Energy Optimization Using Daylight In Lecture Theatres

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***Abstract*—This research evaluates effectives of daylight contributions in the lighting design of selected lecture theatres in Federal university of Technology, Akure, (FUTA) Nigeria and its cost implications. Measured data were collected using measuring tape for dimension of the buildings and TES 1332A digital lux meters for daylight lux level contributions in the buildings under different time of the day (8:00 am to 6:00pm) using room index method to determine the number of measuring points. The Daylight Factor (DLF) was determined from window area, building area, materials reflectance and orientation of the building. Five years' solar radiations data were obtained from Nigerian Meteorological Agency. Using existing algorithm, average daylight contribution was computed from the data. The DLF and correlation statistics were evaluated and analyzed for the measured and computed daylight contributions. The results show that 3-in-1-A building do not requires artificial lighting during the day at all; FBN needs artificial lighting in the evening; and 1000 capacity needs artificial lighting in the morning and evening. Daylight incorporation in this work saves 21.6 % to 100% of energy. The cost of daylight contribution in the three buildings is largely significant, 1.5 million per year, and 47.1 million naira for 30 years amounting to 51.4% of the expected lighting charges for a year and 30 years in this work respectively. A proposed model with effective control is established in this work. This saves substantial cost of energy. The proposed model should therefore be used in lighting design for lecture theatres in order to reduce energy consumption.**

***Keywords*—(Daylight, Daylight Factor, Artificial Lighting and Energy)**

I. Introduction

Daylight (DL) is a treasured natural resource that is useful in passive solar building design [1]. Appropriate DL design saves lighting power energy [2]. Sun is the source of DL that is emitting energy close to 4.5 x 10^9 years [3]. According to [4, 5], the use of daylight energy in illumination of commercial/educational building reduces artificial energy demand and greenhouse effects. DL is a contented light source for end users with luminous variations [6].

One of the principles of sustainable buildings with low lighting cost is to utilize available daylight at all time of the day for lighting. A proper designs of DL design of distributed top lights on either side or on top of building can reduce the electrical lighting consumption [7, 8, 9]. There is possibility of students in daylight schools to experience health benefits of better immunity, growth, and eye- sight comfort [10, 11].

Electric lighting energy utilization in buildings is 40 -50% of the total energy cost and most of the electrical energy use in illumination is produced by burning fossil fuels [4, 5]. This fossil fuel source is characterized by higher illumination load consumption thus increases the price and caused negative impacts on the environment [5]. According to [12], simulation -based and field survey studies from various regions of different climates acknowledge that daylighting design approaches can result in energy savings -30% to 77%. This can be assessed using average daylight factor. The average daylight factor depends on the size and area of windows, the light transmittance of the glass, the brightness, colour of the internal surfaces and finishes, and other external obstructions which may restrict the amount of day lighting entering the room [6, 13]. It has been identified by studies that there is a greater dependency on non-natural source of light for illumination in most libraries, classrooms, and office building to operate despite attendant increase in electricity tariffs which cause an increase in cost of electricity consumption. This research therefore evaluates the contribution of daylight in selected stand-alone lecture theatres in FUTA. The decrease in cost of energy by reducing the number of luminaires has resurrected the need for daylight in buildings. It is thus necessary to determine the daylight factor for different buildings and incorporate it in lighting design for lighting energy cost reduction.

1.1 Light Sources and Cost of Lighting in Buildings

Light sources are sources of light Production which can be divided into natural and artificial sources. However, sources of light differ in provision of energy to the charged particles such as electrons. If the energy comes from heat it is called incandescent while it is called luminescent if it is from chemical or electric energy [14]. Electrical wiring of artificial low voltage lighting (≤ 600V) of a building can last for 30 years [15] while building itself can exist for 60years [16]. The used of daylight for lighting during this period will reduce cost of energy consumption.

