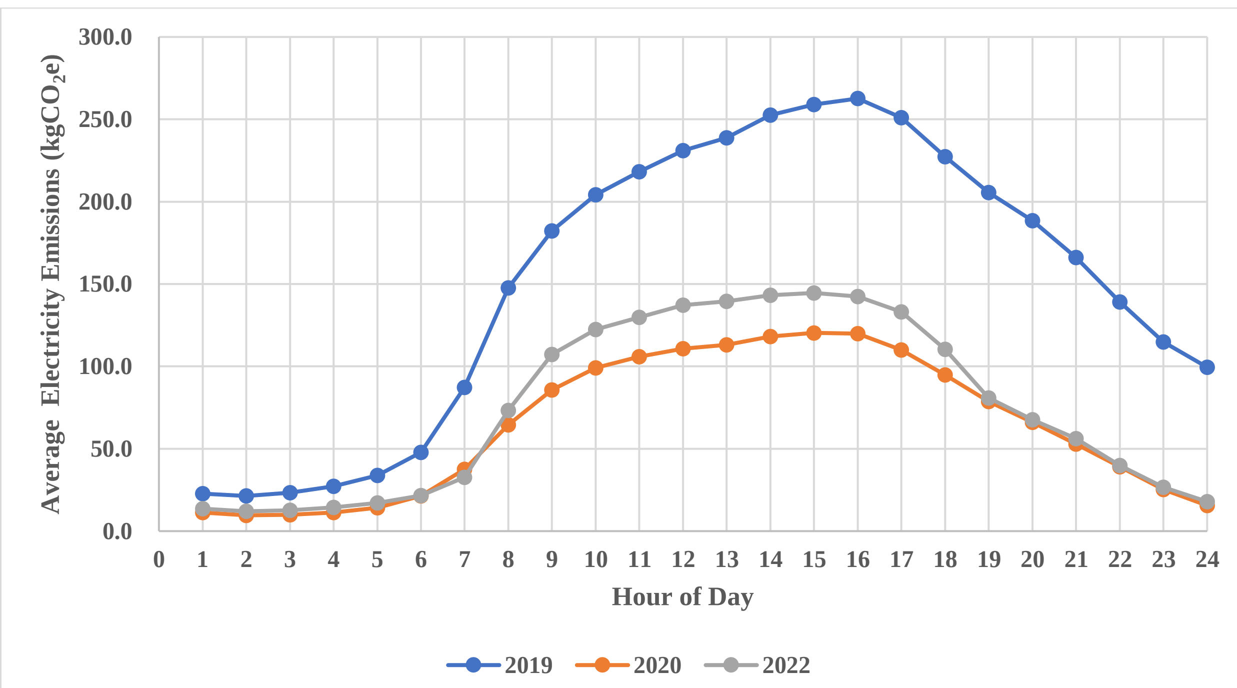


Figure 7: Total tenant lighting average emissions recorded each year from 2019-2022

Figure 8 below portrays the cumulative yearly average emissions of tenant plug loads, calculated using equation 6 to convert electricity data into average emissions by employing AEFs.

The graph illustrates a comparable emission distribution pattern to the preceding graph, wherein emissions exhibit an initial increase at the onset of the day and subsequently decline gradually as the day unfolds. The graph illustrates a gradual rise and fall in emissions rather than a consistent distribution of emissions during peak hours. Furthermore, when analyzing the electricity data used for converting emissions, it is observed that the average emissions yield lower estimations of emissions compared to the marginal emissions.

For the year 2019, the mean emissions from tenant lighting reached a maximum of 413 kgCO_2e. This was followed by a value of 313 kgCO_2e in 2022, and a further decrease to 297 kgCO_2e in 2020. The aforementioned values demonstrate a reduced level of emissions in contrast to the marginal emissions documented in the previous figure.

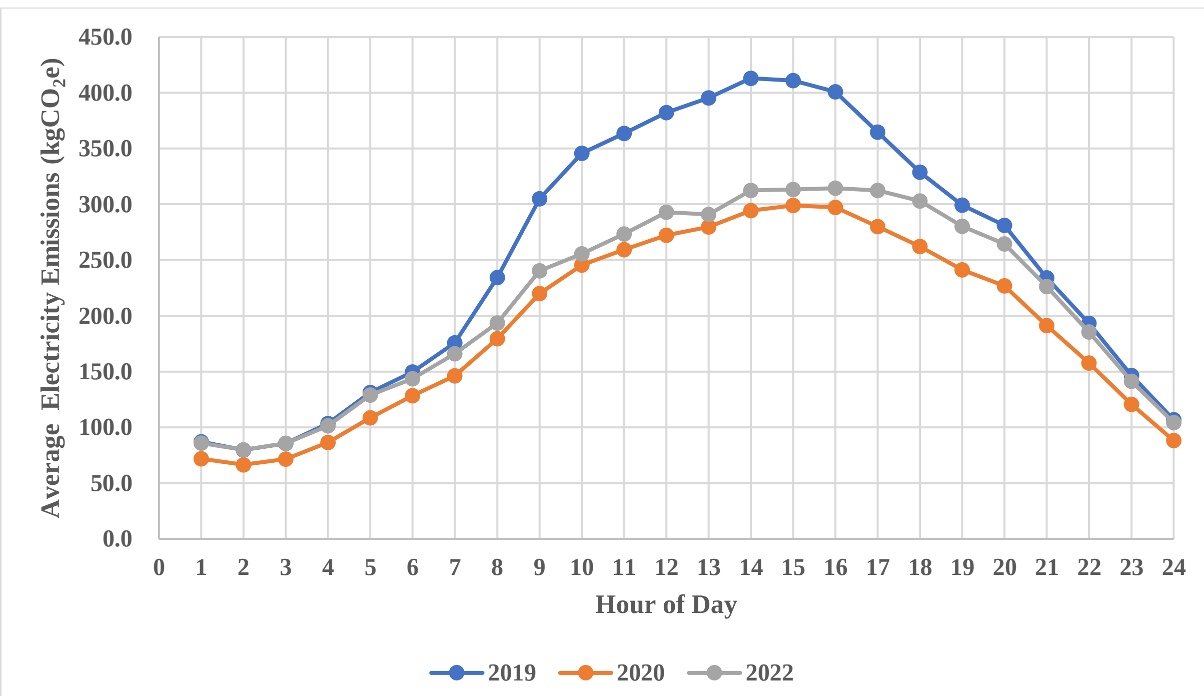


Figure 8: Total tenant plug load average emissions recorded each year from 2019-2022

To substantiate the findings in regard to the greater contributions of plug load emissions in comparison to lighting, the study conducted by Chang and Trappey (2016) can be cited. This study examined the energy consumption of plug loads in commercial buildings. The researchers determined that plug loads constituted a substantial factor in both electricity usage and the release of carbon emissions. The findings of our study align with previous research, indicating that prioritizing energy-efficient practices and devices is needed to mitigating emissions from tenant plug loads.

Furthermore, the results presented in this section sought to ascertain the carbon intensities more accurately by examining MEFs, in contrast to AEFs. Findings collectively demonstrate that there is a variation in which average emissions consistently exhibit lower values compared to marginal emissions. This discovery suggests that the utilization of MEFs presents a more realistic methodology for assessing carbon intensities, as AEFs have a tendency to underestimate the genuine influence of energy consumption on carbon emissions.

To substantiate the inclusion of MEFs in carbon intensity assessments, a recent investigation by Seckinger and Radgen (2021) examined the efficacy of employing MEFs for the purpose of evaluating and mitigating greenhouse gas emissions in sustainable construction. In addition, the study explored the applicability of MEFs in other domains, including smart grid systems and electric vehicle utilization. The utilization of real-time marginal emission factors enables a more dynamic and accurate assessment of strategies aimed at reducing emissions. This approach accounts for the specific time period and the corresponding marginal electricity sources (Mayes & Sanders, 2022). This approach acknowledges that low AEFs at a specific time and location do not necessarily indicate low emissions from marginal sources of electricity during that same period. Consequently, relying solely on AEFs can lead to misleading results.

Additionally, a study conducted by Gilbraith and Powers (2013) found that the utilization of AEFs for assessing the overall reduction in emissions resulting from an intervention, as opposed to using traditional MEFs, may potentially yield misleading outcomes. The case study conducted in the New York City region demonstrates that a substantial proportion of the electricity demand is met by employing efficient natural gas. It is important to emphasize that the emissions mitigated through the utilization of natural gas plants hold greater significance within the framework of the AEFs in comparison to the emissions averted by petroleum plants. However, if the petroleum plant were to function as a marginal plant, it would bear the responsibility of decreasing its electricity generation. Consequently, this intervention would lead to a reduction in emissions from the plant. Hence, MEFs address this issue by specifically considering the carbon emissions resulting from generators operating at partial loads. The assessment of greenhouse gas emissions arising from the utilization of tenant lighting and plug load in a green office building can be enhanced in terms of precision and accuracy through the application of MEFs.

In the context of this research, it is important to comprehend the two fundamental variables of our quantitative analysis: electricity consumption and marginal emission factors (MEF). The aforementioned parameters are of utmost importance in comprehending the complex interplay between energy use and carbon emissions within the scope of our investigation. The research study is centered around the examination of electricity consumption. It embodies the observable acts and behaviours exhibited by the tenants occupying the building. Through the analysis of electricity usage data, valuable insights can be obtained regarding the manner in which tenants engage with energy resources. This factor, which serves as a direct indicator of energy usage, holds immense importance. This method of measurement enables the quantification of the tenants' energy consumption patterns and their tangible influence on carbon emissions.

In contrast, MEFs, which quantify the carbon intensity associated with energy generation, serve as the contextual framework for our investigation. The bridge serves as a crucial link between the consumption of power and its corresponding environmental impacts. MEFs present an analysis of the environmental impacts linked to various methods of energy production. The comprehension of MEF enables us to evaluate not only the quantity of power being utilized but also the carbon emissions produced as a result of that utilization, leaving the two components contingent upon their synergistic relationship. The utilization of electricity provides valuable insights into the behavior of tenants, while the concept of MEF introduces a dimension of environmental consequences. Collectively, these factors allow for the examination of the causal connection between the behaviors of tenants and carbon emissions.

In our research study, we aim to investigate the correlation of three key variables: MEF values, marginal emissions, and electrical consumption. These parameters play a central role in comprehending the intricacies of carbon emissions within the scope of our study. Understanding the complexities of energy use patterns and their direct influence on carbon emissions within our net-zero building relies on these elements. In order to elucidate the importance of these variables, we refer to Figures 9–11, which present linear regression plots illustrating the relationship between marginal emissions of plug load consumption and MEF values over the time period spanning from 2019 to 2022, using data collected on an hourly basis. The coefficient of determination (R^2) values associated with these graphs are 0.620 in 2019, 0.780 in 2020, and 0.827 in 2022. The R^2 values indicate the degree of correlation between marginal emissions and MEF values.

Furthermore, during the period of 2019 and 2020, a moderate correlation was observed, as indicated by the R^2 values. This observation suggests the existence of a discernible, but not strong, correlation between the two variables. Nevertheless, it is important to acknowledge that in 2022, the R^2 value demonstrates an increase above the threshold of 0.8 to 0.827, indicating a stronger correlation. Additionally, the R^2 values reported in this study indicate a positive relationship between marginal emissions and MEF values. The variability in marginal emissions has a direct influence on the values of MEF, highlighting the dynamic nature of their correlation.

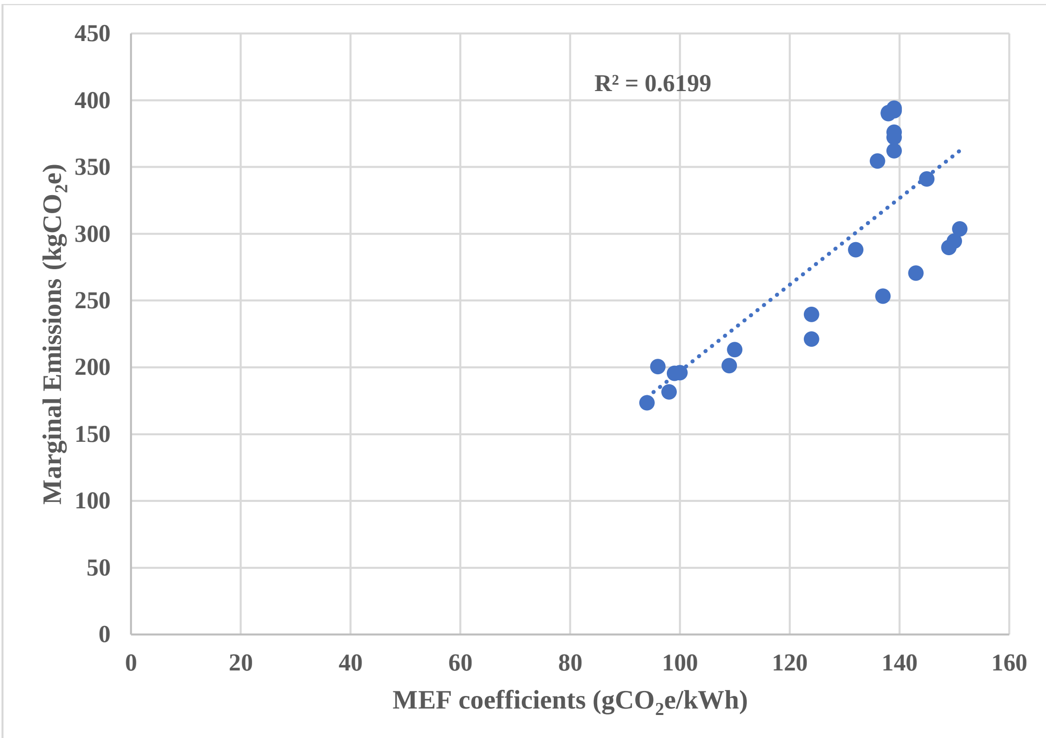


Figure 9: Linear regression model between hourly marginal emissions of plug loads and MEF coefficients in 2019

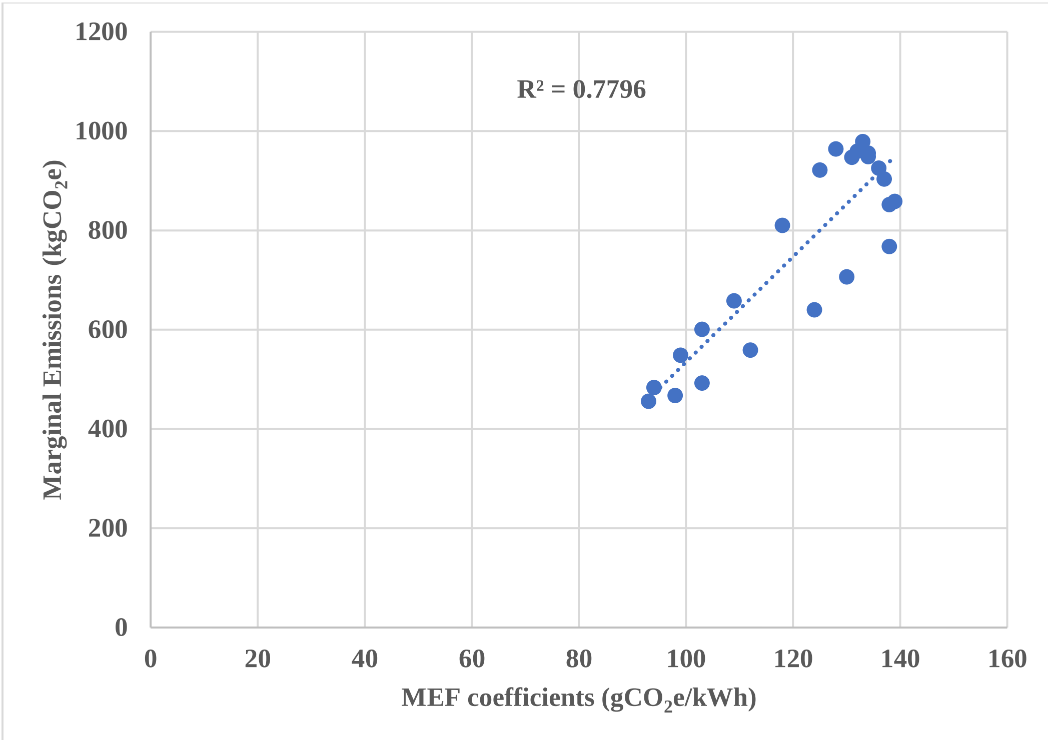


Figure 10: Linear regression model between hourly marginal emissions of plug loads and MEF coefficients in 2020

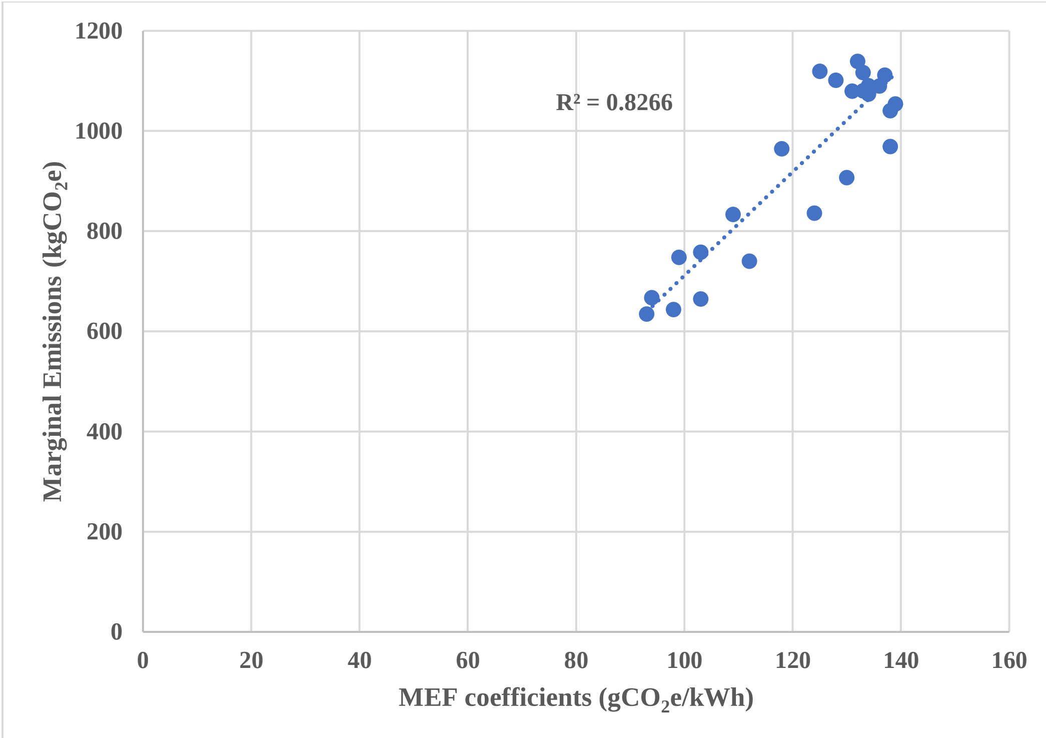


Figure 11: linear regression model between hourly marginal emissions of plug loads and MEF coefficients in 2022

Furthermore, Figures 12–14 present linear regression models that visually represent the relationship between energy consumption and the corresponding marginal emissions of plug loads for the years 2019, 2020, and 2022. In the year 2019, an R^2 value of 0.892 was observed. The obtained R^2 value indicates a strong and positive association between electricity use and marginal emissions. Likewise, in the year 2020, the R^2 value exhibited a positive correlation, albeit with a slightly diminished value of 0.761. In the year 2022, an R^2 value of 0.710 was observed, indicating a reasonable correlation between the aforementioned parameters. Therefore, the persistent pattern of positive associations underscores the importance of simultaneously monitoring electrical usage and marginal emissions. The level of marginal emissions is directly and measurably affected by fluctuations in electricity usage.

