ENERGY EFFICIENCY OPPORTUNITIES FOR LIGHTING SYSTEMS AND MISCELLANEOUS ELECTRICAL LOADS IN COMMERCIAL BUILDINGS – A REVIEW

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ABSTRACT

Lighting and miscellaneous electrical loads (MELs) are important utilities that enhance indoor environmental quality (IEQ), the visual comfort of building occupants and directly affects occupant health and productivity and these utilities consume a significant portion of the total energy in a commercial building, in some cases close to 20% of the total energy consumption can be attributed to lighting and MEL electrical loads. This article aims to review the energy efficiency opportunities for lighting and MELs in office buildings and the current lighting and MELs control strategies that have been used to reduce energy consumption of lighting and MELs, so that the potential for improving energy efficiency for lighting systems and MELs can be identified and implemented. Articles on energy efficiency opportunities and control strategies and frameworks were reviewed. The articles reviewed indicated that there is substantial energy saving potential in the implementation of intelligent control systems.

KEYWORDS: Energy efficiency, lighting systems, MELs, control systems

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INTRODUCTION

Lighting and miscellaneous electrical loads (MELs) are important utilities that enhance indoor environmental quality (IEQ), the visual comfort of building occupants and directly affects occupant health and productivity. In 2012 lighting (one of the subsystems in a building energy system [BES]) United States (US) accounted for 17% of a buildings total electricity consumption, the second highest energy consumer after air conditioning systems[1], [2]. With an increased use of light emitting diodes (LEDs) in commercial buildings, with LEDs making up close to 50% of lighting type in buildings, the electrical energy consumption per meter square has decreased drastically [3]. However, this does not suggest that the energy efficiency targets have been met and we have reached the peak of sustainable buildings.

In 2018 the research carried out by Kwong et al (2018) indicates that the number of electronic devices purchased over the past few years and that correlates to the increase in electrical energy consumption, concluding that MELs have a significant contribution towards energy consumption in commercial buildings [4]. Among the energy consuming system, the energy consumed by electrical appliances falls under the category of MELs (also referred to as plug loads) has been identified by researchers as a significant energy consumer [4]. It has been identified that MELs use 15 – 20% of the total energy consumption in the buildings. A previous study highlighted that MELs, advancing technology and population growth have also contributed to the increase in energy consumption[4]. There is extensive research covering HVAC systems and lighting, however, MELs are often neglected owing to the unpredictable use of these equipment. This has created a niche to identify current MEL

trends and future developments. For this research article, MELs will refer to all office equipment and plug loads.

There is room for improvement of energy efficiency in lighting and MELs within the research field and much of the potential to improve energy consumption of lighting and MELs can be found in intelligent control systems for commercial buildings. This article aims to review the energy efficiency opportunities for lighting and MELs in office buildings and the current lighting and MELs control strategies that have been used to reduce energy consumption of lighting and MELs, so that the potential for improving energy efficiency for lighting systems and MELs can be identified and implemented.

This article is structured such that energy efficiency opportunities for lighting and MELs in commercial buildings will be reviewed, the outcome will provide feedback on the popular energy efficiency measure for lighting and MELs. Thereafter, trending control strategies will be reviewed to determine the best energy efficiency opportunity for lighting and MELs.

Energy Efficiency Opportunities for Lighting and Mels in Commercial Buildings

Lighting Energy Efficiency Opportunities

The three main strategies towards energy efficient and sustainable buildings are retrofitting existing luminaires with energy efficient luminaires, such as LEDs, reducing design illumination levels and implementing control systems [1]. A well-designed lighting system can save energy and provide visual comfort for building occupants.