According to [17], energy savings can be maximized by utilizing daylight in lighting design for buildings that are mainly occupied during the day such as class rooms, libraries, offices and halls. According to [18], in 2010 the building sector accounts for the energy consumption in Table, 1.

Table 1: Energy consumption by commercial and residential buildings [Adapted from 18].

S/N	Energy accounted for by building sector
1.	51% of the global electricity consumption
2.	32% of global energy consumption in building sector
3.	24% of the total energy was consumed by residential buildings
4	8% of the world energy was consumed by commercial building

1.2 Daylighting and daylight factor

1.2.1 Daylighting

[2] defined daylighting as the controlled admission of natural light into a building to reduce electric lighting and thus saves energy consumption. Daylighting helps to create a visually stimulating, productive environment for building occupants, reduce emission and safes 33.3 % of total building energy costs [19, 20].
Daylight is a full-spectrum source of light to which human vision is adapted. Daylighting has two general benefits namely improve quality of light in a space and reduction in the amount of electrical lighting energy required.

1.2.2 Daylight factor

Daylight factor (DLF) is the ratio of the interior illuminance level of a building to exterior illuminance level. According to [21], daylight factors depend on availability of natural light based on latitude of the building site and surrounding conditions of the building, climate, orientation of buildings, transmittance of glazing materials of the building, area of window, vertical angle of sky with respect to the building, the total internal surface area and area weighted average reflectance of all surfaces making up the area. The Illuminating Engineering Society (IES) and British Research Establishment (BRE) remarks on building with daylight factor is presented in Table 2 [22, 23]. The surface reflectance of building material is presented in Table 3 [24].

Table 2: IES and BRE Remarks for DLF [Adapted from 22, 23]

Average DLF	Appearance	Energy implications
< 2%	Gloomy Room	Electric lighting needed most of the day
2 to 5%	Predominantly daylight appearance	Artificial lighting may be needed.
> 5%	Strongly daylight room	Daytime electric lighting not needed.

Table 3: Surface reflectance of materials that make up buildings [Adapted from 24]

S/N	Surface	Reflectance material	Values
1	Ceiling	White paint on plain plasterboard	0.8
		White paint on Acoustic Tile	0.7
		White paint on Non-fines concrete	0.6
2	Wall	White Paint on Plasterboard; Tiles	0.8
		White Fibre cement brick; concrete, light grey smooth	0.4
		Brick, common	0.3
		Concrete, light grey cement, rough; brick, Red: Timber Panelling, light oak, Mahogany	0.25
		Timber Panelling; Dark	0.2
		Brick; Dark	0.15
		Black Chalkboard	0.05
		Paper White	0.8
3	Floor and Furniture		0.45
			0.35
		Timber; medium, PVC Tiles; Brown, Marbled Carpet Green	0.25
		Timber Dark	0.2
		Tiles; Red, Carpet; Dark	0.1

1.3 Room Index

Room Index is used to consider the room proportions and height of the luminaire above the working plane [25]. It is also used to determine the minimum number of measuring position of illumination level of a building as presented in Table 4.

Table 4: Room Index and Minimum Number of Measuring Positions [26, 27]

S/N	Room index value	Minimum number of measuring positions
1	< 1	4
2	1 -1.9	9
3	2- 2.9	16
4	≥3	25

2. METHODOLOGY

2.1 Data collection

Five years' empirical solar radiation data were collected from Nigeria metrological agency (NIMET). Measuring Tape (Figure 1) and a reliable lux meter (Figure 2) previously used on a past research were used for dimensional measurements and lux level values determination in the buildings respectively.