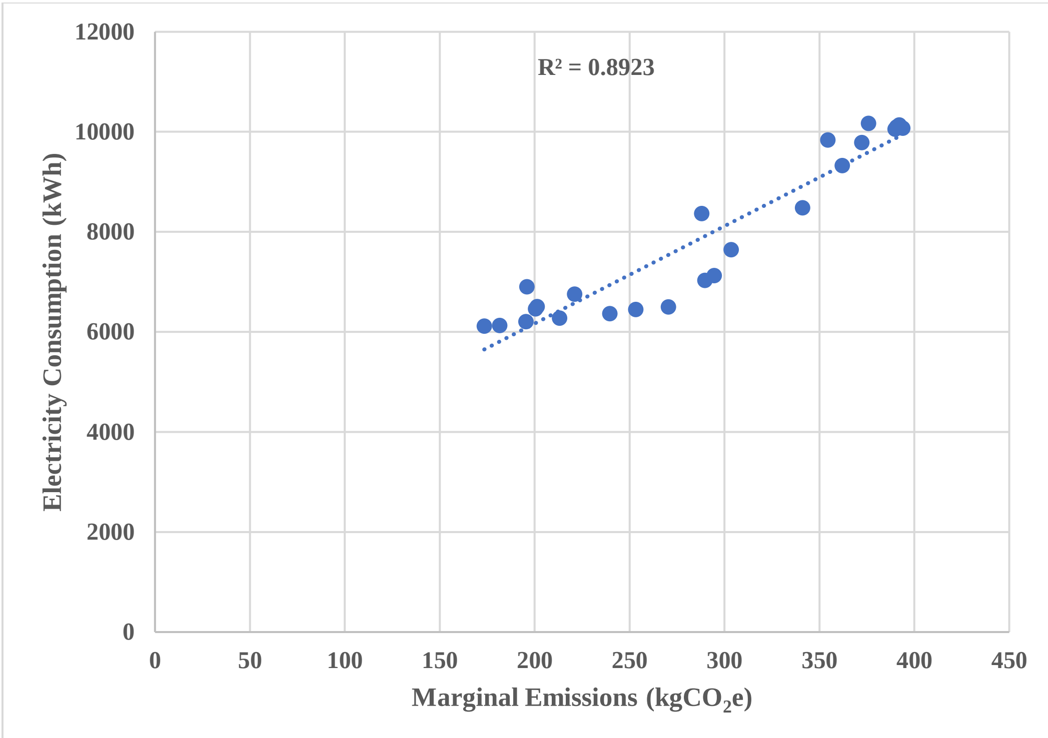


Figure 12: Linear regression model between hourly marginal emissions of plug loads and electricity consumption in 2019

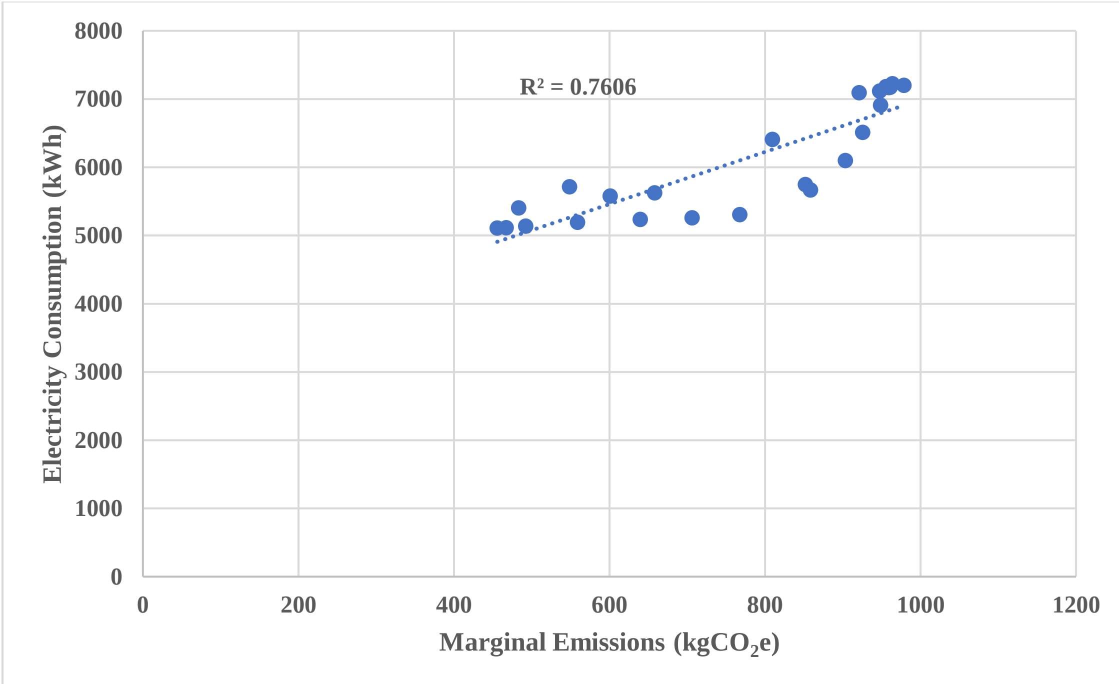


Figure 13: linear regression model between hourly marginal emissions of plug loads and electricity consumption in 2020

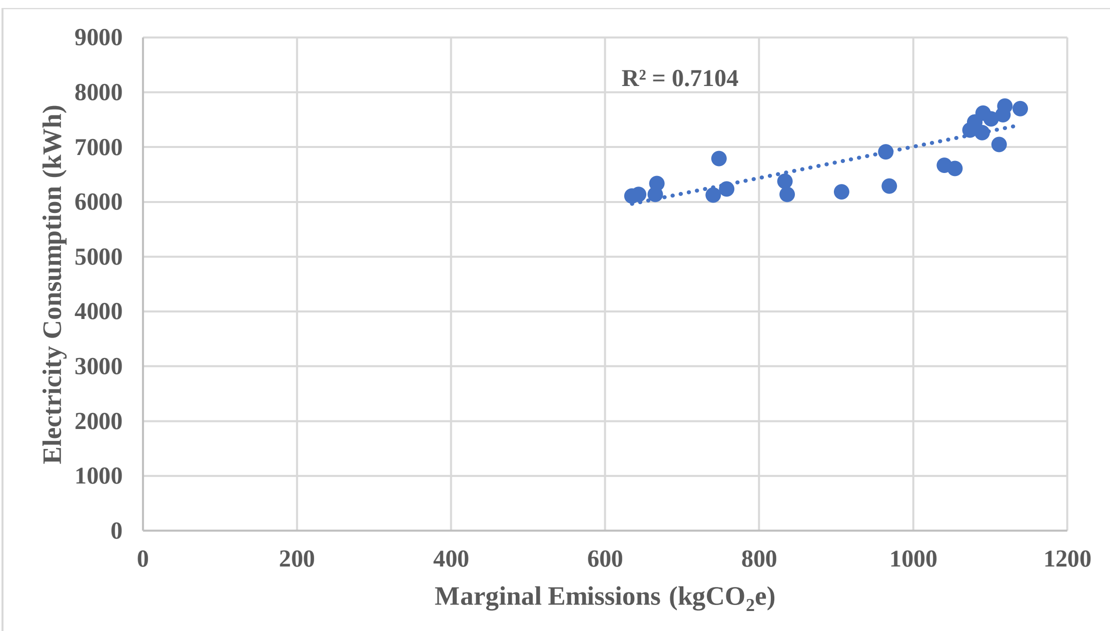


Figure 14: linear regression model between hourly marginal emissions of plug loads and electricity consumption in 2022

Moreover, when analyzing figures 9–14, the linear graphs together demonstrate a noticeable rise in energy consumption during regular working hours. This discovery highlights a distinct possibility for intervention. The data implies that there is potential for effective emission reduction measures to be implemented during office hours, when power usage is elevated. It is important to acknowledge that tenants have a restricted level of influence over variables such as MEF coefficients, which are established by entities such as IESO and TAF. However, tenants do retain the ability to exert agency in shaping their energy consumption patterns. The aforementioned observation highlights the importance of the behavioral approach outlined in our research investigation. Tenants can make an active contribution to reducing the environmental impact of their energy use by promoting sustainable behaviors during periods when emission reductions are recommended.

6.1.2 Annual Seasonal Tenant Lighting and Plug load Emissions.

The bar graph in figure 15 below represents the annual total of tenant lighting marginal emissions, categorized by season, spanning the period from 2019 to 2022. The conversion of cumulative tenant electricity consumptions into marginal carbon emissions was achieved by applying equation 4 and utilizing the MEFs provided in table 5.

The horizontal axis of the graph depicts the four distinct seasons: winter, spring, summer, and fall, whereas the vertical axis represents the quantity of marginal electricity emissions measured in kilograms of carbon dioxide equivalent (kgCO_2e). In 2019, the year displayed the highest emissions during the fall and winter seasons, across all four seasons. In a comparable vein, the summer season of 2019 exhibited the most substantial emissions, with subsequent years of 2022 and 2020 following suit, with exceptions to the fall and winter seasons through which the year 2020 recorded higher emissions than 2022. The summer season of 2019 exhibited the highest marginal emissions among the four seasons, totaling 4.3 TCO_2e. Similarly, the year 2022 also demonstrated high emissions, reaching 3.4 TCO_2e.

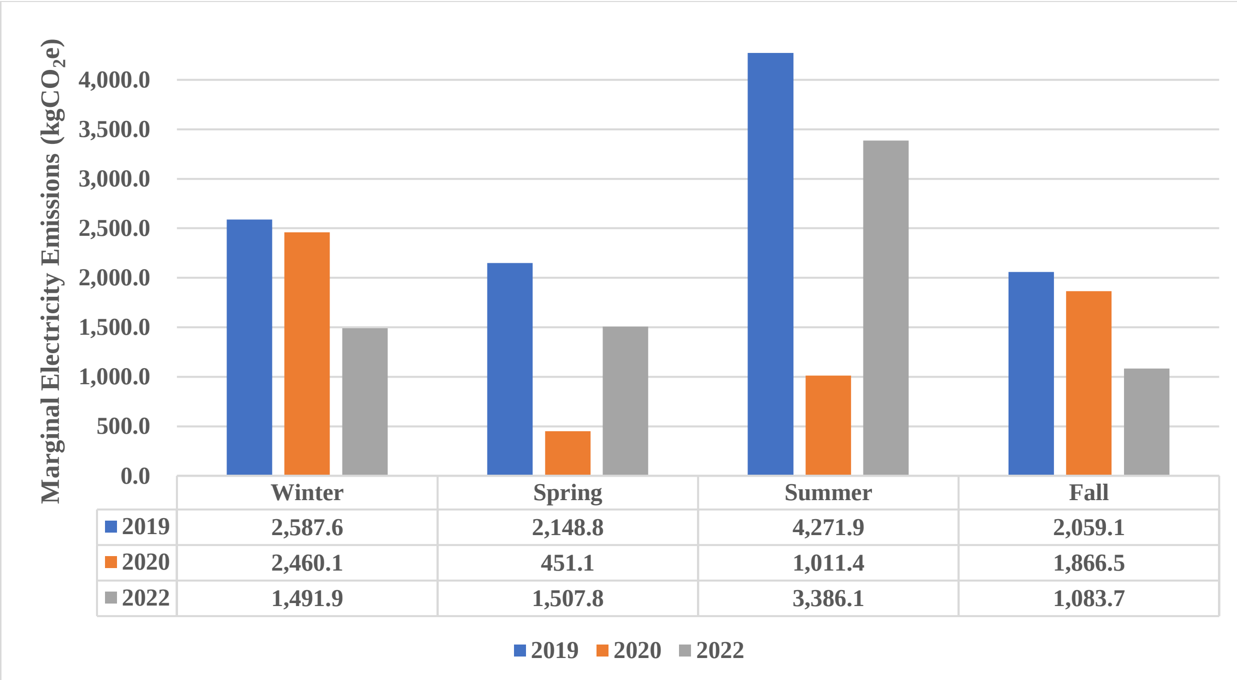
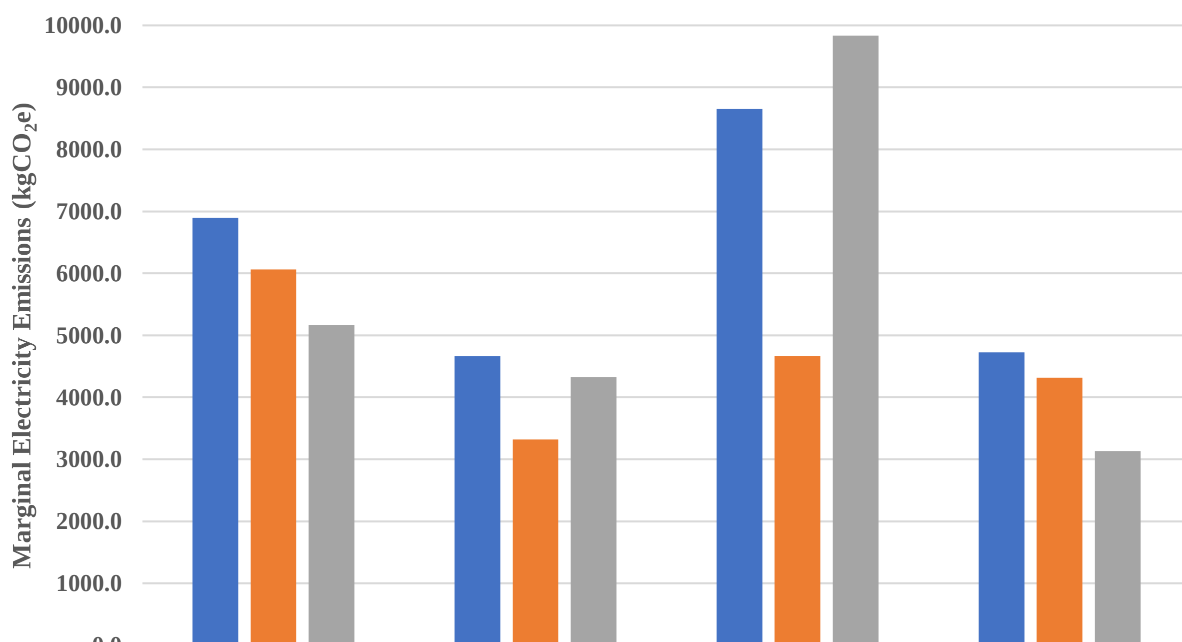


Figure 15: Total tenant lighting marginal emissions recorded each season and year from 2019-2022

Figure 16 demonstrates the yearly aggregate emissions resulting from the utilization of tenant plug loads in the zero-carbon building. These emissions are categorized by season and year ranging from 2019 to 2022. The outcomes of our analysis are depicted in figure 16, with the horizontal axis representing the four seasons throughout the year and the vertical axis representing the marginal emissions of plug loads. The emissions were acquired by employing equation 4 in combination with the MEFs provided in table 5.

As illustrated in Figure 16, the seasonal distribution of emissions demonstrates a consistent pattern, wherein emissions are organized in a descending sequence from 2019 to 2022 for both the winter and fall seasons. Nevertheless, it is notable to acknowledge a notable divergence in the context of the summer season in the year 2022, wherein the levels of emissions exceeded those documented in the year 2019.

An analysis was undertaken to compare the marginal emissions arising from the utilization of lighting by tenants and the usage of plug loads. Considerably, our research findings demonstrate that the emissions originating from plug loads exceeded those emitted by tenant lighting. In the summer of 2022, there was a notable increase in plug load emissions, reaching a maximum of 9.80 TCO_2e. Conversely, the summer of 2019 witnessed the highest emissions from tenant lighting, peaking at 4.20 TCO_2e. The findings underscore the influence of plug load utilization on overall emissions within the zero-carbon structure, particularly during specific periods of the year.



