A Commercial Building Lighting Demand-Side Management through Passive Solar Design

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Abstract. The commercial sector that comprises of schools, libraries, public and private offices is the third largest energy-consuming sector in South Africa. Lighting is a significant contributor to the overall energy consumption in this sector. The aim of this study is to analyse the indoor daylight illuminance of a passive solar office building and the potential demand-side management. A passive solar building in SolarWatt Park, Alice, South Africa was used as a case study. The indoor illuminance that includes electric and daylightings were monitored by two sets of Li-210R photometric sensors. Four cool white fluorescent fittings with each containing two 58W lamps served as the electric lights of the office inner space. The average illuminance of the office space with all electric lights on and without daylight was found to be 460 lux. The indoor average daylighting illuminance was 910 and 170 lux on a typical clear sky and overcast days, respectively. A daily cumulative energy savings of 11.14 kWh on a clear sky day and 0.47 kWh on an overcast day was achieved, assuming the office inner space illuminance was maintained at 300 lux. The monetary savings due to the energy saved was estimated at 1285.36 USD per annum. Based on the findings of the study, daylighting through passive solar design reduces energy consumption without compromising the visual comfort of the occupants. Integration of passive solar design for daylighting with indoor daylight switch controller is recommended for optimum energy savings.

1. Introduction

Globally the building sector consumes over 30% of the total final energy, having increased by more than 35% since 1990. The building sector is also responsible for 30% of greenhouse gas (GHG) emission. Also, it accounts for half of the world electricity demand, with some region electricity consumption increased by 500% [1]. Lighting is among the primary energy consumers in commercial buildings, responsible for 27 to 40% [2]. However, building design has revolutionised to reduce the energy consumption in buildings and mitigate the resultant GHG emission. Morden buildings are designed to harness solar energy to enhance indoor visual conditions [3], this concept is known as passive solar design.

Building design illuminance standards and guidelines have been introduced in many countries to enhance energy efficiency at the same time, promote occupant visual comfort and safety. Thus, the design light level of buildings considers the dominant age of occupants, primary activities, speed, and level of accuracy of the task [4]. The European EN 12464-1 standard, IESNA in the United States, and
CIBSE in the United Kingdom requires a minimum of 300 to 500 lux in office space [5]. The South African Department of Labour [6], find 300 lux favourable for general office work.

The daylighting performance of a building is commonly evaluated using; Daylight Factor (DF), Daylighting Autonomy (DA), and Useful Daylight Illuminance (UDI) metrics. DF is the ratio of internal illuminance to external horizontal illuminance under CIE overcast sky condition [7]. DA is defined as the percentage of annual daytime (occupied) hours that a given point (work plane) is within a specified minimum daylight illuminance level. Nationally recommended standards for specific visual task are often used as DA illuminance threshold; since most standards are based on minimum illuminance [8]. UDI is defined as the percentage of annual occupied time that a given work plane is within a specified range of daylight illuminance, and the daylight illuminance ranges from 100 to 2000 lux [9]. Daylight below 100 lux is considered inadequate and requires electric lighting for visual comfort, between 100 and 500 lux produce adequate light level but can be supplemented by electric lighting, while 500 to 2000 lux is desirable, tolerable and can result in discomfort with direct sun rays present [10]. Also, the amount of light on a surface area or work plane which is quantified by illuminance is another method used to evaluate daylighting of a building [11]. Illuminance is used to define buildings design illuminance standards and guidelines since it is independent of the light source. Daylight illuminance can be considered as a direct and purest approach in evaluating the daylight in a building while the abovementioned daylight metrics are indirect and calculation-based approach [12].

Lighting power density (LPD) is a tool commonly used in estimating the potential lighting energy savings in buildings and is expressed as the installed wattage of lighting per square meter floor area. A reduced LPD which correspond to lower energy consumption can be achieved by energy-efficient light retrofit, daylight switch control, occupancy sensor control, and task light control [13]. Gene-harn et al. [14] adopted a similar concept to evaluate the potential energy saving in daylight assisted office space in Malaysia. They equipped the office electronic light fittings with a daylight sensor of 250 lux set point to control the intensity of electric lights at a depth of 4 m from the office perimeter. Their findings indicate that 78 % lighting energy savings by introducing daylight assist with task light controller. LPD of the office space was reduced to 3.04 W/m² from the recommended 4.48 W/m².