Part of the review carried out by Dubois et al (2015) compared retrofits of existing standard fluorescent lighting (T12) with T8 magnetic and electronic ballasts and T5 electronic ballasts found that the T8 lamps can replace the T12 without any modification to the fixture while the use of T5 lamps require electronic ballasts that can reach a lamp luminous efficacy superior to 100 lm/W [5]. The review indicates that the T5 electronic ballast saves 40% more energy than a T12 and the T8 electronic ballast saves 17% energy when compared to the T12 [5]. According to the review, LEDs have a high energy saving potential, however they indicated drawbacks such as flickering of the light, low illuminance levels and poor beam distribution [5]. Another research article by Chiradeja et al (2015) indicated that a T5 tube with electronic ballast uses less energy than the T8 lamps and the harmonics in the T5 electronic ballast lamp can be reduced by using a passive low-pass filter [6]. In 2013, Asif ul Haq carried out an investigation to determine the energy savings, among other findings, of a project to replace all existing T8 lamps with more efficient T5 lamps in the Universiti Teknologi Malaysia (UTM) [7]. An Average of 8.5% energy savings was achieved from the three buildings blocks analysed [7]. In 2013, Fabrico et al, simulated general lighting retrofit, comparing LEDs, compact fluorescent lamps (CFL) and fluorescent tubulars, which demonstrated that CFLs have the highest annual cost and toxic waste disposal, fluorescent tubulars are a more economical alternative, however, if their lifespan shortens, LED prices drop and achieve a higher energy efficiency, thus making LEDs a more sustainable and economically attractive alternative [8]. In 2013, Gan et al, examines the feasibility of replacing conventional fluorescent lamps with LEDs, it was concluded that LED luminaires have the potential to replace fluorescent lamps, however, LEDs have certain inherent characteristics such as poor total harmonic distortion performance and the quality of illumination [9]. However, with advancing technology, LEDs have developed to overcome their shortfalls, thus currently comprising of 90% of all lighting systems according to [2].

LEDs are a prominent energy efficient lamp with a relatively high photometric performance, and it is simple to control. In 2007, Enkivist et al, carried out a study that indicated investment in energy efficient lighting is one of the most cost effective methods for improving energy efficiency in buildings [10]. Ahn et al examined energy use in commercial

buildings by evaluating lighting energy saving approaches and the effect of using a dimmer control [11]. The study concluded the energy consumption of the reference commercial building was reduced by 20.9% by replacing the linear fluorescent lights (LFL) with LEDs [11]. Currently the use of LEDs has gained moment and has replaced close to 50% of all lighting in buildings. In 2017 Montoya et al carried out a study to analyse the evolution and milestones of indoor lighting [12]. Using research, one of the primary conclusions indicate that the different techniques used in indoor lighting followed three paths simultaneously i.e. better photometrical performance, better energy efficiency and better performance of the installation users [12]. The demand for compact fluorescent lamp (CFL) and LEDs is growing in popularity due to the reduction in energy consumption and its sustainability, now being used in street lamps and robots [12]. However, the high level of performance in LED lighting has not prevented further research in the field of lighting, new and more versatile light sources are being explored, like the Organic Light Emitting Diodes (OLED) [12].

Daylighting is a suitable energy efficient means of reducing illumination levels of a space. The use of daylighting combined with controlled artificial lights substantially increases energy savings. However, daylighting is very dependant on the daylight zones, where certain zones must be controlled independently [13]. The orientation of the building and the design of the building ultimately determines zones with high and low levels of daylighting, standards and buildings codes define these zones accordingly. Lighting design and the daylight harvesting techniques adopted play an important role in determining the number of luminaires (and the lux levels) to be used in the zone, this ultimately governs the the energy savings to be achieved[13]. A study carried out by Mantzourani et al aims to investigate the influence that daylight zones have on energy efficiency in five office spaces [13]. The three different definitions used to estimate the daylight zones are a) EN 15193.1 as implemented in Greek regulation of Energy Efficiency in Buildings, b) CEN Technical Committee 169/WG11 Daylight, and finally c) using dynamic daylight metrics for typical working hours for all four cardinal orientations [13]. It was found that the definitions for daylight zones, yielded different results per space and obviously each daylight zone yielded energy savings according to the amount of natural light the space captured[13]. The energy efficiency results yielded from the investigation are dependant on the method of calculation of daylight zone depth used, the results vary from 61-89%, 53-72% and 69-91% [13].