	Winter	Spring	Summer	Fall
2019	6893.3	4665.9	8650.8	4726.6
2020	6061.1	3319.5	4667.6	4317.2
2022	5167.0	4327.4	9835.2	3133.8

2019 2020 2022

Figure 16: Total tenant plug loads marginal emissions recorded each season and year from 2019-2022

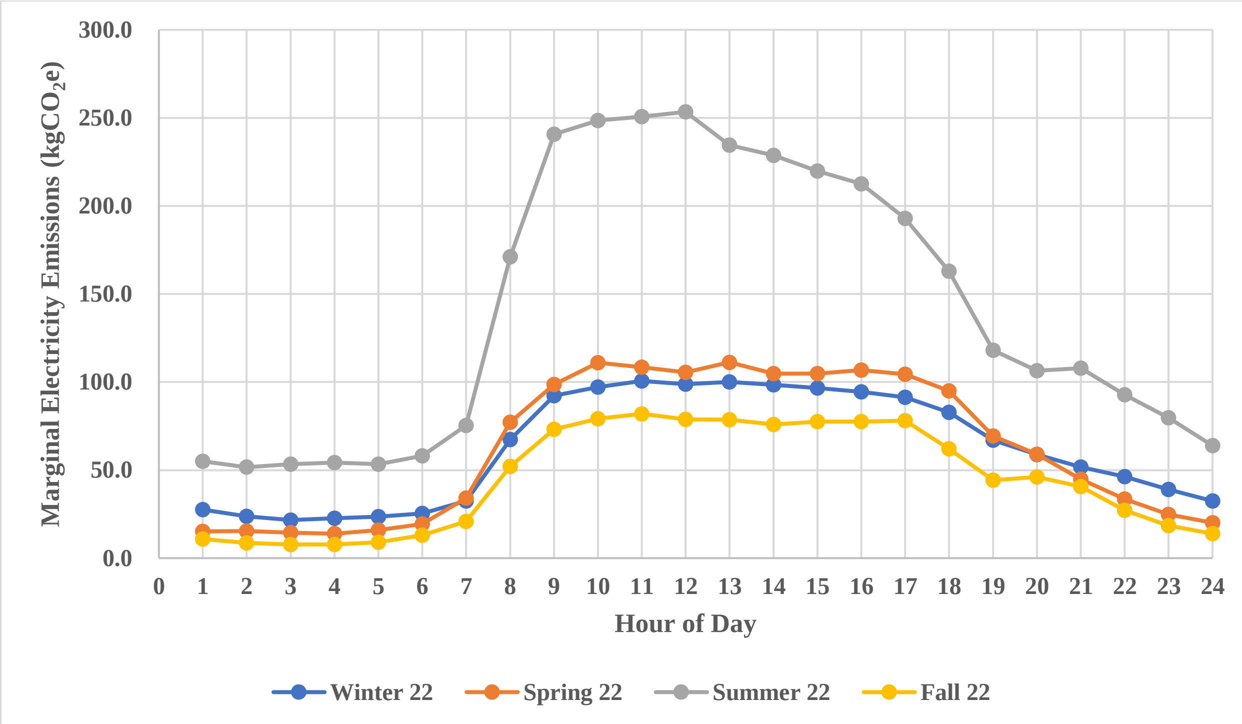


Figure 17: Seasonal marginal emissions of tenant lighting consumption for the year 2022

The line graph presented in figure 17 depicts the cumulative carbon emissions resulting from tenant lighting. It specifically highlights the hourly marginal emissions for each season throughout the year 2022. The horizontal axis of the graph represents the hours of the day, while the vertical axis displays the marginal electricity emissions expressed in kilograms of carbon dioxide equivalent (kgCO_2e).

The graph presents an in-depth overview of the aggregate emissions produced by the tenants included in the building case study. Throughout the course of the day, the emission levels exhibit an upward trajectory starting at 6 a.m. and leading up to 12 p.m. followed by a subsequent gradual descent until the end of the day.

The summer of 2022 exhibited the greatest contribution to emissions amongst the four seasons, followed by the winter season. The levels of emissions observed during the spring and fall seasons demonstrate a notable similarity, suggesting that tenants exhibit identical patterns of energy consumption during these periods.

In addition, to further substantiate the results observed in this section, the TAF (2021) report presents findings on the seasonal distribution of marginal emissions. The report highlights that the MEFs for each season provide a quantitative measure for assessing the carbon emissions resulting from fluctuations in energy use throughout the year. The MEF values are utilized as a tool for quantifying carbon emissions in situations where targeted interventions influence power consumption during particular times of the year. For example, a winter MEF may be utilized for interventions pertaining to heating, while a summer MEF can be employed for interventions linked to cooling. Additionally, the report provides more details regarding the distribution of emissions throughout different seasons, confirming that the highest emissions occur during the summer season. This can be attributed to increased cooling demands resulting from higher daytime temperatures. The aforementioned pattern is also observed during the winter season, when high MEF values can be linked to increased electricity usage stemming from the operation of heating systems. This highlights the impact of temperature on these measurements. Additionally, the fall and spring seasons demonstrate reduced MEF values. The decrease in demand can be attributed to the decreased need caused by moderate temperatures, which in turn has led to an increase in the availability of hydroelectric power.

Moreover, a study conducted by Bae et al. (2016) centered on the deployment of real-time feedback systems within buildings with the aim of encouraging energy conservation and fostering pro-environmental behavior. The results of their study demonstrated that the provision of real-time feedback was successful in reducing energy consumption and mitigating carbon emissions. The findings of our study are consistent with prior research, indicating that the integration of real-time feedback, which is contingent upon hourly and seasonal emissions, has the potential to empower occupants in the zero-carbon building. This empowerment enables them to make well-informed decisions and modify their energy consumption patterns, ultimately leading to a reduction in carbon emissions. This data possesses a meaningful value in comprehending the timing of carbon emissions reaching their highest point and determining the periods that are most vital for implementing interventions aimed at fostering pro-environmental conduct.

Nonetheless, considering the focus of the research study on nudging initiatives in the spring season of 2023 and recognizing the more accurate representation of MEFs compared to AEFs, the forthcoming sections of this analysis will offer a thorough assessment of tenant performances pertaining to lighting and plug loads, with a specific focus on the spring season spanning of 2022. This examination serves as an initial investigation.

6.1.3 Individual Tenant Lighting and Plug Load Emissions.

Regarding the performance of individual tenants, Figure 18 presents the hourly marginal emissions linked to the lighting consumption of each tenant throughout the spring season of 2022, considering the spatial dimensions of their respective areas. The x-axis of the graph shows the hour of the day, while the y-axis represents the marginal emissions of energy utilized for lighting. The application of Equation 5 is initially employed to convert the lighting data into its marginal emissions, utilizing the MEF values obtained from table 5. Equation 6 is subsequently employed to demonstrate the emissions in relation to the spatial area of each tenant, as presented in table 2. The graph depicts a notable increase in emissions during the early morning hours, followed by a period of rather stable emission levels throughout the peak hours of the day. At the end of the day, there is a notable reduction in emissions.

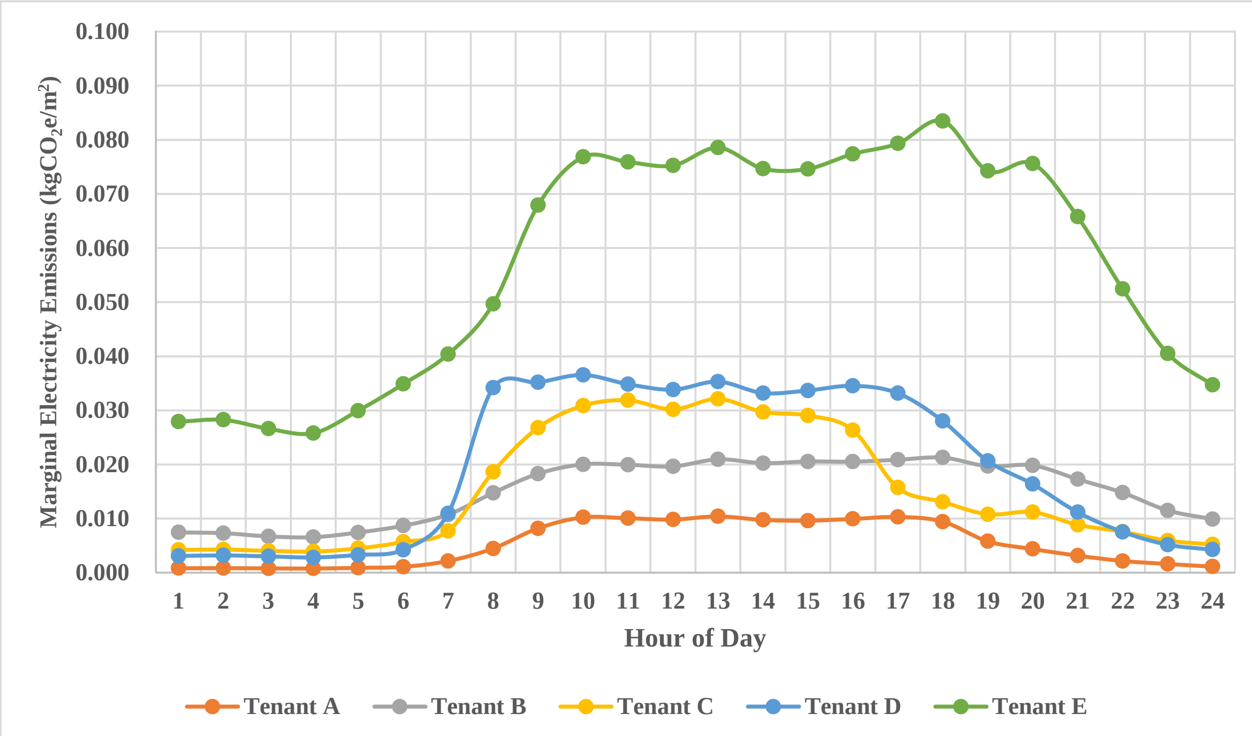


Figure 18: Individual tenant lighting marginal emissions/m^2 for the season of spring 2022

The tenant light meters that have been documented indicate that Tenant E and Tenant D demonstrate the highest emissions, with Tenant B, Tenant C, and Tenant A following in descending order. This information provides useful insights into the emissions behavior that particular tenants displayed during the spring season. When considering the area as an additional variable in conjunction with marginal emissions, the available data does not clearly indicate a direct relationship between the assigned space dimensions and the emissions attributed to individual tenants. In a rather unexpected manner, Tenant E, who occupies the lowest spatial area of 100 m^2, exhibited the greatest emissions with an average of 0.0571 kgCO_2e/m^2. In contrast, Tenant D, occupying the second greatest area of 1220 m^2, similarly exhibited the second highest level of emissions with an average of 0.0195 kgCO_2e/m^2. A similar pattern can be observed in the case of Tenant C, which has a surface area of 230 m^2, the second smallest among the tenants. Despite its relatively small size, Tenant C had the third greatest emissions contribution, with an average of 0.0154 kgCO_2e/m^2.

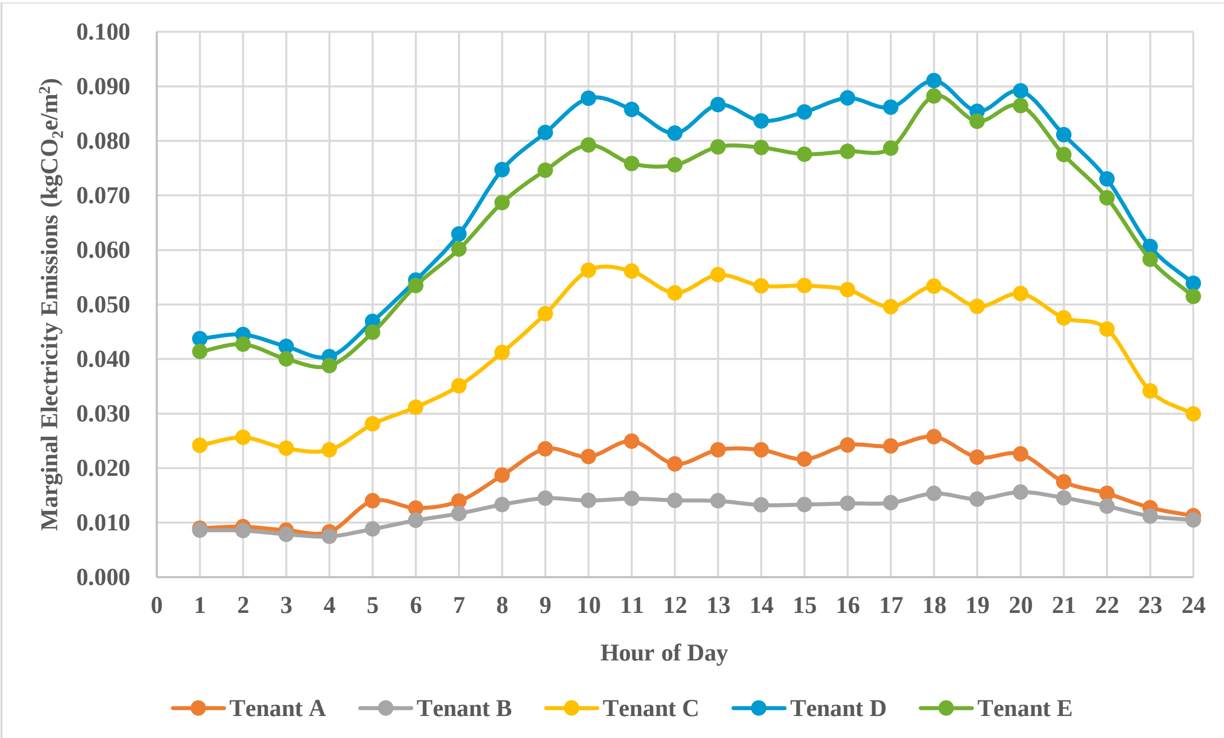


Figure 19: Individual tenant plug loads marginal emissions/m^2 for the season of spring 2022

The line graph represented by figure 19 above exhibits hourly marginal emissions/m^2 resulting from plug load usage in the zero-carbon building during the spring of 2022. The graph employs the horizontal axis to show the hours of the day, while the vertical axis corresponds to the marginal emissions/m^2 derived from plug load usage. Similar to the calculation of lighting emissions, equation 5 is employed to convert the plug load data into its marginal emissions using MEF values from table 5. Equation 6 is then used to demonstrate the emissions with respect to the dimensional spaces of each tenant provided in table 2.

The graph illustrates a noticeable trend in emissions over the course of the day. Beginning with a rise in emissions, the day has a brief period of relative stability. Following this, the emissions undergo a gradual decrease as the day draws to a close.

When examining the impact of individual tenants on plug load usage emissions, Tenants D and E were the largest contributors, with an average of 0.0713 and 0.0688 $kgCO_2e/m^2$ respectively. Next in line is Tenant C, with an average of 0.0426 $kgCO_2e/m^2$. Similar to the previous analysis conducted on tenant lighting, when the physical dimensions are incorporated as an additional variable alongside marginal emissions, the data does not clearly demonstrate a direct correlation between the assigned space dimensions and the emissions associated with each tenant. It is worth mentioning that the utilization of plug loads results in a considerably greater consumption of electricity in comparison to the usage of tenant lighting. As an illustration, Tenant E exhibited a peak of 0.0571 $kgCO_2e$/m2 in terms of lighting emissions, while plug load usage reached 43% higher, with Tenant E reaching a maximum of 0.0883 $kgCO_2e$.

Furthermore, figures 20 and 21 depict the seasonal average of lighting and plug load emissions, respectively. The emissions were calculated by converting the data on lighting and plug load into their marginal emissions with respect to each season, using equation 4, and referencing the seasonal average MEF values provided in table 5. Following this, the emissions were converted into a measurement per square meter of the tenant spaces using equation 7. These figures also include an additional indicator, namely emissions per square meter. The findings demonstrate that although tenant D and tenant A are the primary contributors to emissions, when accounting for emissions per square meter, tenant D and tenant E also rank among the highest. The recorded lighting peak emissions for tenants D and E were 0.0195 $kgCO_2e$ $/m^2$ and 0.0571 $kgCO_2e$ $/m^2$, respectively. The emissions from plug loads for tenant D and tenant E were measured to be 0.0713 $kgCO_2e/m^2$ and 0.0668 $kgCO_2e$ $/m^2$, respectively. Both scenarios, in which tenant C and E have relatively small dimensional spaces, also exhibit high emissions output per square meter.

The results obtained from the case study indicate that while tenant D and tenant A were identified as the primary contributors to carbon emissions in the zero-carbon building, it is important to note that tenants C and E also make substantial contributions when accounting for emissions per square meter. The two graphs present common observations that indicate the lack of a direct association between spatial dimensions and emissions from individual tenants. It is worth noting that there are notable differences in both the ordering and distribution of lighting emissions when comparing the same graph to that of plug loads. Tenant E, which occupies the smallest office area, exhibited an unexpected trend of having the highest emissions, while emissions from the remaining tenants were more evenly distributed. In contrast, Tenant D, which occupies the second-biggest area, and Tenant E exhibited the highest levels of emissions. This necessitates a demand for additional research into the intricate relationship between tenant spaces and their corresponding emission levels.