Figure 1: Measuring Tape

Figure 2: TES 1332A Lux Meter

2.2 Determination of Daylight Factor (DLF)

In order to determine the DLF, the window to wall area ratio, the angle of the building to the sun, the reflectance of the material that make up the building area and the transmittance of the glazing material were determined.

i. Determination of window to wall area ratio (WWAR)

In order to determine the DLF "(1)", "(2)", "(3)" and "(4)" were used to compute the windows area, A_{WD}; total wall area plus window area, A_{TW+WD}; window area, A_W; and window to wall area ratio, (WWAR) respectively.

$$A_{WD} = \sum_{w=1}^{n} L_w \: X \: B_w \qquad (1)$$

Where L_w is length of the window, B_w is breadth of the window, w is first number of window and n is last number of the window.

$$A_{TW+WD} = \sum_{i=1}^{n} L_i \: X \: B_i \qquad (2)$$

Where A_{TW+WD} is the total wall area including window, i is the first number of section a building was divided into, Lis the length of each section, B is the breadth of each section and n is the last section of the building.

$$A_W = A_{TW+WD} - A_{WD} \qquad (3)$$

Where A_W is the area of wall.

Equation 4 was used to determine window to wall area ratio, WWAR.

$$\text{WWAR} = \frac{A_{WD}}{A_W} \: X \: 100 \qquad (4)$$

ii. Determination of sun angle

The sun angle in respect to each building was computed using "(5)".

$$O = \text{Tan}^{-1} (H_B/Hs) \qquad [1] \qquad (5)$$

Where H_B is height of the building and H_S is height of the shadow of the building which was determined at measurement time of 8:00am, 12:00pm and 5:00Pm.

iii. Reflectance of the materials

The percentage of reflectance of the materials, R, that make up the building area was determined using Table 3.

iv Transmittance of the glazing materials

The transmittance of the window was determined based on the nature of the materials used from building catalogue.
"6" was used to obtained the daylight factor for each of the buildings.

$$DLF = \frac{\sum A_W * J * O * M}{A(1-R^2)} \qquad [22, 28] \qquad (6)$$

Where A_w is Area of the window in (m^2) of the building, J is transmittance of glazing material of the building, O is angle of sun from the building, M is maintenance factor (walls, doors, ceilings), A is total internal surface area and R^2 is area weighted average reflectance of all surfaces making up A.

2. 3 Determination of Daylight Contribution (DLC)

In order to determine daylight contribution, two methods namely lux meter measurement and daylight factor computation were used. Lux meter was used to measure the daylight contribution in the buildings. Daylight factor was used to compute the daylight contribution based on the data collected.

2.3.1 Determination of daylight contribution using lux meter

Room index method was used to determine the measuring points in the building in order to determine the daylight contribution using lux meter. Lux meter was used to measure the lux level at the specific measuring points.
"7" was used to determine the room index, RI, [24, 25].

$$RI = \frac{L \: X \: W}{H_m X \: (L+W)} \qquad (7)$$

Where L is internal length of the building, W is width, and H_m is height.
The number of measuring point corresponds to room index value (Table 4).

Figure 3: 1000 Capacity LT

Figure 4: FBN LT

Figure 5 :3-In-1-A LT

Two different lux meters were used to measure the lux level of the study area at regular interval during the day. The measurements were taken under different condition of the day -morning (8-9 am), afternoon (12-1 pm) and evening (5-6pm) in the month of August, 2020, due to the usage of the lecture theatres.

2.3.2 Determination of daylight contribution using daylight factor

The outdoor illumination level (lux) was determined from solar radiation (SR) data obtained using “(8)” to “(10)”. The energy of the solar radiation (E_{SR}) and outdoor illumination (Visible radiation) level (E_{VR}) were obtained using “(8)” and “(9)” respectively. The percentage of outdoor illumination level (η) in the solar radiation was obtained using “(10)”.
The outdoor illumination level obtained from “(11)”is converted to lux using equation “(12)”.