Ubiquitous control systems are finding a way to make systems smarter and now more intelligent to enhance human life and, in this case, improve energy efficiency. Research by [14] suggest that the average obtainable savings from daylighting in actual buildings simulations are overestimated by a minimum of 10% [14]. The meta-analysis carried out goes onto show that individual control strategies save between 25-30% of the lighting energy used and multiple control strategies can save up to 40% of energy [14]. Lighting systems can be controlled in various ways, at the user level, there is the simple on and off switch and dimming regulators that provide users with the option of controlling the brightness [1]. More advanced electronic switches can be programmed to operate in ways such as toggling or changing light intensity in steps [1]. More flexibility in lighting control is provided with building automation, the user can control lighting from their smart phones or their pc. Lately, lighting is being controlled over the internet using smart apps and the control of lighting is inclined towards artificial intelligence control. From the review carried out by [1] control systems can provide significant energy savings and result in energy cost savings [1]. Bunjongjit et al (2020) proposed a control circuit for LEDs based on the amount of daylight[15]. The desired illuminance in a work place was achieved using natural daylight and artificial light[15]. The test results showed that the LED control circuit reduced power consumption of the lighting system whilst maintaining the desired illuminance levels [15].

Miscellaneous Electrical Loads Energy Efficiency Opportunities

MELs are often defined as all electrical loads that do not fall under conventional end uses such as lighting, Heating, ventilation and air-conditioning and refrigeration (HVACR), therefore MEL will often be office equipment, plug loads and ICT equipment[16]. In the research carried out by [17], MELs get referred to as the diverse electric loads emanating from electronic devices not responsible for HVAC or lighting [17]. The number of MELs have been increasing due to the number of electronic equipment, however, the main loads in commercial buildings are becoming more efficient, therefore resulting in MELs accounting for a larger percentage of the buildings electrical load [16]. According to the literature survey carried out by Kamilaris et al in 2014, MELs account for more than 20% [18]. Another study by Syed and Hachem carried out a simulation study of greenhouse retail complex and found that MELs account for 23% of the buildings total energy consumption [19]. The total annual energy consumption for key MELs in commercial office buildings is given in Figure 1. The annual unit consumption for personal computers (PCs) is equivalent to 450 kWh, the highest energy consumer in commercial office buildings[16]. In the research by McKenney et al. the energy consumption is further broken down for PC equipment as shown in Figure 1[16].

Figure 1: Estimate Power Consumption for PCs [16]

Figure 2: Annual energy consumption for key MELs in commercial buildings [16]

Depending on the use of the office commercial building, the size and occupancy, key MELs will vary. However, McKenney et al (2010) provides a breakdown of other office MELs with printers consuming more than 50% of the energy consumption as shown in Figure 2. The high energy consumption of printers is attributed to the high installed base load and the relatively high average power draw on standby mode of up to 70% [16]. Laser printers account for 75% of energy consumed by printers with the remaining consumption being inkjet and impact printers [16]. The next highest energy consumer, servers, consume about 16% with copiers consuming 15% of total MELs energy consumption. The energy consumption of multi-function devices (MFDs), faxes and scanners are negligible.

Energy consumed by MELs can be reduced through various control strategies, industry standard specifications and power management (PM). Under industry standard specifications called Advanced Configuration and Power Interface (ACPI), operating systems provide interfaces for users to configure the conditions under which their PCs go into low power mode or switch off [16]. PM reduces the energy consumption of PCs by controlling the operating voltage and/or clock frequency in response to computational loads obtained from the operating system [16]. Currently most PCs are purchased with factory enabled PM, however the settings are user defined which makes it, dependant on the whether the user enables power saving mode or not.

Energy star is a program used to promote energy efficiency by providing the energy consumption of appliances and electrical/electronic devices using different standardised methods. Energy star also provides an energy rating depending on the amount of energy consumed, enabling building managers and building owners to know how much of energy is consumed by all the equipment and the level of energy efficiency of the device. Energy star performance criteria for most IT and office equipment have focused primarily on having equipment enter low-power mode and capping power draw values for different equipment types in low power mode [16]. Network software can facilitate and provide a means to centralize PM across a range of equipment connected to the network [16]. Another method for reducing energy consumption is maintaining fuser rolls at a high temperature could reduce energy consumption by 50% in laser printers and copiers [16]. Advances in fuser systems with a lower melting temperature can contribute to energy savings in laser printers and copiers during stand-by mode [16]. Another method that significantly saves energy is automating device shut down or

low power mode based on the PCs activity[16].

Energy reductions can be broadly categorised by software and hardware-based [18]. PM and virtualization, are common software based techniques which claim significant energy savings of up to 60% [18]. Current PM and virtualisations products are reliable and efficient, offering advanced features and significant savings [18]. Hardware-based savings involve physical equipment such as smart plugs and SPS for controlling IT devices and indicate substantial energy savings[18]. Replacing hardware with more energy efficient equipment can be effective and result in 40-60% energy savings [18]. According to [18] savings resulting from hardware need to be quantified to allow for the calculation of ROI when considering these options [18].