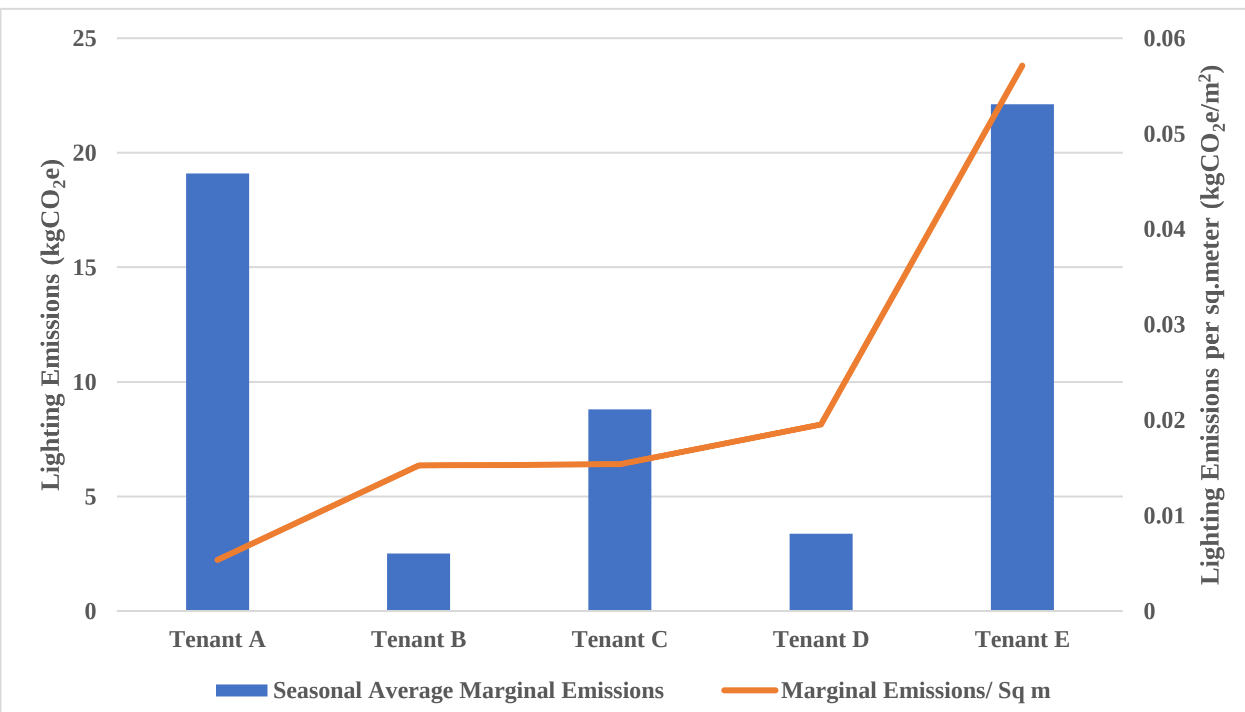


Figure 20: Tenant lighting emissions and square meter emissions for the 2022 spring season

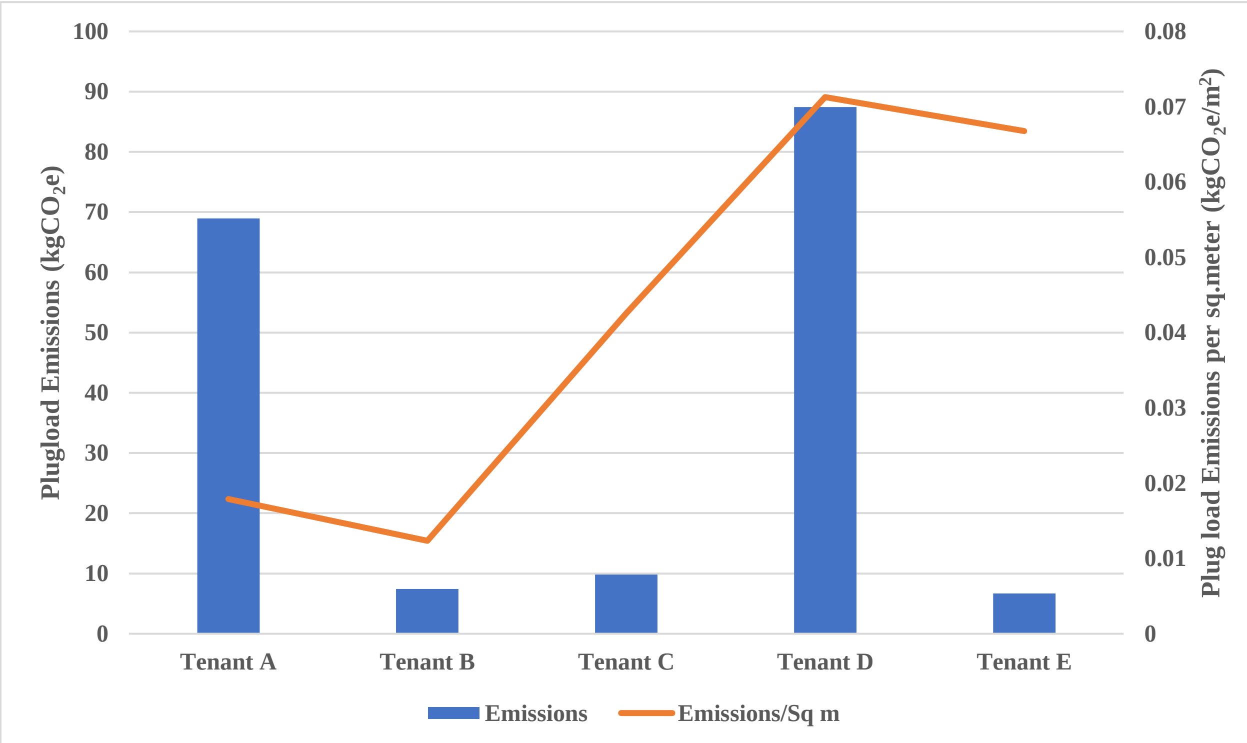


Figure 21: Tenant plug load emissions and square meter emissions for the 2022 spring season

In order to tackle the matter of elevated electricity consumption and emissions resulting from plug load usage in building facilities, it is imperative to adopt strategies that prioritize the efficient management and control of these loads. Research by Hong and Rahmat (2022) has drawn attention to the impact that plug loads have on the overall energy consumption within these structures. The aforementioned findings highlight the importance of giving priority to energy-conservation measures for plug loads as a means to achieve notable reductions in carbon emissions. The lighting system employed in the zero-carbon building, as described in the case study, is predominantly reliant on sensor technology. This sensor-based approach enables the system to operate automatically, thereby facilitating control and optimization of energy consumption. Nevertheless, plug loads, which heavily rely on manual control, have not yet reached the same level of automation and energy optimization. The absence of automation and energy optimization for plug loads leads to superfluous energy consumption and emissions, even during periods of equipment and appliance inactivity (Huang et al., 2019).

6.2 Case Study Building Parameters

The present section undertakes a thorough investigation of the distribution of performance regarding energy consumption in the case study building over the course of the entire calendar year 2022. The primary aim of this analysis is to determine particular time periods, particularly the seasons, that require the adoption of additional measures to reduce carbon emissions. The primary objective of our research is to develop a standardized framework that promotes pro-environmental behavior. The evaluation of a building's comprehensive performance in relation to its resource import, export, PV generation, and overall consumption will accomplish this. *Section 6.2.1*, we will examine the performance of the building in terms of its monthly PV generating levels relative to the building's overall energy consumption. The main objective of this discussion is to analyze the mechanisms by which PV production contributes to the energy supply of the building as well as identify the specific seasons during which excess energy is sourced from the conventional power grid. Through a comprehensive analysis of this dynamic interaction, our objective is to discern the recurring trends in which the structure effectively utilizes solar energy and potentially enhances its energy consumption efficiency throughout the course of the year.

In Section 6.2.2, an analysis is conducted to examine the performance of the building in relation to its monthly import levels and the corresponding marginal emissions. The primary objective of this study is to investigate the associations between the distribution of emissions and the quantities of imports seen in the building throughout the year. Through an in-depth exploration of this relationship, we aim to gain valuable insights into the impact of the building's energy imports on its carbon emissions as well as the potential correlation between specific time periods and elevated emission levels. *Section 6.2.3* of the report examines the performance of the building in relation to monthly import levels, specifically focusing on the months of April and May. These months align with the duration of the nudging phase. The aim of this analysis is to determine the correlation between import consumption and PV generation throughout the course of these two months. Additionally, the quantitative analysis is essential for comprehending whether there are particular days distinguished by reduced sunshine exposure and the potential implications for the efficacy of PV generation in delivering constant power to the zero-carbon building.

6.2.1 Monthly PV Generation and Total Consumption

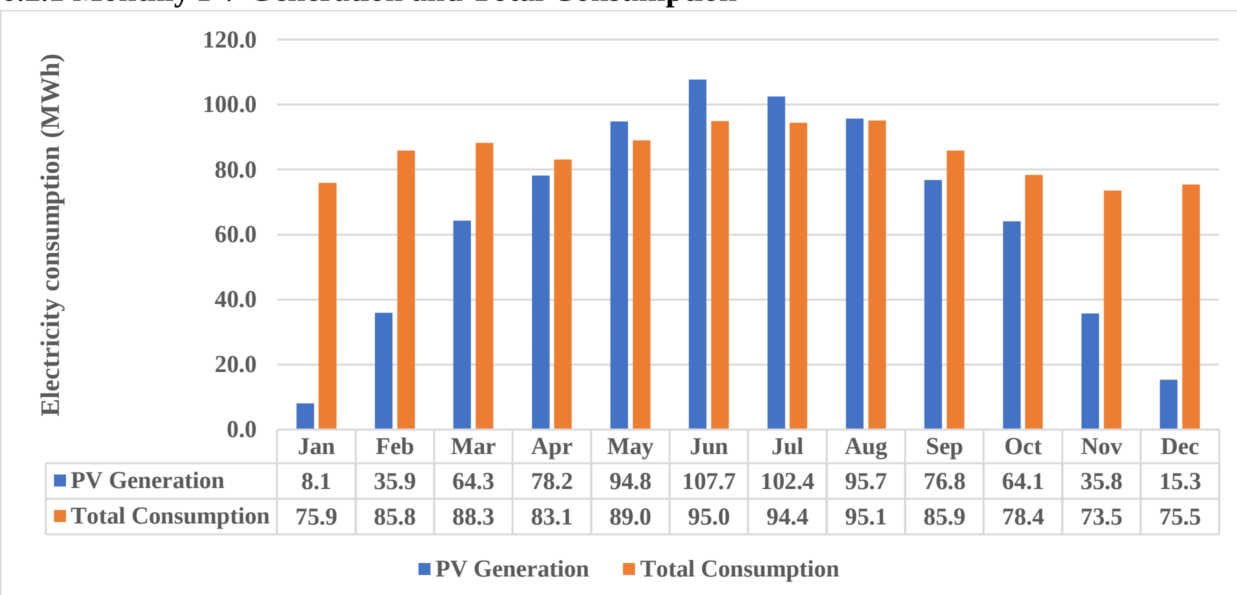


Figure 22: Monthly PV generation against the total consumption of the case study building for the year 2022

The provided visual representation in figure 22 illustrates the monthly allocation of electricity production derived from the solar panels that have been installed at the green office building, in conjunction with the aggregate energy usage of the building and EV chargers in the car park. By utilizing equation 9, it becomes possible to make an estimation of the total energy consumption of the building under investigation. The analysis conducted indicates a consistent distribution of total energy consumption over the course of the year 2022. The average electricity consumption commences at 61.1 MWh and exhibits a gradual increase throughout the spring season, culminating in an average of 65.9 MWh. The energy consumption reaches its highest point during the summer months, with an average of 70 MWh, and subsequently decreases during the fall season to an average of 58.2 MWh.

On the other hand, photovoltaic (PV) generation demonstrates a comparable pattern, albeit with more prominent fluctuations. The winter season exhibits the least amount of solar energy production compared to the other three seasons, with an average of 28.5 MWh. Nevertheless, there is a notable surge observed in the spring season, with an average of 64.8 MWh, which is subsequently followed by a peak in the summer season, averaging 72.6 MWh. The observed data reveals a robust positive correlation between electricity consumption and PV generation within the specified timeframe. This finding suggests that the solar panels are effectively mitigating a substantial proportion of the building's energy requirements, thereby reducing dependence on the conventional power grid.

With the onset of the fall season, there is a noticeable decrease in both electricity consumption and PV generation. The decline in electricity consumption to 58.2 MWh can be attributed to the influence of more temperate weather conditions. Simultaneously, there is a reduction in PV generation, which amounts to 36.5 MWh. However, solar panels continue to make a sizable contribution towards fulfilling the energy requirements of the building, particularly throughout the spring and summer periods.

In the fall, winter, and early spring, the aggregate electricity consumption exceeds the generation capacity of the building's solar panels. The difference between the amount of electricity consumed and generated requires the acquisition of supplementary power from the electrical grid in order to fulfill the building's energy requirements (AlKandari & Ahmad, 2020). To effectively tackle this matter and promote the long-term viability of energy usage, it is imperative to implement sustainable measures during instances when energy consumption surpasses PV generation capacities.

6.2.2 Monthly Imports vs Emissions

The provided visual representation, figure 23, illustrates the monthly import levels of the case study building in correlation with its emissions output over the course of the year 2022. The horizontal axis of the graph represents the twelve months of the year, while the vertical axis corresponds to the electricity consumption measured in megawatt-hours (MWh) and the carbon emissions measured in metric tons of carbon dioxide equivalent (TCO_2e). The application of equation 5 enabled us to convert the imported electricity into marginal carbon emissions by incorporating the season-specific marginal emission factors provided in table 5.

The graph displays a U-shaped curve, suggesting a positive correlation between the rise in imported electricity consumption and the associated emissions output. Import consumption peaks during the winter season at an average of 5.3 TCO_2e, then gradually declines to an average of 3.1 TCO_2e during the spring season. There is a noticeable decrease in emissions during the summer, with an average value of 2.9 TCO_2e. Subsequently, as summer progresses and transitions into fall, there is a gradual increase in emissions, reaching an average value of 4.1 TCO_2e.

On the other hand, it can be observed that during the seasons of spring and summer, there is a decrease in both the consumption of imported electricity and the associated emissions. The decrease in imports can be attributed to the increased solar energy generation during these periods, resulting in a diminished demand for electricity from the grid (Tamoor et al., 2021). The results align with the observations made in *section 6.2.1*, indicating that the building's highest emissions are correlated with its import levels during the fall, winter, and early spring months.

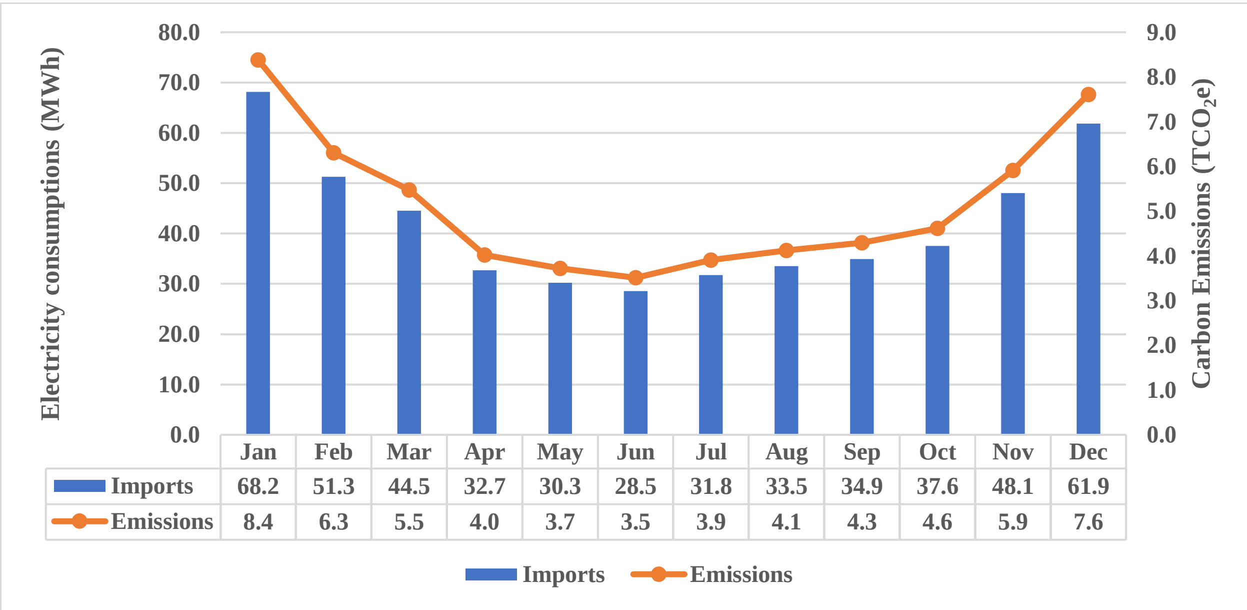


Figure 23: Monthly import consumption and marginal emissions

6.2.3 Monthly Imports vs PV Generation

Figure 24 illustrates the import consumption in relation to the total PV generation of the case study building for the month of April. The horizontal axis represents the days in the month of April, while the vertical axis corresponds to the electricity consumption measured in kilowatt-hours (kWh). The average total PV generation is observed to be 2.7 megawatt-hours (MWh), whereas the average import consumption amounts to 1.2 MWh. Nevertheless, the graph also illustrates a notable observation: the levels of import consumption exceeded the levels of PV generation during the second-last week of April.

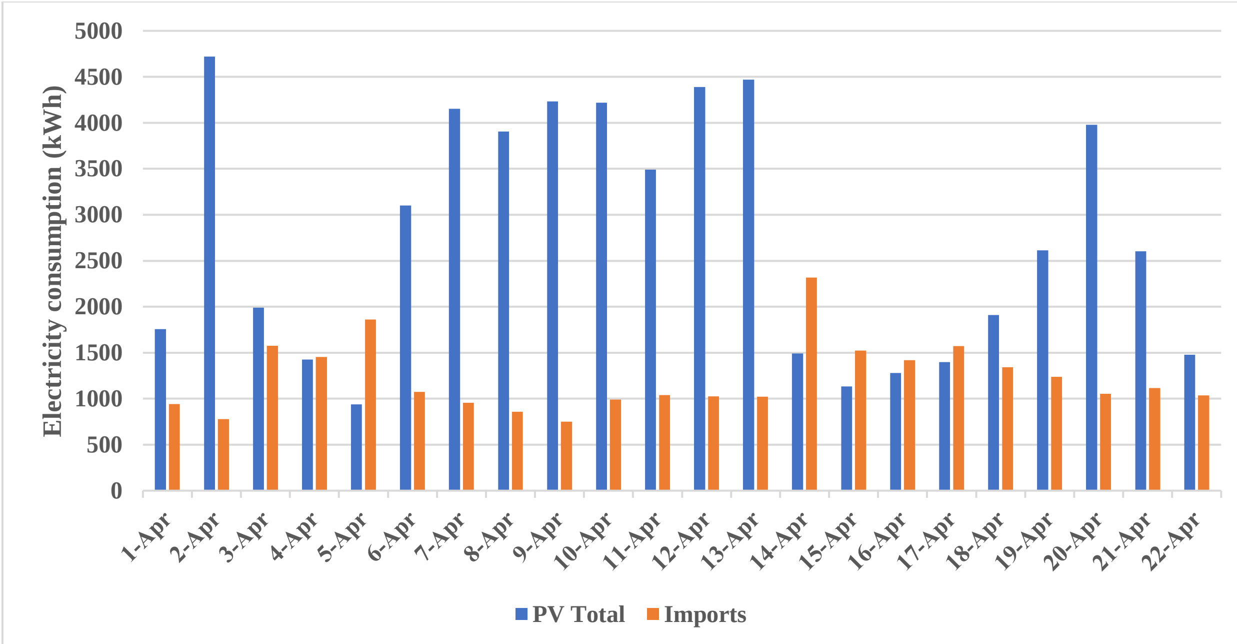


Figure 24: Total PV generation against imports for the month of April 2022

Furthermore, the bar graph presented in figure 25 illustrates the import consumption when compared to the total solar generation of the case study building, specifically for the month of May. In a similar manner to the observed trend in April, the data demonstrates that the electricity generated by the solar panels exceeds the amount of electricity imported during this specific timeframe. The mean value of total solar generation is 2.4 MWh, whereas the mean value of import consumption is 0.6 MWh. This observation demonstrates a persistent pattern in which solar generation consistently surpasses import consumption, thereby emphasizing the efficacy of solar panels in fulfilling the electricity requirements of the building.