$$E_{SR} = \int_{\lambda 1}^{\lambda 2} 3.74 \text{ x } 10^{-16} \lambda^{-5} . \left(e^{\frac{1.44 \text{ x } 10^{-2}}{\lambda T}} - 1 \right) d\lambda \quad [29, 30] \quad (8)$$

$$E_{VR} = \int_{\alpha 1}^{\alpha 2} 3.74 \; x \; 10^{-16} \alpha^{-5} . \left(e^{\frac{1.44 \; x \; 10^{-2}}{\alpha T}} - 1 \right) d\lambda \quad [29, 30] \quad (9)$$

$$\eta = \frac{E_{VR}}{E_{SR}} \quad [29, 30] \quad (10)$$

Where $\lambda 1$ *and* $\lambda 2$ are the wavelength range of the Solar radiation and $\alpha 1$ *and* $\alpha 2$ are the wavelength of the visible light and T is the temperature of the sun.
The visible radiation is obtained from solar radiation using equation 11

$$VR = \eta \; X \; SR \quad (11)$$

$$1 \text{ Lux} = 0.0092 \text{W/M}^2 \quad (12)$$

The daylight contribution (DLC) was computed using “(13)”

$$\text{DLC} = \text{DLF x } VR \quad (13)$$

Where DLF is the daylight factor, VR is the outdoor visible radiation

2. 4 Correlation of Measured and Computed Data

The correlation between the measured and computed available data for five years were evaluated using “(14)”.

$$Correl\ (DL_C, DL_m) = \frac{\sum (DL_m - DL_c)(DL_m - ADL_c)}{\sqrt{\sum (DL_m - DL_c)^2 \sum (DL_m - ADL_c)^2}} \quad (14)$$

Where DL_m is measured daylight, and DL_c is computed daylight.

2. 5 Evaluation of Energy Cost Using Daylight

The number of fittings expected in a building using existing standard, lumen per watt method, -N_s, is given in “(15)”.

$$N_s = \frac{E_s * A}{L * U_f * M_f} \quad [14, 25] \quad (15)$$

Where E_s is lux level base on the task performed in the building, A is area of the building, U_f and M_f are utilization and Maintenance factor respectively, L is lamp lumen.
The total wattage of luminaries (T_w) in the building was computed using “(16)”.

$$T_w = N * W \quad (16)$$

Where W is wattage of the luminaries and N is number of luminaries
The Cost per hour in the building was computed using “(17)”.

$$C_h = T_w * T_r \quad (17)$$

Where T_r is the tariff rate.
The cost of electrical lighting energy for 30 years is considered in this works based on electrical wiring system life span [15].

2.6 Optimization Model for Lighting Design with Daylight Factor (OMLDDF)

Required number of lamp with daylight contribution (N_{RDC}), is optimization model given in “(18)”.

$$N_{RDC} = \frac{(E_S - E_{DLC})}{L * U_f * M_f} \quad (18)$$

Where E_s is standard lux level base on the task performed in the building, E_{DLC} is lux level contributed by daylight, A is the area of the building, U_f and M_f are utilization and Maintenance factor respectively and L is the lamp lumen.

2.6.1 Effective Lighting Control System

The number of luminaries Ns will be switched ON during darkness or when it is cloudy. In the presence of daylight contribution, the modelled number of required lamp (N_{RDC}) will only be switch ON.

Journal of Multidisciplinary Engineering Science and Technology (JMEST)
ISSN: 2458-9403
Vol. 8 Issue 5, May - 2021

3. Results and Discussions

3.1 Results

The Results of the research are presented in Figure 6 and Table 5 to 9.

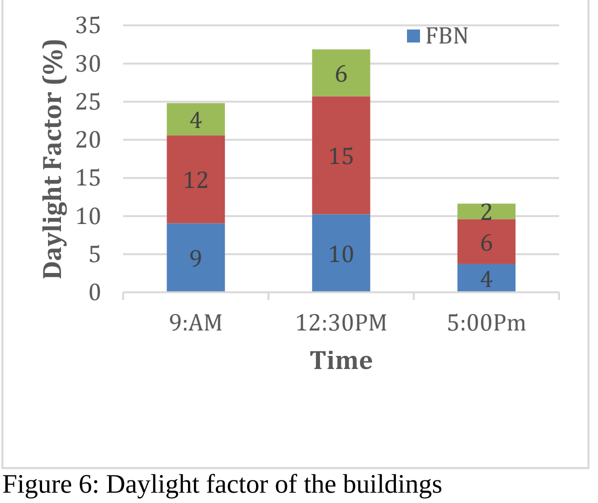

Figure 6: Daylight factor of the buildings

Table 5: Room index and corresponding position

Buildings	Room index	Minimum measuring position
3-in 1-A	7.9	25
FBN	7.2	25
1000 Capacity	15.7	25