A more direct approach was used to estimate the potential lighting energy savings in this study. In this approach, it was assumed that all electric lights are switched off by a daylight switch controller (DSC) pre-set at 300 lux, and switch on with the indoor daylight illuminance lesser than 300 lux. The consumable electric light energy during daylighting (≥ 300 lux) period serves as the potential daylight energy savings. The aim of this study is to evaluate the daylight performance of a passive solar office building and the potential demand-side management. In the context of this study, demand-side management is the reduction of consumer’s lighting energy consumption and equivalent energy expenditure. Based on the targeted output and adopted approach in the study, illuminance was found suitable to evaluate the lighting performance of the building; since illuminance provides values that are a direct comparison with building design illuminance recommendation.

2. Description of the building and location
A passive solar building in the SolarWatt Park at the University of Fort Hare, Alice campus was used as a case study. Alice is located in latitude 32.8° south and longitude 26.8° east at an altitude of 540 m in the Eastern Cape of South Africa. The local climatic is characterised by an average dry bulb temperature of 29.0°C in summer and 15.0°C in winter. The average solar radiation experienced in summer is 606.06 W/m² and 346.17 W/m² in winter [15]. A photo of the passive solar building and space layout is shown in Fig. 1.

The building is orientated approximately 15° east of north with a total floor area of 137.60 m². The space layout of the building is made up of a conference room at the east wing, office space and indoor solar simulator laboratory occupies the west wing. The conference room and office space stretch from the north to the south elevation of the building.
The two-sash glass sliding north facing door in the conference room admit the low angle sun’s rays to the north floor area, as well as the three-sash glass folding-door in the office space. Likewise, the clerestory windows are used to channel solar radiation to the southern floor area of the conference room and office space. The design was targeted to achieve maximum daylight harvest and passive thermal regulation of the inner space of the building [16]. The findings and discussions of the study going forward will be limited to the office space.

3. Methodology

3.1. Indoor illuminance measurement
The illuminance level of the office space was measured by two sets of LI-210R cosine correction photometric sensors. The sensitivity of the sensor is 30 µA per 100 klux and a response time of <1 µs [17]. The illuminance level of the office space as perceived by an occupant on a work plane (desk) was the target of the measurement; since the light level perceived by the occupant working at the desk will usually determine the use of electric lighting. To this effect, one photometric sensor each was placed on the left (east side) and right (west side) desk array, as shown in Fig. 2.

The sensors were located in an open space, free of light rays obstacle to avoid shading. Also, the occupants were requested not to tamper with the sensor and obstruct light rays around the measurement area.

3.2. Demand-side management estimation
The switching off of all electric lights in periods were the indoor daylight illuminance is greater or equal to 300 lux by an automated daylight switch controller (DSC) is the lighting energy savings
strategy adopted in this study. Therefore, the baseline \( B_{\text{lit}} \) is the lighting energy consumption without the use of DSC, which can be obtained by:

\[
B_{\text{lit}} = \omega_{\text{lit}} t_{\text{op}}
\]

(1)

where \( \omega_{\text{lit}} \) is the total installed electric lights wattage (W) and \( t_{\text{op}} \) is operation hours (h) of the lights. The lighting energy consumption during the use of DSC is denoted as \( D_{\text{lit}} \) and can be estimated by

\[
D_{\text{lit}} = \omega_{\text{lit}} t_{\text{op}}
\]

(2)

Combining eq. (1) and (2), the energy saved (kWh) due to the utilisation of daylight in the office space is given by

\[
\gamma_{\text{lit}} = \frac{B_{\text{lit}} - D_{\text{lit}}}{1000}
\]

(3)

Furthermore, the economic impact or benefit \( f \) due to the lighting energy consumption or savings, respectively can be determined using:

\[
f = \left( \frac{B_{\text{lit}} - D_{\text{lit}}}{1000} \right) \theta_{\text{e}}
\]

(4)

where \( \theta_{\text{e}} \) is the energy charge per unit (c/kWh). Energy charges in South Africa depend on the tariff structure that a consumer is operating under. Consumer tariff structures in South Africa include; Urban, Residential and Rural tariff. Urban tariff structure that is designated for commercial consumers is subdivided into MegaFlex, MiniFlex, Business rate, and public lighting. The University in which the passive solar building is located is operating under the MegaFlex tariff structure [18].