Furthermore, it is apparent that in the month of April, there is a noticeable decrease in both PV generation and import consumption. The blockage of sunlight caused by a high percentage of cloud coverage throughout this month poses a challenge to the efficacy of PV cells in harnessing an adequate amount of solar radiation. Research by Kelly and Gibson (2009) as well as Mehrjerdi et al. (2019), which specifically examines the impact of cloud cover on the production of solar energy, supports this claim. In contrast, the month of May offer a more optimistic situation in which the overall solar generation surpasses the consumption of imported energy. According to Modi et al. (2017), it can be inferred that solar panels have the capability to adequately fulfill the electricity needs of the building during periods of increased sunlight.

Upon analyzing the provided quantitative data sets, it becomes apparent that the months of April and May potentially have an impact on the efficacy of nudging interventions aimed at encouraging sustainable behavior among the occupants of the building. During the months characterized by reduced levels of recorded solar radiation and diminished PV generation, it is imperative to emphasize the adoption of sustainable practices, particularly with regard to plug load consumption. The research conducted by Schweiger et al. (2020) provides empirical evidence that behavioral interventions can effectively promote pro-environmental behavior during periods of low renewable energy generation.

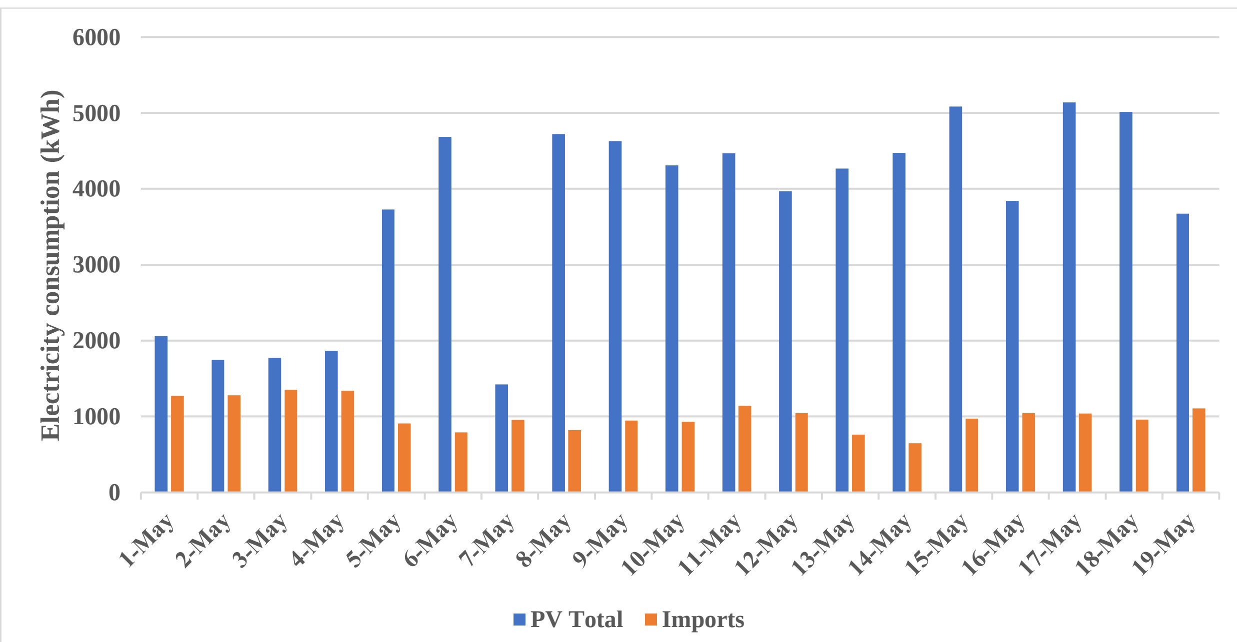


Figure 25: Daily PV generation and electricity imports, May 2022

6.3. Nudging Phase

This section provides a thorough examination of the performances exhibited by tenants during the nudging phase. The first step of the analysis involved comparing the electricity consumption data from weeks 1 and 2 (baseline) with the data from weeks 3 and 4. This comparison provided valuable insights into the effectiveness of the information interventions during the nudging phase. The study period is centered on weeks 3 to 6 of April and May, as specified in table 6, aligning with the execution of the nudging interventions, as specified in Table 7. To establish a baseline, the data on electricity consumption for weeks 1 and 2 was initially recorded and monitored. The baseline data served as reference points, allowing us to determine the extent of electricity savings achieved by the tenants during the intervention weeks. By employing a comparable methodology, the results from the final two weeks (weeks 5 and 6) will also be analyzed during the follow-up phase, which will provide further evidence of the long-term impact of the nudging interventions.

Weather conditions were considered potential influencing factors on tenant behaviors and electricity consumption patterns. Figures 26 and 27 display the weather data for weeks 3-6 in both April and May. The inclusion of weather data is required as it helps contextualize the electricity consumption patterns during the nudging phase. For instance, foggy and cloudy atmospheres during week 3 may have led to increased indoor lighting usage, impacting electricity consumption. By acknowledging these external factors, we can better interpret the tenants' responses to the nudges.

<table>
<tr><td>2
Scattered Showers
Actual:
72° | 66°
0 in</td><td>3
Scattered Showers
Actual:
79° | 64°
0 in</td><td>4
Foggy
Actual:
86° | 57°
0 in</td><td>5
Mostly Sunny
Actual:
88° | 59°
0 in</td><td>6
Foggy
Actual:
84° | 63°
0 in</td><td>7
Mostly Sunny
Actual:
75° | 55°
0 in</td><td>8
Scattered Showers
Actual:
73° | 48°
0 in</td></tr>
<tr><td>9
Foggy
Actual:
75° | 55°
0 in</td><td>10
Mostly Sunny
Actual:
81° | 52°
0 in</td><td>11
Thunderstorm
Actual:
82° | 63°
0 in</td><td>12
Mostly Cloudy
Actual:
73° | 52°
0 in</td><td>13
Thunderstorm
Actual:
70° | 57°
0 in</td><td>14
Foggy
Actual:
77° | 50°
0 in</td><td>15
Scattered Showers
Actual:
75° | 59°
0 in</td></tr>
<tr><td>16
Cloudy
Actual:
79° | 64°
0 in</td><td>17
Mostly Sunny
Actual:
77° | 59°
0 in</td><td>18
Average:
79° | 57°
0 in</td><td>19
Average:
79° | 57°
0 in</td><td>20
Average:
79° | 57°
0 in</td><td>21
Average:
79° | 57°
0 in</td><td>22
Average:
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Average:
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Average:
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79° | 57°
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<tr><td>30
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79° | 57°
0 in</td><td>31
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79° | 56°
0 in</td><td>1
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79° | 56°
0 in</td><td>2
Average:
79° | 56°
0 in</td><td>3
Average:
78° | 56°
0 in</td><td>4
Average:
78° | 56°
0 in</td><td>5
Average:
78° | 56°
0 in</td></tr>
</table>

Figure 26: Weather conditions over weeks 3-4 in the month of April 2023. ***Retrieved from:*** [***https://www.wunderground.com/calendar/ca/cambridge/CYKF/date/2023-5***](https://www.wunderground.com/calendar/ca/cambridge/CYKF/date/2023-5)

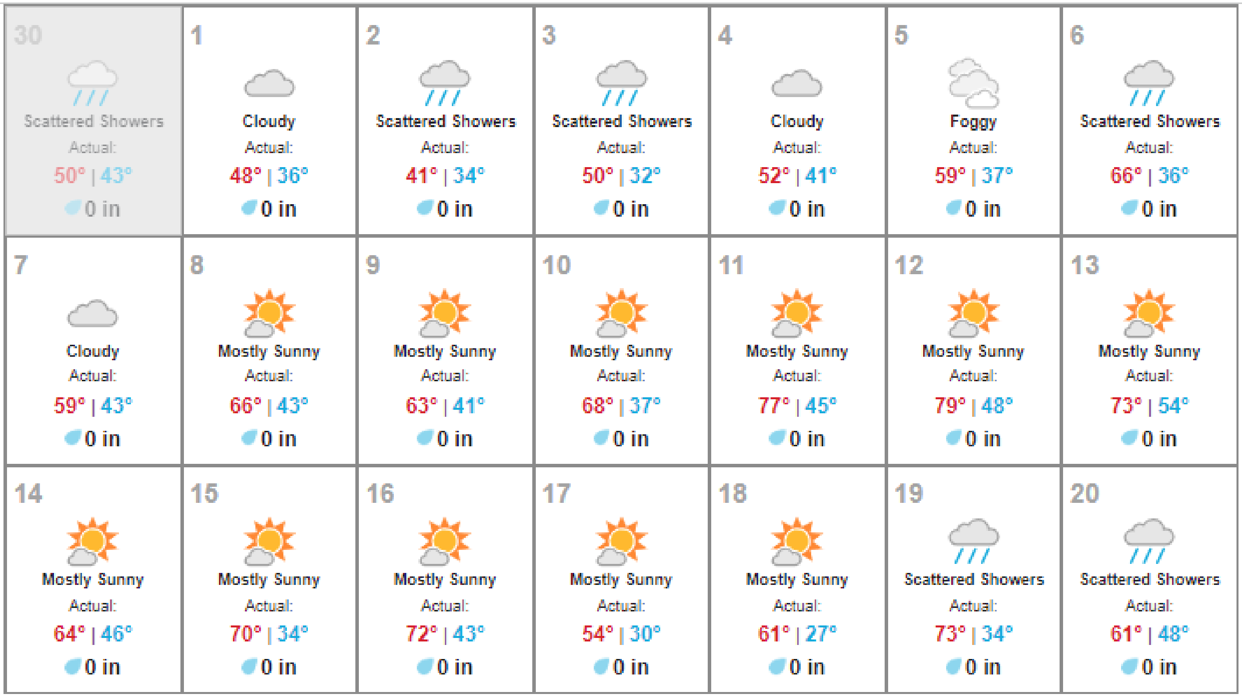

Figure 27: Weather conditions over weeks 4-6 in the month of May 2023. ***Retrieved from:*** ***https://www.wunderground.com/calendar/ca/cambridge/CYKF/date/2023-5***

6.3.1 Nudging Phase: Week 3-4

6.3.1.1 Tenant Lighting

Tables 8 and 9 reflect the data on daily tenant lighting consumption for weeks 3 and 4, respectively, during the period in which the information interventions were introduced. The interventions encompassed sending out announcements and behavioral strategy flyers to the tenant representatives who had taken part in the recruitment phase of the focus group. The tables additionally incorporate the corresponding meteorological conditions for each day, along with the documented measurements for the mean and standard deviation. Figures 26 and 27 are presented below to offer a more comprehensive visual presentation of the results pertaining to the distribution of electricity consumption throughout weeks 3 and 4, specifically across the days of the week.

Tenant Lighting Consumption in Week 3 (kWh)								
Tenant ID	**4/28 (Friday)**	**4/29 (Saturday)**	**4/30 (Sunday)**	**5/1 (Monday)**	**5/2 (Tuesday)**	**5/3 (Wednesday)**	**5/4 (Thursday)**	**5/5 (Friday)**
	Scattered Showers	**Cloudy**	**Scattered Showers**	**Cloudy**	**Scattered Showers**	**Scattered Showers**	**Cloudy**	**Foggy**
A	84.0	13.9	13.9	83.0	77.5	83.0	76.1	73.9
B	38.4	21.0	24.2	40.5	40.5	40.9	38.9	32.4
C	10.5	4.1	4.3	13.0	13.5	12.0	17.4	12.4
D	82.1	20.5	11.0	84.5	90.1	79.5	86.2	74.4
E	23.7	19.5	19.4	24.2	24.6	25.5	24.2	25.2
Mean	**47.7**	**15.8**	**14.5**	**49.0**	**49.2**	**48.2**	**48.5**	**43.7**
Standard Deviation	**33.7**	**7.2**	**7.7**	**33.2**	**33.2**	**31.9**	**31.0**	**28.7**

Table 8: Individual tenant lighting consumption in week 3

Tenant Lighting Consumption in Week 4 (kWh)								
Tenant ID	**5/5 (Friday)**	**5/6 (Saturday)**	**5/7 (Sunday)**	**5/8 (Monday)**	**5/9 (Tuesday)**	**5/10 (Wednesday)**	**5/11 (Thursday)**	**5/12 (Friday)**
	Foggy	**Scattered Showers**	**Cloudy**	**Mostly Sunny**	**Mostly Sunny**	**Mostly Sunny**	**Mostly Sunny**	**Mostly Sunny**
A	73.9	14.9	14.1	70.3	93.4	95.4	79.4	68.2
B	32.4	18.5	18.5	34.4	38.0	38.1	41.5	25.2
C	12.4	4.1	5.2	12.8	11.1	14.1	10.7	10.2
D	74.4	25.3	23.9	89.4	95.7	84.7	92.7	67.4
E	25.2	19.5	19.4	26.3	24.2	20.2	26.6	24.0
Mean	**43.7**	**16.4**	**16.2**	**46.6**	**52.5**	**50.5**	**50.2**	**39.0**
Standard Deviation	**28.7**	**7.9**	**7.1**	**32.0**	**39.6**	**37.4**	**34.8**	**27.0**

Table 9: Individual tenant lighting consumption in week 4

Line graphs illustrating the patterns of lighting consumption during weeks 3 and 4 are depicted in Figure 28 and Figure 29, respectively. Both graphs indicate the days of the week along the horizontal axis, while the vertical axis represents the tenant lighting consumption measured in kilowatt-hours (kWh).

The line graphs clearly illustrate a visible variation in the consumption of lighting between weekdays and weekends. Over the course of the two-week period, there is a consistent pattern of lower lighting consumption during weekends in comparison to weekdays. This observation suggests that there may be potential avenues for promoting pro-environmental behavior and energy conservation, particularly on weekdays when energy consumption levels tend to be higher. Upon conducting an examination of the mean average of tenant lighting consumption on weekdays, it was observed that the recorded value was 49 kWh during week 3, followed by a slightly elevated figure of 52.5 kWh during week 4. Following this, there is a gradual decrease in consumption starting on Friday, indicating a decrease in activity and lighting usage as the weekend approaches.

In relation to tenant performances, it is worth mentioning that tenants D and A exhibited the highest levels of electricity consumption during both weeks 3 and 4. The lighting consumption of these two tenants consistently demonstrated higher levels in comparison to the remaining three tenants.

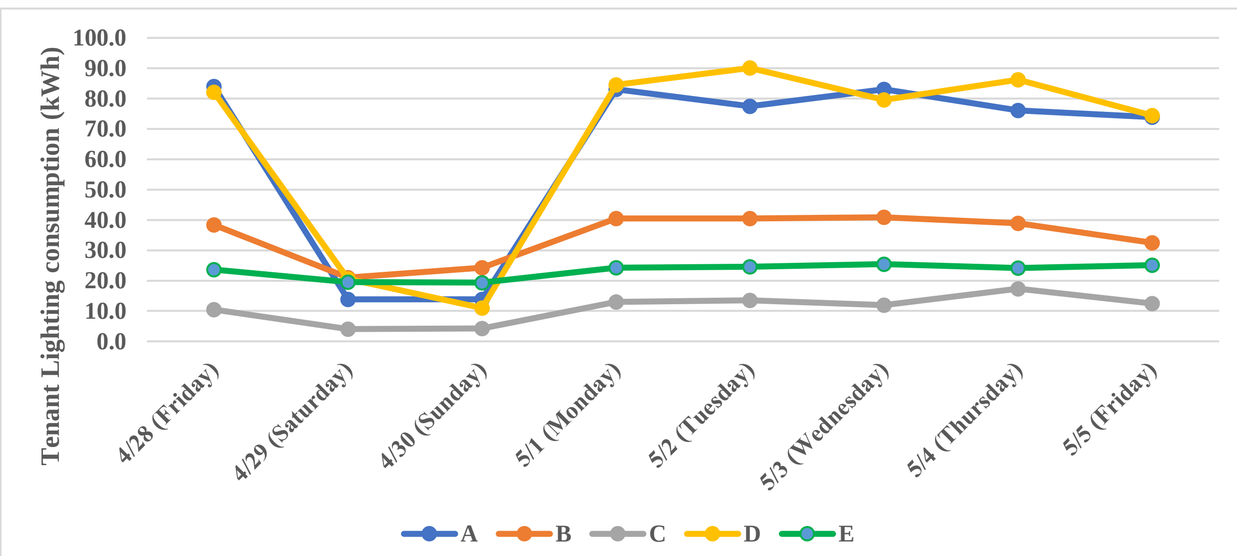

Figure 28: Individual tenants lighting consumption in week 3

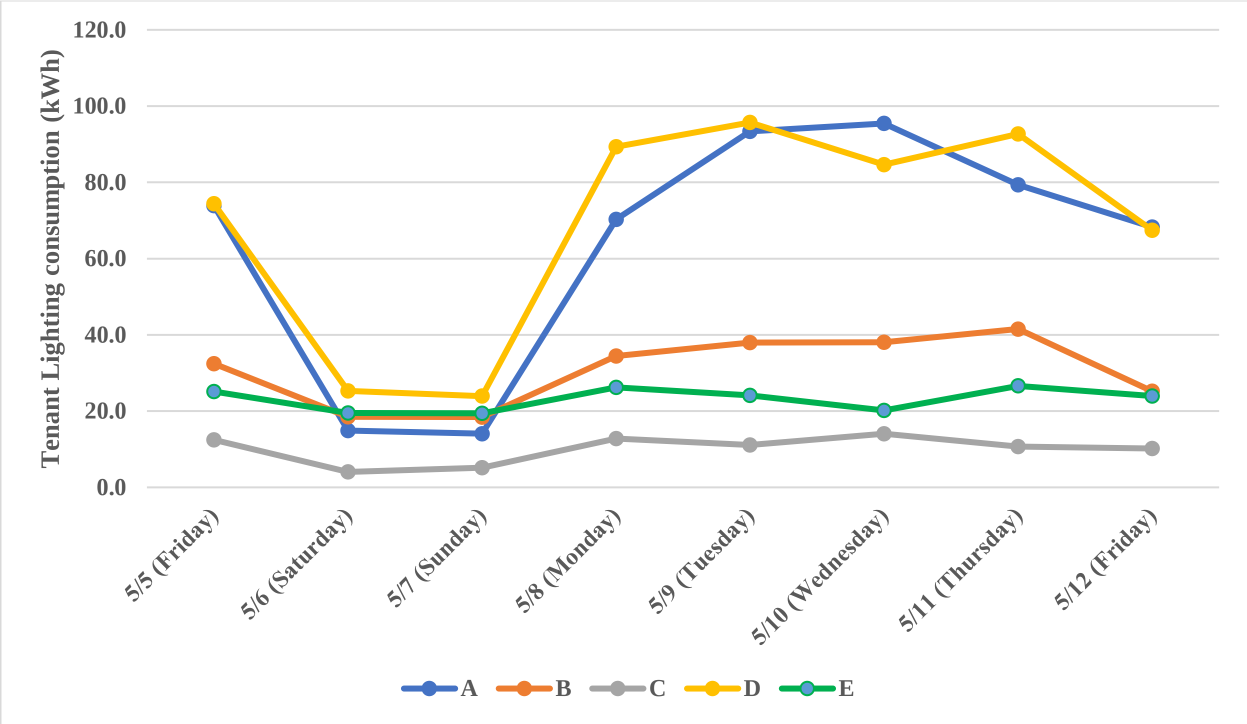

Figure 29: Individual tenants lighting consumption in week 4

The subsequent section in figure 30 provides a review of the percentage of electricity savings attained in tenant lighting usage, as illustrated in the bar graph provided. The x-axis represents the percentage of electricity savings, while the y-axis corresponds to the individual tenants in the building being studied. In order to determine the percentage savings, the electricity consumption data from weeks 1 and 2 was compared to that of weeks 3 and 4, utilizing equation 9.