Table 6: Computed daylight (DL_C) and experimental daylight (DL_E) contribution

TIME	Buildings 3-in-1-A		FBN		1000 Capacity	
Year 2015						
	DL_C	DL_E	DL_C	DL_E	DL_C	DL_E
Morning	903	422	677	170	301	60
Afternoon	2754	837	1836	363	1102	151
Evening	204	658	136	173	68	107
Year 2016						
	DL_C	DL_E	DL_C	DL_E	DL_C	DL_E
Morning	1016	422	763	170	339	60
Afternoon	3314	837	2209	363	1326	151
Evening	197	658	131	173	66	107
Year 2017						
TIME	DL_C	DL_E	DL_C	DL_E	DL_C	DL_E
Morning	951	422	713	170	317	60
Afternoon	3081	837	2054	363	1232	151
Evening	289	658	193	173	96	107
Year 2018						
TIME	DL_C	DL_E	DL_C	DL_E	DL_C	DL_E
Morning	951	422	713	170	317	60
Afternoon	3081	837	2054	363	1232	151
Evening	289	658	193	173	96	107
Year 2019						
TIME	DL_C	DL_E	DL_C	DL_E	DL_C	DL_E
Morning	756.7	422	568	170	252	60
Afternoon	3202	837	2135	363	1281	151
Evening	240.3	658	160	173	80	107

Table 7: Correlation of the experimental value against computed Data

Building/Year	2015	2016	2017	2018	2019
3-in 1-A	0.64	0.65	0.68	0.67	0.72
FBN	0.95	0.95	0.96	0.96	0.98
1000 Capacity	0.73	0.73	0.76	0.75	0.78

Table 8: Determination of number of luminaries in buildings in the absence of DLC

Buildings	Area (m^2)	Recommended lux	Bulb rating	Bulb lumen	No of Luminaries N= $(E_s*A)/(Lumen*U_f*M_f)$
3-in 1-A	301.37	500	85	5500	49
FBN	289.5	500	85	5500	47
1000	422.6	500	85	5500	69

Table 9: Cost of energy saved by incorporating daylight

	PowerWithout Daylight (W)	PowerWithout Daylight (kW)	Proposed Model [Number of Required Artificial Luminaries = (Es-E_{DLC})*A/(Lumen*Uf*Mf)]	Power of required Artificial luminaries = (No of required artificial luminaries x Lamp rating) W	Power of required Artificial luminaries = (No of required artificial luminaries x Lamp rating) kW	Cost of Daylight Contribution (N)	% of Power of Daylight Contribution = [(Power of Daylight Contribution)/(Actual designed Power)]*100	Tariff Rating(N)	Cost of Required Artificial Lighting Per Year (N)	Net Cost of Energy Per Year(N)	Net Cost of Energy For 30 Years
2020 3in 1-A	4159	4.16	0	0	0	907,520.96 /yr	100	60.62	907,520.96/yr	0	0
FBN	3995	3.99	31	2613	2.61	301,634.71/yr	34.6	60.62	871,776.61/yr	570,141.91	17,104,257.30
1000	5831	5.83	54	4583	4.58	272,332.78/yr	21.4	60.62	1,272,583.06/yr	1,000,250.29/	30,007,508.70
						1,481,488.45/yr			**3,051,880.63/yr**	1,570,392.20	47,111,766.00
						44,444,653.50 **/30yrs**			91,556,418.90 **/30yrs**		47,111,766.00 **/30yrs**