Reviewing Control Strategies and Frameworks

The popularity of smart sensors and building management system, building operations have become more information intensive and a large amount of data is recorded to provide a basis for the building performance. Part of the building data can incorporate energy consumption data and thus be monitored and controlled electronically. There are various control strategies that could be implemented for lighting and MELs. With the progress of artificial intelligence, most of these control strategies are leaning towards intelligent control systems.

Lighting Control

The integration of sensor technologies, advanced architecture and intelligent control techniques have provided a perfect situation for implementing intelligent lighting control systems to reduce energy consumption. An intelligent lighting control system is capable of enhancing the visual comfort of occupants whilst reducing energy consumption [1]. The lighting control system can be broadly categorised into three main techniques, controller-based control, optimization-based control and a hybrid system [1].

The paper by [1] presents current state of the art interior lighting system control techniques for commercial buildings with a focus on sensing technologies, objective functions and constraints, techniques, tools and energy performance[1]. The outcome from the analysis indicated that the optimization-based control technique is widely used, as it achieves a greater energy savings whilst satisfying visual comfort of occupants and simultaneously solving multi-objective problems [1].

Studies have presented that energy efficient smart LED lighting systems provide better visual comfort working environment and are more energy efficient when compared to conventional lighting systems. An article by [15] proposes a control circuit for LED luminaires based on the amount of daylight, using natural light and artificial light to maintain the desired illuminance of the space [15]. A light sensor was used to determine the illuminance of the space and compared it with the desired value set on the microcontroller, thereafter sending a control Pulse Width Modulation (PWM) signal to the LED driver, thus regulating the light intensity of the LED as represented by Figure 3[15]. The results from the field test showed that the LED control circuit was able to reduce power consumption by maintaining the illuminance level of the work space [15]. The results from both, the simulation and the experimental, showed that the maintaining the desired illuminance level in the space by controlling the lighting can improve energy efficiency [15].

Figure 3: Daylight CONTROL CIRCUIT for LED Luminaire Strategy [15]

Daylighting systems can regulate the light intensities using smart sensor communication technologies to meet the required illuminance levels of the space. Without compromising occupant visual comfort, [20] implemented a smart LED lighting system using different energy efficient techniques with the aim of reducing energy consumption by 60-70% [20]. ZigBee and Wi-Fi communication protocol was used to control the lights according to the natural light lux levels to provide satisfactory visual comfort for the occupants [20]. The results indicated that the implemented control system was able to provide the recommended lux levels between 300 to 750 lux [20].

Figure 4: Personalized Visual Comfort WSN Framework [20]

MELs Control

Understanding the MELs energy consumption patterns is important to optimize the operation of all MELs and to manage

and forecast building energy consumption. Occupant behaviour is closely related to energy consumption of MELs, making it difficult to predict the energy consumption of MELs. However, recent research has found a niche for understanding, monitoring, and evaluating the relationship between occupant behaviour and energy consumption in buildings.

Energy consumption in office buildings largely depends on occupant behaviour and managing these behaviours could improve energy efficiency [21]. [21] proposes an occupant-level energy usage approach which uses data from the internet of things (IoT) to provide information on occupant energy use behaviour of workstations and shared appliances [21]. An energy behaviour index which quantitatively compares individual occupants energy consuming data to identify high energy consumers and inefficient behaviour [21]. The proposed approach used the comprehensive occupant-level energy-usage (COLE) framework to provide personalized energy use behaviour [21]. Figure 5 demonstrates the COLE framework used, where the occupants first entry and last departure events in working schedule is detected, the building load data is then correlated with this information lastly the correlated load data is normalised to identify personalised energy usage [21]. The experiment conducted in an office building demonstrated the feasibility of the proposed approach to classify occupants in different energy usage categories [21].

Figure 5: Comprehensive Occupant Level Energy Usage Framework [21]

An analysis on using a deep learning method to predict MEL energy consumption was carried out by [17]. The data set was made up of the energy consumption of each occupants MEL and the associated device utilization, which was used to develop the baseline long-short term memory (LSTM) model for MEL energy consumption predictions over a short period of time [17]. The results from the baseline model was compared with two other deep learning models, Bi-Directional Short Term Memory (Bi-LSTM) and Gated Recurrent Units (GRU), which showed that the Bi-LSTM and GRU were better than the baseline LSTM model [17].