Moreover, it becomes evident that an observable pattern emerges in terms of electricity consumption reduction among the majority of the tenants, with the exception of tenant A. Tenant D has emerged as the primary contributor to electricity savings, demonstrating a noteworthy reduction of 19%. Tenant E came next with a 12% decrease, then tenant B showed a reduction of 17% after that. Although these results may indicate that some tenants were more receptive to the nudging interventions, leading to substantial energy savings, further investigation into attendance numbers would have provided more clarity on whether the reductions in energy usage were due to lower attendance numbers than the baseline or if the tenants were in fact nudged.

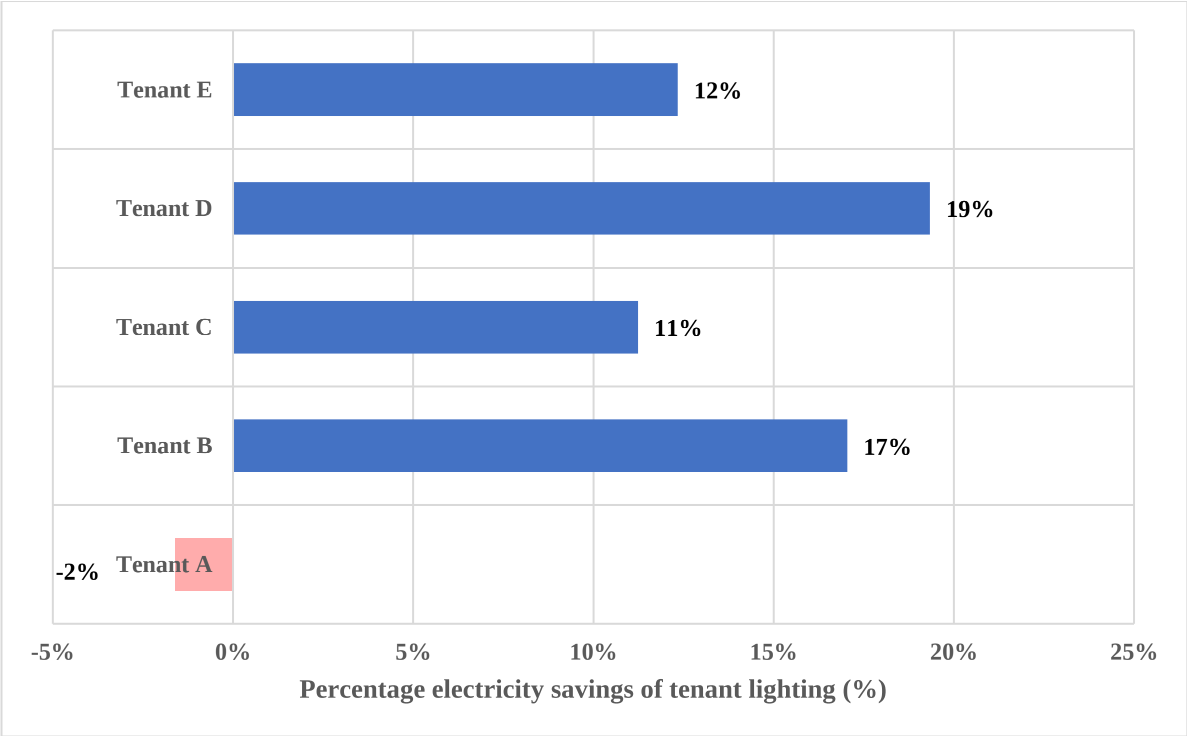

Figure 30: Percentage electricity savings of tenant lighting for weeks 3-4.

6.3.1.2 Tenant Plug Load

Tenant Plug Load Consumption in Week 3 (kWh)								
Tenant ID	**4/28 (Friday)**	**4/29 (Saturday)**	**4/30 (Sunday)**	**5/1 (Monday)**	**5/2 (Tuesday)**	**5/3 (Wednesday)**	**5/4 (Thursday)**	**5/5 (Friday)**
	Scattered Showers	**Cloudy**	**Scattered Showers**	**Cloudy**	**Scattered Showers**	**Scattered Showers**	**Cloudy**	**Foggy**
A	197.9	162.4	160.4	202.0	198.7	210.4	199.6	204.4
B	37.3	27.6	28.2	43.1	45.9	46.7	45.8	35.3
C	30.1	29.1	27.8	30.4	35.4	29.1	33.1	29.0
D	239.3	226.9	225.1	248.1	250.5	249.8	262.9	240.8
E	24.0	24.0	23.5	25.0	26.1	24.6	24.7	25.3
Mean	**105.7**	**94.0**	**93.0**	**109.7**	**111.3**	**112.1**	**113.2**	**106.9**
Standard Deviation	**104.2**	**94.7**	**93.9**	**106.8**	**105.2**	**108.9**	**110.3**	**106.4**

Table 10: Individual tenant plug loads consumption in week 3

Tenant Plug Load Consumption in Week 4 (kWh)								
Tenant ID	**5/5 (Friday)**	**5/6 (Saturday)**	**5/7 (Sunday)**	**5/8 (Monday)**	**5/9 (Tuesday)**	**5/10 (Wednesday)**	**5/11 (Thursday)**	**5/12 (Friday)**
	Foggy	**Scattered Showers**	**Cloudy**	**Mostly Sunny**	**Mostly Sunny**	**Mostly Sunny**	**Mostly Sunny**	**Mostly Sunny**
A	204.4	162.3	161.4	199.1	207.6	217.9	204.8	202.7
B	35.3	28.5	27.9	42.5	42.7	45.2	42.1	20.6
C	29.0	27.1	27.1	34.9	28.2	33.7	29.7	27.8
D	240.8	233.3	232.6	252.9	259.6	250.9	264.4	244.1
E	25.3	24.1	23.8	27.4	25.5	24.2	26.1	24.1
Mean	**106.9**	**95.1**	**94.6**	**111.4**	**112.7**	**114.4**	**113.4**	**103.9**
Standard Deviation	**106.4**	**97.1**	**96.9**	**106.5**	**112.1**	**110.4**	**112.8**	**110.1**

Table 11: Individual tenant plug loads consumption in week 4

The following tables 10 and 11 present a comprehensive representation of the distribution of electricity consumption among the respective tenants during weeks 3 and 4, specifically in relation to plug load usage. Similar to the methodology employed for collecting data on tenant lighting, the process of gathering electricity consumption data pertaining to plug load usage was initiated at the commencement of the nudging phase, specifically from week 3 onwards. Additionally, the tables include data regarding the prevailing weather conditions for each day within the designated weeks.

During the third week, the prevailing weather conditions were characterized by foggy and cloudy atmospheres, resulting in limited exposure to sunlight. Week 4 in contrast had a few days with little sun exposure, despite being primarily sunny. A visual representation illustrating the distribution of plug load electricity usage among tenants is provided in figures 31 and 32.

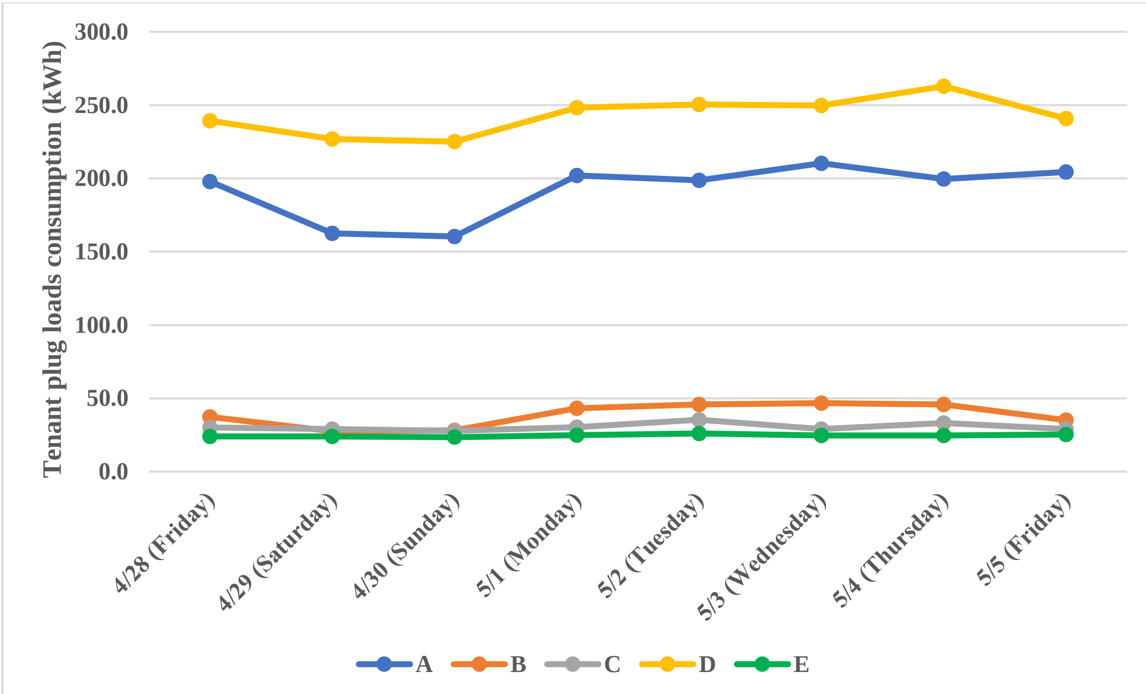

Figure 31: Individual tenants plug load consumption in week 3

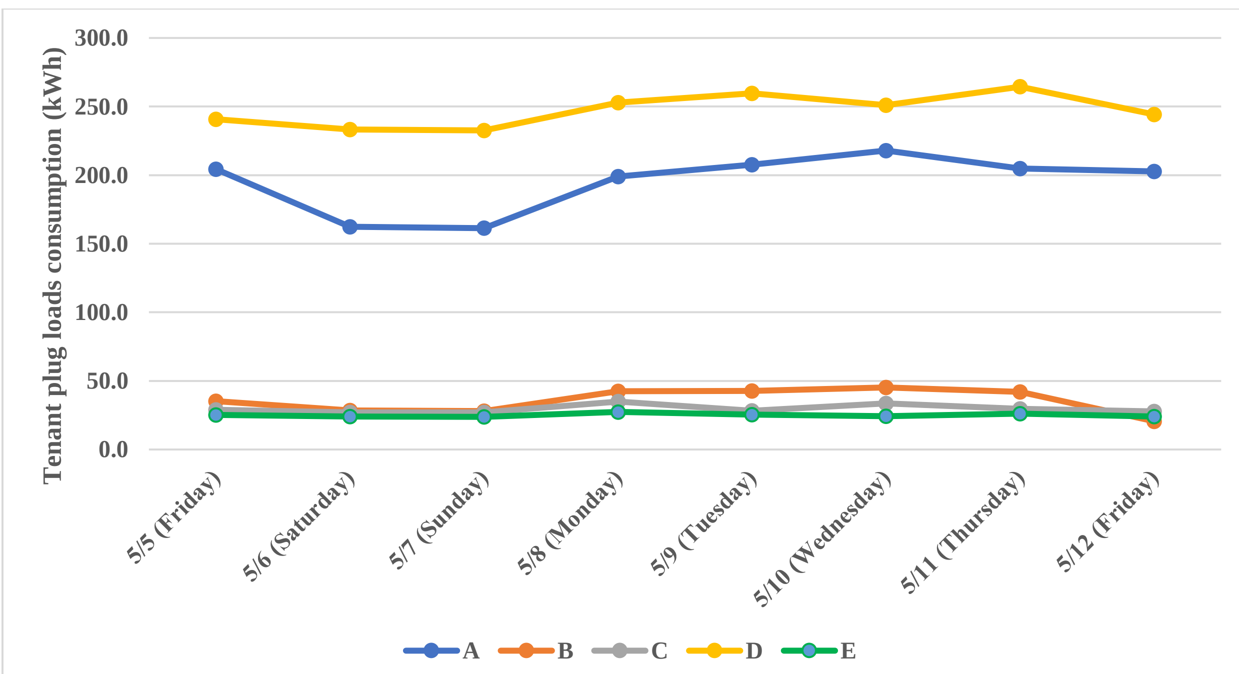

Figure 32: Individual tenants plug load consumption in week 4

The two-line graphs in figures 28 and 29 illustrate the energy consumption of plug loads across the days of the week. The graphs clearly demonstrate a consistent pattern observed in both datasets, indicating a decrease in energy consumption during weekends compared to weekdays. The mean peak consumptions during weekends were observed to be 94 kWh and 95.1 kWh, whereas higher values of 113.2 kWh and 114.4 kWh were recorded for weekdays during weeks 3 and 4, respectively.

In relation to the performances of tenants, it was observed that tenants D and A demonstrated the highest levels of plug load consumption during both weeks in comparison to the remaining tenants Understanding the various patterns of energy consumption that the building's occupants exhibit is of the utmost importance. Considering the diverse patterns of energy consumption among tenants, it is essential to tailor interventions to address the specific behaviors of each individual or group. For example, targeting tenants D and A, who consistently exhibited high consumption levels, with tailored nudges might lead to greater energy savings.

In order to evaluate the effects of the implemented nudge strategy on electricity consumption, the percentage of savings observed during weeks 3-4 was compared to the baseline period of weeks 1-2 prior to the implementation of the nudge. The following figure 33 illustrates the percentage of electricity consumption savings obtained from plug loads. The percentage savings are represented on the horizontal axis, while the individual tenants are represented on the vertical axis.

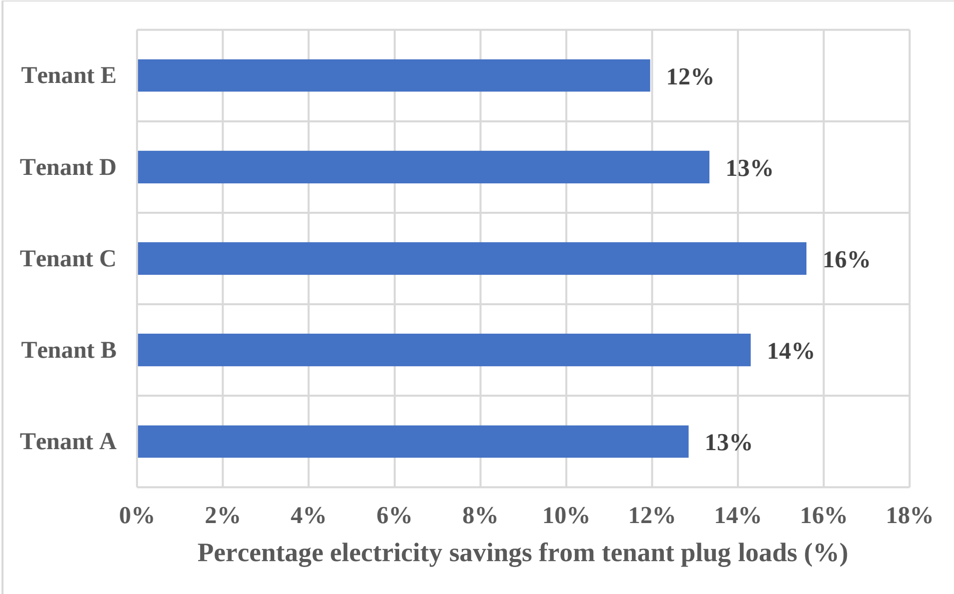

Figure 33: Percentage electricity savings of tenant plug loads for weeks 3-4

The bar chart in figure 33 offers valuable insights into the patterns of electricity consumption exhibited by each tenant. The data clearly indicates that there was a substantial decrease in electricity usage among all tenants during weeks 3-4, leading to a notable increase in the percentage of energy savings. Tenant C demonstrated the highest level of contribution to electricity savings among the tenants, with tenant B, tenant D, tenant A, and tenant E following in descending order. As mentioned in the previous section, the aforementioned findings may suggest that certain tenants exhibited greater responsiveness to the nudging interventions, resulting in observable energy savings. However, a more comprehensive examination of attendance figures would have yielded a clearer understanding of whether the observed reductions in energy consumption were attributable to decreased attendance relative to the baseline or if the tenants were indeed influenced by the nudging strategies.

6.4 Follow-up Phase

During the follow-up phase, data pertaining to tenant performances regarding lighting and plug load usage was collected, specifically focusing on the final two weeks of the 6-week nudging period. Following this, a comprehensive evaluation of these performances was presented to the tenant representatives who actively participated in the recruitment phase of the focus group. The purpose of this presentation was to elucidate the observed discrepancies in behavioral consumption patterns and explore potential underlying justifications.

Through engaging with tenant representatives, important insights were obtained through discussions pertaining to the factors that contribute to the aforementioned disparities in energy consumption patterns. The purpose of these discussions was to uncover essential information that could be used to inform and enhance future nudging interventions. Considerable emphasis was placed on the identification of strategic methodologies aimed at enhancing the efficacy of nudging interventions, particularly during periods when the promotion of sustainable behaviors is required.