4. Results and discussions

4.1. Daylight and electric light illuminance

The indoor illuminance, which comprises electric and natural daylight, was monitored from April to May 2017. As stated earlier, the illuminance measurement focuses on the light perceived by an occupant at the left (east side) and right (west side) desk arrays in the office space. The average illuminance measured at both desk arrays is, therefore, the office space (indoor) illuminance. The indoor and both desk arrays illuminance are given in Fig. 3.
In Fig. 3, the indoor illuminance distribution of the office space can be categorised into; region (a) period with all lights switched on and region (b) period with all lights switched off. The average indoor illuminance without daylight (absence of the sun) in region (a) was 460 lux and 31 lux in region (b). The observed illuminance in region (a) without daylight is the illuminance of the electric light fittings in the office space. Ambient lights such as street and moonlights resulted in the illuminance observed in region (b). In the presence of the sun (07h00 to 17h00), 460 lux was deducted from the illuminance in region (a) to obtain the average daylight illuminance of 850 lux for the entire period. A combination of daylight and electrical lights are used the most (see Fig. 3) in the office, during such period the average illuminance of the office space was found to be 1300 lux. Also from Fig. 3, 4th and 12th of May were considered as overcast days, while the other days represent clear sky days. The sky conditions classification was based on the distribution pattern and magnitude of the illuminance in the assumed days. Hence, typical clear sky and overcast days illuminance of the office space is presented in Fig. 4.

![Figure 4. Average indoor illuminance on typical clear sky and overcast days.](image)

In Fig. 4, daylight illuminance, either with all lights switched off or on (combined), occurs between 07h00 and 17h00 in both days. In support of the sky formation assumption, a fairly regular daylight illuminance distribution with an average of 910 lux and a combined illuminance of 1360 lux was observed on a typical clear sky day. Overcast sky resulted in an irregular daylight illuminance with an average of 170 lux, and 620 lux with all lights switched on.

According to the South African Department of Labour [6], clear sky produces more than the recommended amount of light for general office work. The daylight observed in the office space on a typical overcast day was approximately half of the recommended illuminance for office activities. Based on the UDI bin classification by Chi et al. [10], the amount of daylight observed in the office space on a clear sky day is favourable without supplementary electric lighting. However, it could also result in visual discomfort in the presence of direct sunlight. Although the indoor daylight in the overcast day is adequate, additional electric lighting is required to achieve visual comfort.

4.2. Light demand-side management

4.2.1. Lighting energy consumption and savings. During the period of this study, the office space was a workplace for postgraduate students conducting research activities at the premises. Their operation hours were observed to be between 08h00 and 16h30 on weekdays, while some students occasionally visit the facility on weekends. However, the electric lights inside and outside the facility were all switched on during and outside office hours due to security reasons. Four sets of cool white fluorescent fittings were used to illuminate the office space, with each fitting consist of two 58 W lamps. Assuming that the office space is equipped with a DSC, which maintains the indoor illuminance within the South
African office task light recommended level. In other words, the controller switches off all electric lights when the indoor illuminance is \( \geq 300 \) lux and on when it is below. Based on the above assumption, and ignoring power factor and reactive energy of the lighting fittings, Fig. 5 present simulated lighting energy profile of the office space on a typical clear sky and overcast days.

Figure 5. Typical clear sky and overcast days lighting demand and energy profile of the office space

Total wattage of 0.46 kW was used in generating the lighting energy profile in Fig. 5. The resultant daily baseline cumulative energy consumption was 11.14 kWh. On a clear sky day, the daily cumulative lighting energy of the office space was reduced by 35 %, amounting to 3.94 kWh daily energy savings. A relatively lower energy saving was achieved on an overcast day, with the DSC switching off the electric light for only an hour. Moreover, 4 % energy savings was achieved, reducing the cumulative daily energy by 0.46 kWh.