Monitoring the changes of the operational states of MELs over time is important in analysing the dynamics of operations in smart buildings, this data can then be used for various energy management applications, inferring the occupant behaviour and energy usage patterns [22]. [22] proposed a self-configuring event detection framework for detecting changes in operational appliances [22]. The contextual characteristics from the environment are learnt autonomously by the framework, thereafter adapting to the event detection parameters [22]. Figure 6 illustrates the components and the process of the framework there are 2 essential steps to the framework, 1) the self-training stage for motif processing and 2) the proximity-based event detection [22]. The results indicate that the proposed event detection framework outperforms the conventional event detection in detecting the operational states of different classes of load across different environments [22]. The proposed framework has the potential to facilitate human-building interactions in training smart home applications [22]. Considering the potential that the self-configuring detection framework has in monitoring operational changes of appliances and adapts to the environment's parameters, it could potentially be used to monitor energy usage of MELs and occupant behaviour associated with the energy consumption of MELs.

Figure 6: The Framework for the Motif-Based Event Detection [22]

Discussion

Energy efficient lighting opportunities and trending control strategies to reduce energy consumption was reviewed to identify the potential for improving energy efficiency for lighting systems and MELs.

Energy Efficiency Opportunities

According to research, the 3 main techniques for reducing energy consumption of lighting systems is by retrofitting conventional lighting with more energy efficient lighting systems, design lighting systems with a low illuminance level and the use of a lighting control system that controls the lux levels in the space. The use of LEDs in lighting systems is more prominent than other types of lights due to the ability to control LEDs and LEDs are more energy efficient than other types of lights. Another plausible energy efficiency opportunity is daylighting which has proven to reduce the energy consumption of lighting systems. The amount of energy saved with daylighting depends on the type of daylighting system implemented. A control system for lighting is becoming more common as smart homes and offices take over, lighting control systems have proven to reduce energy consumption drastically and with advancing technology, lighting control systems are developing to a greater level of accuracy and energy savings.

The research articles reviewed indicated that the three ways of reducing energy consumption of MELs is through using software and energy efficient hardware and the third method is occupant behaviour. the use of energy efficient hardware and software that promotes energy efficiency have been proven to contribute to the reduction in energy consumption. However, the unpredictable nature of building occupants has made it difficult for researchers to identify suitable means of reducing energy consumption related to occupant behaviour. however, this challenge has opened a new avenue in the field of artificial intelligence (AI).

Reviewing Control Strategies and Frameworks

There are various control strategies and frameworks that have been researched to reduce energy consumption in lighting systems and for MELs in commercial buildings. Control strategies and frameworks can be broken in two categories, 1) smart systems and 2) intelligent systems. Smart systems are often used in cases where the control system is programmed to perform a certain task without human intervention whereas intelligent systems are designed to learn occupant behaviour and adjust the system accordingly. Energy efficient of lighting systems can be improved significantly by implementing a type of lighting and/or MEL control system in the commercial buildings. The control system must ensure that the desired lux levels are maintained to ensure visual comfort. The optimization-based control system has been confirmed to achieve greater energy savings whilst maintaining visual comfort. The other control system, a form of daylighting, controls the LED lux levels based on the amount of natural light in the space has also proven to improve energy efficiency of the lighting system.

The energy consumption of MELs is closely related to occupant behaviour which is relatively unpredictable. However, research has presented opportunities to monitor and predict occupant behaviour thus evaluating the relationship between MEL energy consumption and individual occupant behaviour. Using the IoT as a tool to monitor occupant behaviour can be used to evaluate the amount of energy consumed based on occupant dynamics. Deep learning methods and a self-configuring event detection control system, both have the potential to improve energy consumption of MELs.

CONCLUSIONS

Energy efficiency of lighting systems and MELs in commercial buildings have the potential to be improved and the methods discussed have indicated energy savings. The implementation of a control system to monitor, predict and adjust electrical energy consumption according to occupant needs has a great potential to increase energy savings. Therefore, intelligent control systems are gaining more attraction in the field of research. To improve on energy consumption of lighting and MELs, it is important that future research looks at an intelligent control system that encompasses lighting systems and MELs.

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