6.4.1 Final Nudging Phase: Week 5-6

6.4.1.1 Tenant Lighting

Tenant Lighting Consumption in Week 5 (kWh)								
Tenant ID	**5/12 (Friday)**	**5/13 (Saturday)**	**5/14 (Sunday)**	**5/15 (Monday)**	**5/16 (Tuesday)**	**5/17 (Wednesday)**	**5/18 (Thursday)**	**5/19 (Friday)**
	Mostly Sunny	**Mostly Sunny**	**Mostly Sunny**	**Mostly Sunny**	**Mostly Sunny**	**Mostly Sunny**	**Mostly Sunny**	**Scattered Showers**
A	68.2	18.6	18.4	70.1	80.0	102.1	89.2	68.7
B	38.4	21.0	24.2	40.5	40.5	40.9	38.9	32.4
C	10.5	4.1	4.3	13.0	13.5	12.0	17.4	12.4
D	82.1	20.5	11.0	84.5	90.1	79.5	86.2	74.4
E	23.7	19.5	19.4	24.2	24.6	25.5	24.2	25.2
Mean	**44.6**	**16.7**	**15.4**	**46.5**	**49.7**	**52.0**	**51.2**	**42.6**
Standard Deviation	**30.0**	**7.2**	**7.8**	**30.2**	**33.8**	**37.7**	**34.3**	**27.4**

Table 12: Individual tenant lighting consumption in week 5

Tenant Lighting Consumption in Week 6 (kWh)								
Tenant ID	**5/19 (Friday)**	**5/20 (Saturday)**	**5/21 (Sunday)**	**5/22 (Monday)**	**5/23 (Tuesday)**	**5/24 (Wednesday)**	**5/25 (Thursday)**	**5/26 (Friday)**
	Scattered Showers	**Scattered Showers**	**Mostly Sunny**	**Mostly Sunny**	**Mostly Sunny**	**Mostly Sunny**	**Mostly Sunny**	**Mostly Sunny**
A	68.7	22.6	13.9	13.9	79.3	88.2	73.8	61.9
B	32.4	18.5	18.5	34.4	38.0	38.1	41.5	25.2
C	12.4	4.1	5.2	12.8	11.1	14.1	10.7	10.2
D	74.4	25.3	23.9	89.4	95.7	84.7	92.7	67.4
E	25.2	19.5	19.4	26.3	24.2	20.2	26.6	24.0
Mean	**42.6**	**18.0**	**16.2**	**35.4**	**49.6**	**49.0**	**49.1**	**37.7**
Standard Deviation	**27.4**	**8.2**	**7.1**	**31.5**	**36.3**	**35.3**	**33.7**	**25.3**

Table 13: Individual tenant lighting consumption in week 6

The following tables 12 and 13 present a thorough analysis of the electricity usage trends for tenant lighting from weeks 5 to 6. The weather conditions corresponding to each day within the specified weeks have been delineated as well. During the two-week period, the majority of days were characterized by sunny weather, with the exception of Friday and Saturday, when scattered showers occurred.

In relation to the behavior of tenants regarding consumption, it was noted that the average electricity usage for lighting on weekends was comparatively lower than on weekdays for both weeks 5 and 6. It is worth mentioning that the highest levels of consumption were observed on Tuesdays, with recorded values of 49.7 kWh and 49.6 kWh in weeks 5 and 6, respectively.

In order to enable a comparative analysis of the consumption patterns among the tenants, line graphs have been constructed to visually represent the lighting usage of the tenants (figures 34 and 35). The x-axis of the graph represents the days of the week, while the y-axis represents the consumption of lighting in kilowatt hours. Both graphs exhibit comparable patterns of consumption, characterized by an initial rise in electricity usage at the onset of each week, followed by peak levels of consumption throughout the remainder of the week. Consequently, there is a discernible decline in electricity usage as the weekend draws near.

In the fifth week, Tenant D and Tenant A were identified as the tenants with the highest consumption of tenant lighting. Tenant D recorded a peak consumption of 90.1 kWh, while Tenant A reached 102.1 kWh. During week 6, a similar consumption pattern was observed, although Tenant A displayed a lower level of usage on May 22nd, which was the first day of the week. The aforementioned observation appears to be unusual given the consumption patterns previously depicted in the graphs and data pertaining to tenant behavior. On the other hand, in week 6, Tenant D's energy consumption reached a maximum of 95.7 kWh, surpassing the consumption in week 5. In contrast, Tenant A's energy consumption reached its highest point at 88.2 kWh, suggesting a decline in energy utilization in comparison to the previous week, specifically week 5.

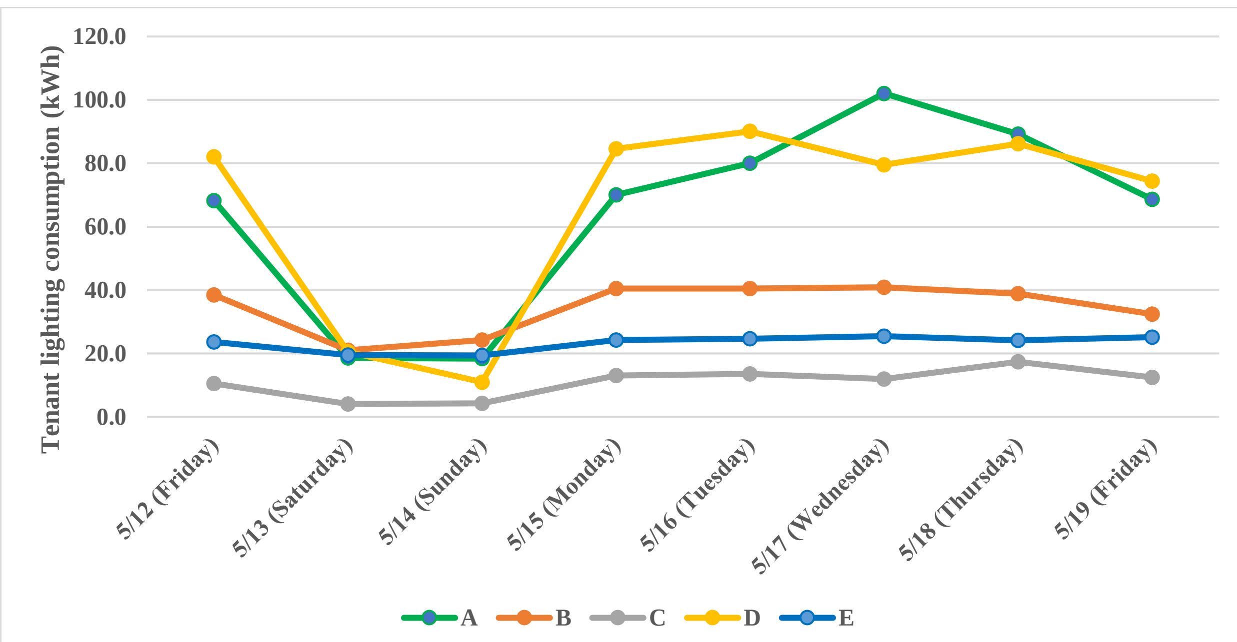

Figure 34: Individual tenant lighting consumption in week 5

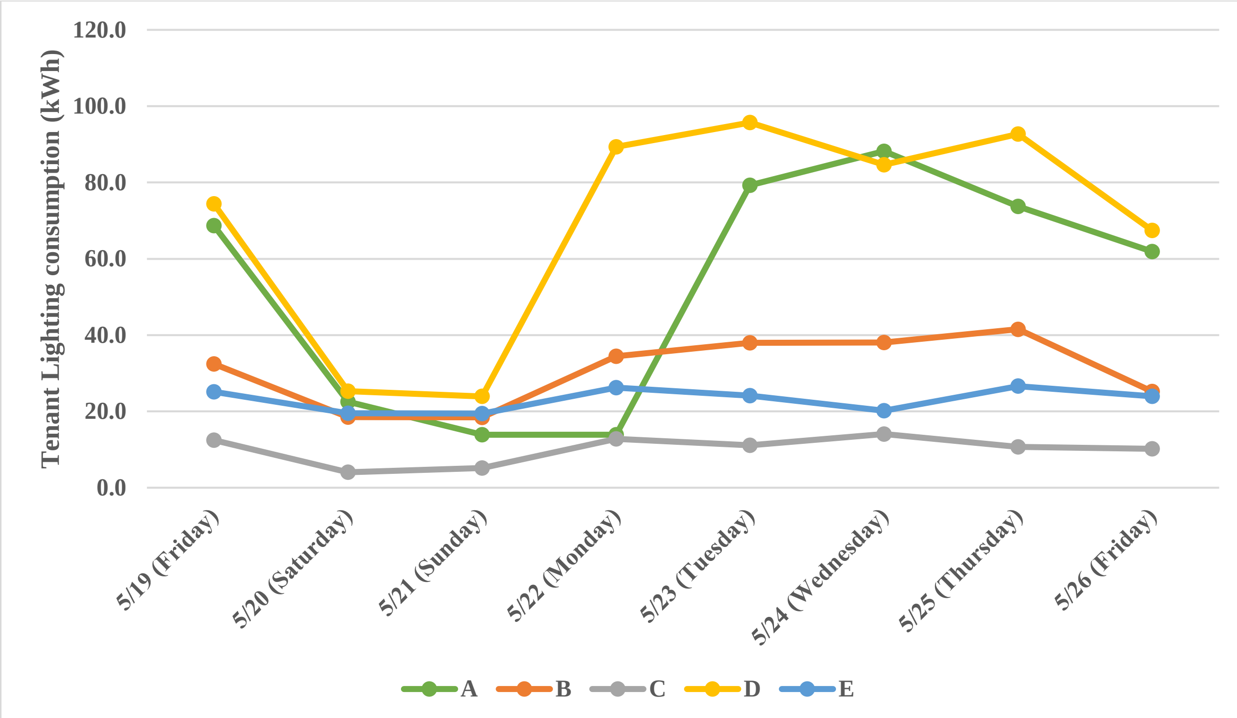

Figure 35: Individual tenant lighting consumption in week 6

The bar chart in figure 36 offers a comprehensive representation of the proportion of energy savings obtained from tenant lighting during weeks 5-6, in comparison to the consumption patterns observed in weeks 3-4. Additionally, distinguishable differences in consumption behaviors among the respective tenants become apparent. Tenant A and Tenant B both demonstrate positive percentages, indicating a decrease in electricity consumption and a corresponding increase in the percentage of electricity savings.

Specifically, the electricity savings of Tenant B exhibit a notable improvement during weeks 5-6, demonstrating a noteworthy rise from 14% in weeks 3-4 to 17% within the designated timeframe. In contrast, the energy savings of Tenant A exhibit a comparatively less notable performance during weeks 5-6, with a recorded savings of 8%, in contrast to the 13% achieved during weeks 3-4. In contrast, the consumption patterns of Tenant C, Tenant D, and Tenant E exhibit an inverse relationship, wherein their electricity usage demonstrates an increase during weeks 5-6, resulting in a subsequent decrease in the corresponding percentage of electricity savings.

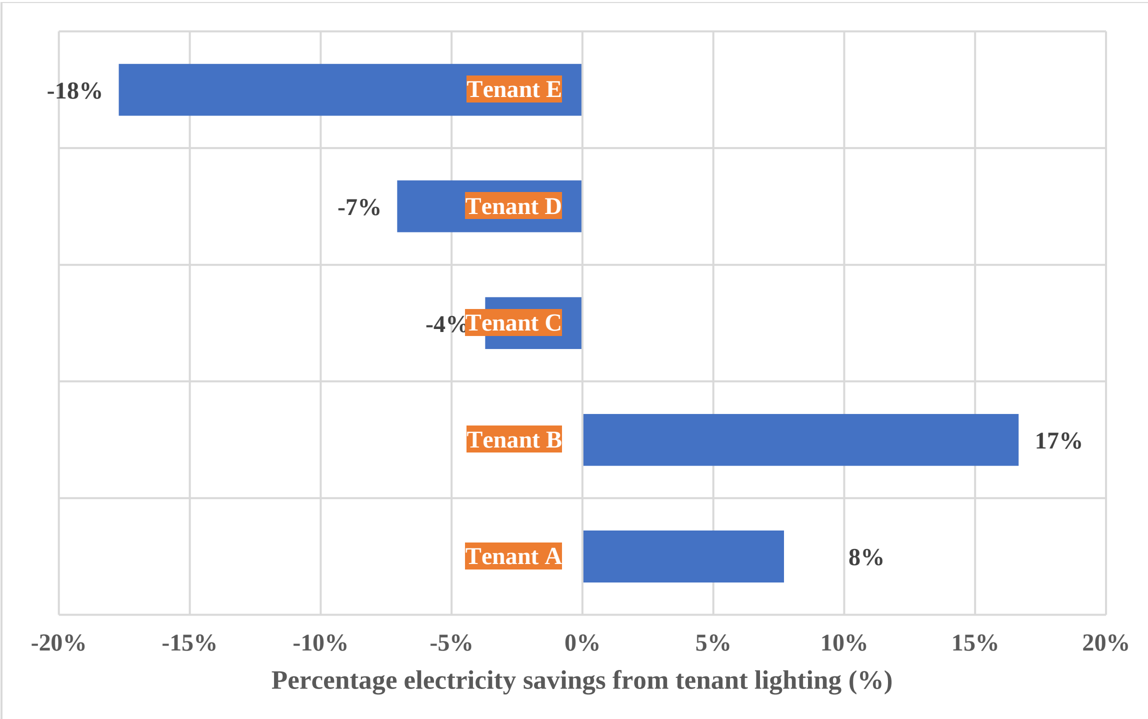

Figure 36: Percentage electricity savings of tenant lighting for weeks 5-6

6.4.1.2 Tenant Plug Loads

Tenant Plug Load Consumption in Week 5 (kWh)								
Tenant ID	**5/12 (Friday)**	**5/13 (Saturday)**	**5/14 (Sunday)**	**5/15 (Monday)**	**5/16 (Tuesday)**	**5/17 (Wednesday)**	**5/18 (Thursday)**	**5/19 (Friday)**
	Mostly Sunny	**Mostly Sunny**	**Mostly Sunny**	**Mostly Sunny**	**Mostly Sunny**	**Mostly Sunny**	**Mostly Sunny**	**Scattered Showers**
A	202.7	163.9	162.1	199.6	209.4	224.5	203.2	196.9
B	37.3	27.6	28.2	43.1	45.9	46.7	45.8	35.3
C	30.1	29.1	27.8	30.4	35.4	29.1	33.1	29.0
D	244.1	238.1	236.7	251.0	257.4	258.9	252.9	228.9
E	24.0	24.0	23.5	25.0	26.1	24.6	24.7	25.3
Mean	**107.7**	**96.5**	**95.7**	**109.8**	**114.9**	**116.8**	**112.0**	**103.1**
Standard Deviation	**106.8**	**98.9**	**98.3**	**107.2**	**109.8**	**115.0**	**107.7**	**101.0**

Table 14: Individual tenant plug loads consumption in week 5

Tenant Plug Load Consumption in Week 6 (kWh)								
Tenant ID	**5/19 (Friday)**	**5/20 (Saturday)**	**5/21 (Sunday)**	**5/22 (Monday)**	**5/23 (Tuesday)**	**5/24 (Wednesday)**	**5/25 (Thursday)**	**5/26 (Friday)**
	Scattered Showers	**Scattered Showers**	**Mostly Sunny**	**Mostly Sunny**	**Mostly Sunny**	**Mostly Sunny**	**Mostly Sunny**	**Mostly Sunny**
A	196.9	163.7	160.1	187.3	202.6	199.2	197.1	198.9
B	35.3	28.5	27.9	42.5	42.7	45.2	42.1	20.6
C	29.0	27.1	27.1	34.9	28.2	33.7	29.7	27.8
D	228.9	227.5	229.5	232.0	254.6	245.0	261.0	238.4
E	25.3	24.1	23.8	27.4	25.5	24.2	26.1	24.1
Mean	**103.1**	**94.2**	**93.7**	**104.8**	**110.7**	**109.5**	**111.2**	**102.0**
Standard Deviation	**101.0**	**95.3**	**95.5**	**97.1**	**109.4**	**104.3**	**110.1**	**107.5**

Table 15: Individual tenant plug loads consumption in week 6

Tables 14 and 15 provide an analysis of the patterns of plug load consumption demonstrated by tenants in weeks 5-6. The meteorological conditions, which were previously examined in relation to tenant lighting, were also documented. When comparing tenant lighting and plug load usage, it was observed that plug load usage exhibited elevated levels of electricity consumption. As previously noted, there was a consistent pattern of reduced electricity consumption during weekends. Nevertheless, the highest levels of electricity usage were observed during the fifth week, specifically on Tuesday and Wednesday, with recorded values of 114.9 kWh and 116.8 kWh, respectively. During the sixth week, the days with the highest levels of electricity consumption were Tuesday and Thursday, where the recorded values were 110.7 kWh and 111.2 kWh, respectively.

In order to enhance the visual representation of tenants' behavioral patterns regarding plug load usage, the following figures 37 and 38 illustrate the energy consumption of plug loads during the fifth and sixth weeks of the observation period.