4.2.2. Economic impact and benefits. In any given tariff structure, energy charges vary with transmission zone, supply voltage, demand season and time of use (TOU). Transmission zone refers to the cost associated with the delivery and transmission of energy from the substation to consumer’s premises. It is expressed in distance and ranges from \( \leq 300 \) km to > 900 km. Voltage is typically supplied between < 500V and 133kV. Demand season relates to the influence of the season on the rate of energy consumption and generation in a year. It is divided into low-demand season that covers summer (1 September to 31 May) energy consumption and winter (1 June to 31 August) energy consumption is classified as high-demand season. TOU is the daily time-based classification of energy consumption, and it includes peak, standard, and off-peak period. Peak period refers to high-energy demand period, which is sub-divided into morning peak (07h00 to 09h30) and evening peak (18h00 to 19h30). Standard and off-peak periods address mid- and low-energy demand period, respectively. Standard period consists of morning standard (06h00 to 06h30), midday standard (10h00 to 17h00), and evening standard (20h00 to 21h30), while between 00h00 and 05h30 is morning off-peak and 22h00 and 23h30 is evening off-peak [18]. The University energy charge (MegaFlex) tariff structure is presented in Tab. 1 having taken the above energy charge influencing factors into consideration.

Table 1. The University energy charge tariff structure.

| Transmission zone (km) | Supply voltage | Energy charge (c/kWh) |
|------------------------|----------------|----------------------|
|                        |                | High demand season    | Low demand season |
|                        |                | Peak                 | Standard          | Off-peak          | Peak                 | Standard          | Off-peak          |
| \( \leq 300 \)        | \(< 500V\)     | 23.65                | 7.20               | 3.93              | 7.75                | 5.34               | 3.41              |

Source: Eskom Tariffs & Charges 2018/2019
In Tab. 1, ≤ 300 km transmission zone was used, given that the nearest substation is lesser than 60 km from the University premises, and the supply voltage is less than 500 V. Also, the University is a direct customer of the national utility company. All TOU period were taken into consideration since the lights in the passive solar building were switch on all through the day. The energy charges are given in US Dollar (USD) with 1.00 USD equivalents to 14.24 Rand (ZAR), and 15 % VAT rate were included. Using eq. (4), Fig. 5 and Tab. 1, the daily cumulative lighting energy expenditure of the office space is given in Fig. 6.

Figure 6. Clear sky and overcast daily cumulative energy expenditure of the office space.

In clear sky and overcast days, the daily cumulative electric lighting energy expenditure was 27.53 USD in high demand season and 14.84 USD in low demand season. DSC intervention reduces the daily energy expenditure by approximately 35 % and 5 % on a typical clear sky and overcast days, respectively in both seasons. Seasonal monetary savings amounted to 853.41 USD on a clear sky day and 109.00 USD on an overcast day during high demand season. Saving obtained during low demand season were 1421.04 and 187.28 USD on a clear sky and overcast days, respectively. Realistically, clear and overcast skies condition randomly occur in any given month or season during the year. Hence, isolating the DSC savings considering both skies condition is not a straightforward process practically. In the content of this study, clear sky could be viewed as a best-case-scenario, while overcast day as a worst-case-scenario. In this regard, the sum of the average clear skies and overcast days monetary savings in high and low demand seasons give a more realistic estimate of the annual DSC economic savings, which is 1285.36 USD.

5. Conclusion
This study aims to evaluate the daylighting of a passive solar building and the potential demand-side management. Hence, the indoor illuminance that includes electric lighting and daylighting was measured over a month period. The measurements and findings of the study were limited to the office space of the building.

The four sets of 58 W cool white fluorescent lamp used to lit the 33.51 m² office floor area was found to have an average illuminance of 460 lux. An average daylighting of 850 lux with all electric lights off was also observed over the entire measurement period. Moreover, the daylight illuminance was divided into clear sky and overcast illuminance. On a typical clear sky day, the average daylight illuminance of the office space was 910 lux, while an average of 170 lux was observed on an overcast day. The use of DSC to maintain the office space illuminance within 300 lux, amounted in a daily cumulative energy savings of 3.72 kWh on a clear sky day and 0.47 kWh on a typical overcast day. The resultant monetary saving was estimated at 1285.56 USD per annum. Installation of DSC to regulate the electric light fittings based on the indoor illuminance of the targeted space is recommended for optimum demand-side management.
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