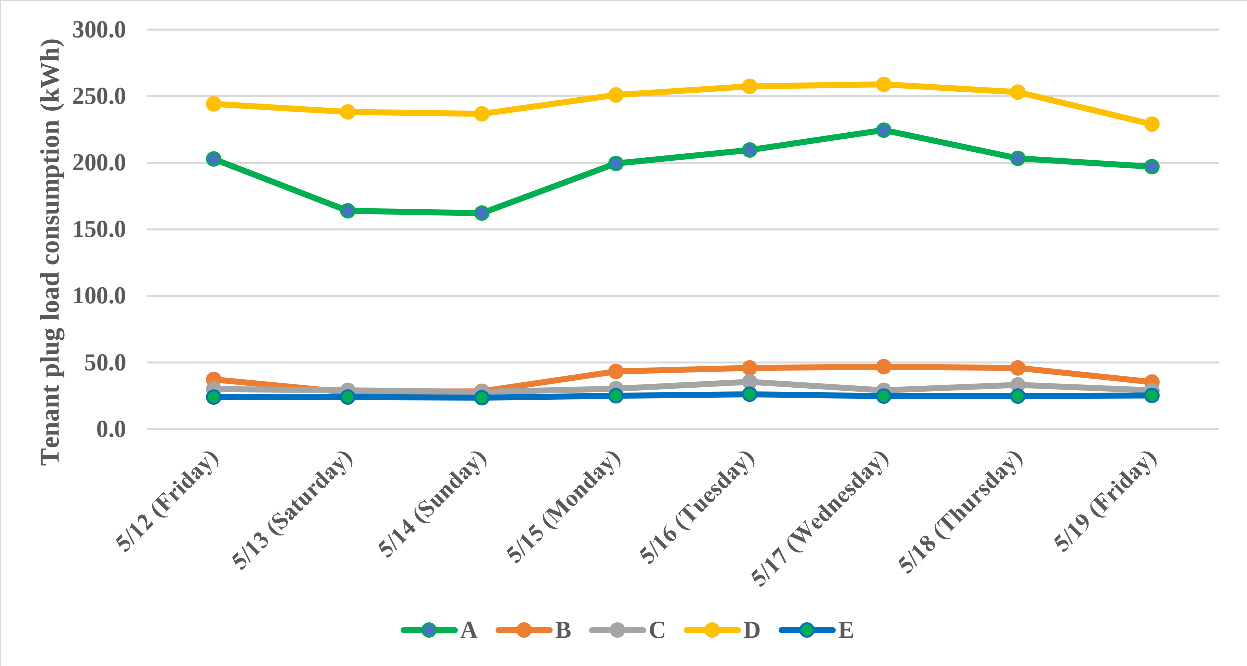

Figure 37: Individual tenant plug loads consumption in week 5

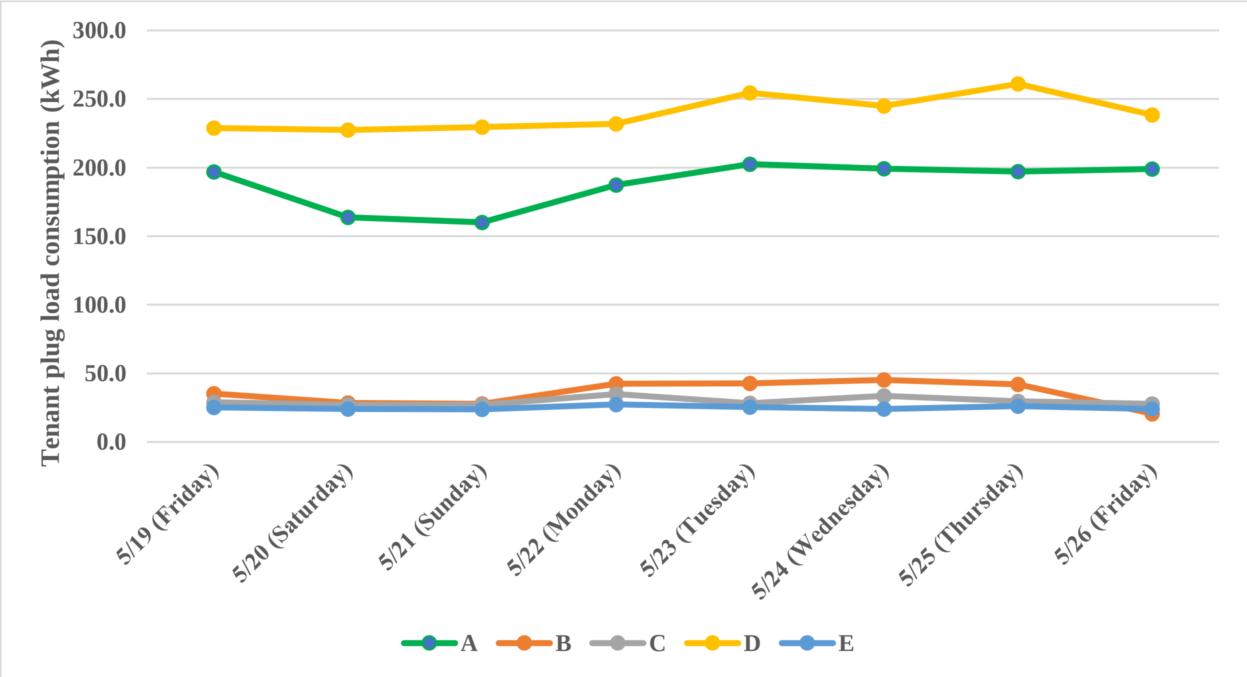

Figure 38: Individual tenant plug loads consumption in week 6

Consistent with the previous graphical representations, similar observations can be made regarding consumption patterns. It is apparent that consumption reaches its lowest point during weekends, and there is a notable increase in consumption on Mondays during weeks 5-6, followed by a gradual decrease towards the end of the week. Both observed weeks demonstrate similar patterns, with tenant A and tenant D emerging as the primary consumers of plug load usage. In contrast, the contribution of the other tenants to the overall electricity consumption remained relatively insignificant during the entire period under observation. Additionally, during the fifth week, the energy consumption of tenant D exhibited a relatively consistent trend throughout the week, with a prominent peak of 258.9 kWh documented on May 17th, which fell on a Wednesday. In contrast, the plug load consumption of tenant A also reached its highest point on Wednesday, totaling 224.5 kWh.

Moreover, during week 6, there was a noticeable rise in energy consumption in comparison to the previous week. This increase was characterized by two clear spikes on Tuesday and Thursday, with recorded values of 254.6 kWh and 261.0 kWh, respectively. Nevertheless, it is important to acknowledge that the plug load usage of tenant A only reached its maximum level on Tuesday, amounting to 202.6 kWh, which is comparatively lower than the peak recorded in the preceding week.

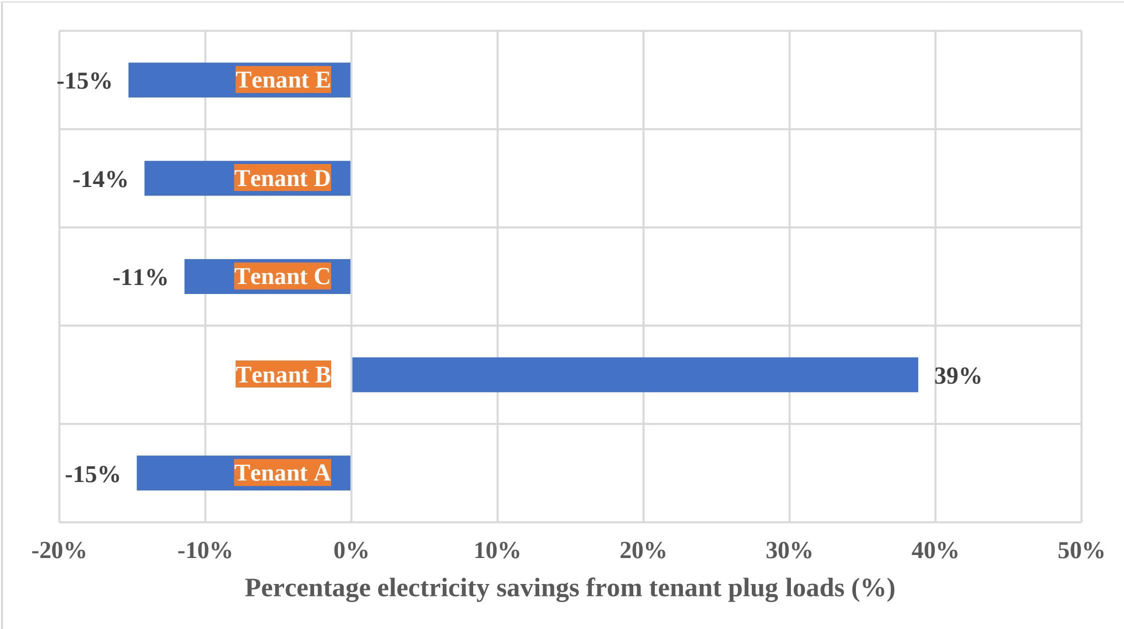

Figure 39: Percentage electricity savings of tenant plug loads for weeks 5-6

The graph in figure 39 provides the proportion of savings obtained from the utilization of tenant plug loads, with a specific focus on the individual tenants within the case study building. A discernible differentiation becomes apparent upon comparing the aforementioned graph with its preceding counterpart, particularly within the time frame of weeks 5-6. Tenant B exhibits a notable increase in electricity conservation, achieving a noteworthy 39% reduction. In contrast, the remaining occupants collectively exhibit an escalation in plug load consumption, resulting in a proportional decline in the percentage of electricity conservation.

Among the tenants who have shown an upward trend in consumption, tenant E and tenant A emerge as the primary contributors, with both exhibiting a decrease of 15%. Following that, tenant D experiences a decrease of -14% in electricity savings, while tenant C demonstrates a reduction of -11%. The examination and analysis of fluctuations in plug load usage and the resulting electricity savings are worthy of comprehensive investigation in order to identify the underlying factors that influence these patterns.

6.5 Tenant Feedback and Recommendations

Table 16 presents a concise overview of the feedback received, along with the recommendations. The purpose of this analysis is twofold: first, to gather insights into the behavioral impact of the information interventions implemented, and second, to understand the underlying reasons for the notable disparities in energy consumption between weeks 3-4 and weeks 5-6.

Feedback	Recommendations
• During weeks 1-3 of May, there were more tenant workers at the office due to project deadlines. • The last weeks of May saw a decrease in worker attendance owing to vacations, with some staff working remotely. • Flat panels were routinely left on during work hours. • Plug load increased due to workplace electric desks.	• Implement frequent nudges to remind tenants of energy-saving activities in their premises. • Displaying nudges on desktop screens instead of emails. • IT staff may monitor desk and screen panels to ensure they are turned off when tenants leave, reducing energy waste. • European type plugs with manual switches allow tenants to conserve energy by turning off loads when not in use. • Use visual reminders during lunch breaks to evaluate tenant attention and promote eco-friendly practices. • Implemented interactive dashboards to visualize tenant performance and promote energy-saving activities. • Tenants might be encouraged to participate in sustainability by offering incentives for meeting emission reduction targets. • Include more indicators to accurately evaluate and measure the impact of offered nudges. • Active tenant participation in intervention distribution can improve engagement and effectiveness of nudges.

Table 16: Tenant feedback and recommendations during the follow-up phase interview

The feedback received from the tenants does not align with the conclusive evidence derived from the data collected throughout the nudging and follow-up phases of the study. Within the specified timeframe interval in May, whereby project deadlines were imposed upon all individuals, the collected data revealed a higher ratio of energy conservation in relation to both lighting and plug load usage during the third and fourth weeks. In contrast, weeks 5-6 demonstrated an opposing pattern, characterized by a decrease in the magnitude of electricity conservation. This statement presents a contradiction to the feedback obtained, as it indicates a decrease in attendance numbers during the final weeks of May compared to the beginning weeks. The decline in attendance is attributed to the increase in individuals taking holidays, as reported by one of the tenant representatives. The lighting technology utilized in the building under examination is based on sensors. It is noteworthy to mention that the observed decline in lighting consumption levels could indicate a matching fall in attendance. On the other hand, there was a discernible increase in consumption. Hence, it is not appropriate to make a direct assumption that the fall in attendance numbers during the latter weeks of May leads to a decrease in electricity usage, as the available data contradicts this notion.

The feedback from the tenant representatives highlights the importance of including extensive evaluation indicators to analyze the effectiveness of green nudges as information interventions to promote pro-environmental behavior. It has been noted that the utilization of email as the sole means of circulating the announcement and behavioral strategy flyers may have limited their exposure and distribution among other individuals residing on the premises. Unfortunately, because of the constraints imposed by confidentiality restrictions, we were unable to directly communicate with the remaining tenants or obtain attendance data during the nudging phase. As a result, our ability to explicitly examine the hypothesis regarding the efficacy of green nudges in promoting pro-environmental behavior among individuals in the green office building was limited.

The main aim of this study, given its constraints, was to get an understanding of behavioral intentions and the underlying determinants that drive individuals to make sustainable changes. The aforementioned findings encapsulate the most extensive and thorough insights that were obtained from the qualitative aspect of the investigation. Nevertheless, it is important to provide precedence to forthcoming research initiatives that focus on integrating attendance data and extending the analysis period. This should be accompanied by regular reminders of interventions to comprehensively evaluate the likelihood of effectively encouraging tenants to decrease their emissions. By obtaining this data, it becomes feasible to build a more precise correlation between the behaviors of tenants, energy consumption patterns, and the impacts of established behavioral interventions, thereby generating conclusive evidence. The integration of attendance data will provide valuable information for the development of future interventions aimed at promoting sustainable behavior. This will provide a deeper understanding of the relationship between nudging tactics and the responses of tenants.

The recommendations proposed by the tenant representatives align with existing research on the concepts of sustainable nudging and their influence on fostering pro-environmental behavior. Previous studies (Nielsen et al., 2017; Zimmermann et al., 2021) have shown that nudges, which involve changing the physical environment through visual cues and performance feedback, can be used to change people's behavior in ways that save energy and reduce waste. Moreover, current research studies highlight the importance of incorporating nudges alongside other behavioral methods to attain more substantial and long-lasting outcomes (DellaValle et al., 2020). The proposal made by the tenants regarding the incorporation of permanent nudges, information technology assessments, and the use of European-style plugs aligns with the notion of utilizing a combination of nudges to reinforce sustainable behaviors, as advocated by Zimmermann et al. (2021).

7. Further Recommendations

The previously discussed sections of this research study provide a basis for understanding the conditions under which interventions need to be carried out. The results obtained in *section 6.2* offer a thorough examination of the operational patterns of the case study building with respect to seasonal fluctuations. The documentation indicates that the utilization of nudges occurs during the fall, winter, and early spring seasons, which correspond to the periods when the building under examination relies on the power grid to meet its excess energy demands. In the context of tenant engagement, it is essential to secure the active participation of all tenants in order to thoroughly evaluate the degree of behavioral change that arises from nudging interventions designed to promote sustainable behavior. Moreover, DellaValle et al. (2020) discussed how using comprehensive evaluation methods can provide useful insights into the effectiveness of nudging strategies and facilitate evidence-based decision-making for future interventions. According to Thaler and Sunstein (2009), effective nudge interventions frequently need active and direct user engagement as they are intentionally crafted to alter behavior. The effectiveness of a nudge technique depends on individuals' degree of awareness towards nudges and their propensity to modify their behaviour accordingly.

1. *Informational feedback and Goal Setting and Progress Tracking.*

The previously discussed strategy involves providing tenants with prompt feedback regarding their energy usage. The execution of energy conservation goals and the ongoing monitoring and dissemination of progress have the capacity to stimulate behavioral changes. The provision of real-time feedback on energy consumption and emission patterns has the potential to incentivize individuals to modify their behaviours, resulting in a reduction in plug load. Based on Darby's (2006) review, the implementation of direct feedback mechanisms, such as sophisticated meters or in-home displays, has the capacity to yield energy savings ranging from 5% to 15%. By offering behavioral strategies to improve energy efficiency and providing users with visual trend lines of their household's energy consumption, savings can be achieved. Additionally, Abrahamse et al. (2007) conducted a study that demonstrated that households that received personalized information about their energy consumption, set energy savings goals, and monitored their progress consistently and continuously achieved a 5.1% greater reduction in energy usage compared to households that did not receive such information.

2. *Competition and Incentivized Rewards.*

Furthermore, the integration of office-wide competitions, which provide incentives to departments that demonstrate the highest reduction in energy consumption, has promise as a motivational strategy to foster tenant engagement in energy conservation efforts. This phenomenon not only fosters a competitive spirit but also amplifies the attractiveness of energy saving through social influence. Costa and Kahn (2013) conducted a study wherein they found that the introduction of a social comparison-based nudge, which entailed providing homes with information regarding their energy consumption in comparison to that of their neighbors, resulted in a decrease of around 2% in energy usage. The introduction of a competitive process led to an observable improvement in energy conservation.

3. *Normative Comparisons.*

Normative comparisons pertain to the act of appraising or evaluating something by utilizing predetermined norms or criteria. These comparisons entail evaluating an individual's energy consumption in contrast to that of their peers. This comparative analysis can act as a catalyst for inspiring individuals to reduce their energy usage in order to comply with the established norm.

Schultz et al. (2007) conducted a study that found that the inclusion of normative comparison information led to a notable decrease in energy overuse. The implementation of this intervention resulted in a reduction in energy consumption by homes, with an average decrease ranging from 6% to 8%. Moreover, a study conducted by Schultz et al. (2007) indicated that treatments focused on disseminating information yield the highest efficacy when they integrate social norm comparisons. The study findings indicate that when individuals are provided with information comparing their energy usage to that of their neighbors, it can serve as an effective incentive for them to reduce their energy consumption.

4. *Visual Cues and Reminders.*

Visual cues and reminders have a substantial impact on facilitating cognitive processes and enhancing the preservation of memory. Visual stimuli, such as colorful stickers, posters, or placards, can be carefully placed near electrical outlets, switches, and other electrical appliances to serve as effective visual prompts, encouraging users to adopt energy-saving practices. Lehman and Geller (2004) propose that cues, like stickers and placards, have the potential to serve as enduring prompts for renters, subtly motivating them to maintain their energy-saving practices.

8. Conclusion

In conclusion, this thesis research addresses the urgent demand for a net-zero carbon future within the building sector by examining the complex interaction among technical improvements, human behavior, and interventions in the pursuit of sustainable outcomes. The study used an explanatory sequential mixed methods approach to assess energy use, carbon emissions, and the efficiency of nudges in promoting pro-environmental behavior, with a particular focus on a zero-carbon building in southern Ontario, Canada.

The examination of energy consumption and carbon emissions trends among tenants revealed the complex interaction among various aspects, including weather conditions, solar panel generation, and electricity usage. The study revealed that weather conditions had a noteworthy influence on tenant behaviors and energy usage patterns, providing vital information for the development of targeted energy conservation programs.

Furthermore, the research also revealed the importance of emission parameters in precisely measuring carbon intensity. The study assessed average emission factors (AEFs) and marginal emission factors (MEFs), finding that MEFs offer a more accurate representation of the actual impact of energy usage on carbon emissions. Moreover, the analysis of real-time feedback systems has revealed their capacity to notably reduce energy usage and address carbon emissions. The previous sections of this study laid the foundation for the intervention circumstances. The quantitative findings presented in this study offer a thorough examination of the operating patterns of the case study building. These results emphasize the implementation of nudges during the fall, winter, and early spring seasons, when there is a significant reliance on the grid. The study examined the effectiveness of behavioral interventions by utilizing biweekly flyers as a means of implementing nudges. While certain tenants demonstrated increased energy use during specified weeks, the study emphasized the necessity of reliable evaluation indicators for accurately assessing the efficacy of green nudges.

This study provides a basis for future research endeavors. The intricacies associated with behavior, the influence of technology, and the potential solutions discovered in this study indicate promising avenues for further investigation. Studies that include a wider range of tenant behaviors, more energy-efficient strategies, and more thorough evaluation frameworks may help us understand the complexities of pro-environmental behavior better.

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