3.2 Discussions

From Figure 6, the results of daylight factor (DLF) varies from time to time. The DLF for 3 in -1-A building is 12 % 15% and 6 % in morning, afternoon and evening respectively. According to IES and BRE recommendations, a building with daylight factor greater than 5% do not need artificial light during the day. This implies that the 3 in 1-A building do not need artificial lighting during morning afternoon and evening. The FBN building has a DLF of 9%, 10% and 4% in the morning, afternoon and evening respectively. The daylight factor is greater than 5% in the morning and afternoon period, hence artificial lighting is not needed. However, in the evening when the daylight factor is less than 5%, artificial light is needed to complement the daylight. The daylight factor of 1000 capacity building varies from 4%, 6% and 2% for morning, afternoon and evening respectively. Afternoon daylight factor is greater than 5%, artificial light is not required. However, in the morning and evening artificial lighting is required for good illumination in the building.

From Table 5, the room index of the buildings varies from 7.2 to 15. 7 which corresponds to 25 minimum measuring point used in this research.

From Table 6, there are variations in the measured and the computed values from time to time. However, Table 7, shows correlation between the two values at all time. the correlation varies from 0.64 to 0.98. The correlation result shows that there is close similarity between the measured and computed data. However, the measured daylight contribution is preferred in this analysis because it is a direct physical measurement on site. This implies that with the DLC in 3 in 1-A building do not need artificial lighting at all time; FBN building do not need artificial lighting in afternoon but morning and evening while 1000 capacity needs artificial lighting in morning afternoon and evening.

From Table 8, the number of luminaries needed for the buildings shows that 1000 capacity required the highest number of luminaries follows by 3 in 1-A and FBN buildings respectively. This implies that the building area is directly proportional to number of luminaries.

From Table 9, the percentage of energy saved during the day (8am – 6pm) in each of the building shows that 3 in 1-A building saved energy by 100%, FBN and 1000 Capacity saved energy by 34.6 % and 21.4 % respectively. For year, 2020 the cost of daylight contribution is 0.91, 0.3 and 0.27 million naira for 3 in 1-A, FBN and 1000 capacity buildings respectively. The cost of artificial lighting in the absence of daylight is 0.91, 0.87 and 1.27 million naira for 3- in-1, FBN and 1000 capacity building respectively. The net cost of energy per year is zero naira; 0.6 million naira and 1 million naira for 3 in 1-A, FBN and 1000 capacity buildings respectively. It means that the use of DLC in the lecture theaters saves 1.5 million naira per year. For 30 years, without variation in the tariff order, the cost of daylight contribution alone is 44.4 million naira; the cost of artificial lighting alone is 91.6 million naira and the net cost of energy is 47.1 million naira for the three lecture theatres in consideration. This implies that contribution of daylight saves 44.4 million naira; the lighting energy without daylight is 91.6 million naira; and cost of energy payable for 30yrs is 47.1 million naira in the buildings under consideration. Thus daylight renewable source of energy can be incorporated in lighting design with control circuit for the buildings energy optimization.

4. Conclusions

The research evaluated the contribution of daylight in lighting design for stand-alone lecture theatres. The research shows that 3-in-1-A building do not require artificial lighting during the morning afternoon and evening, FBN needs artificial lighting in the evening, 1000 capacity needs artificial lighting in the morning and evening. The three buildings in this study are in alignment with existing literature of 5% daylight factor. Buildings incorporates daylight in lighting design in this work saves 21.6 % to 100% of energy. The cost of daylight contribution in the three buildings per year varies from 0.27 million naira to 0.96 million naira; the DLC in the studied lecture theatres saves 1.5 million naira per year base on the present tariff.

This work established lighting optimization model. Large significant amount of money is saved in incorporating established model. This research established that building that base its evaluation of DLC on 5% recommendation of IEC and BRE optimize electrical energy of lighting.

The established model of lighting energy optimization, in this research, with effective lighting control should be used in lighting design for lecture theaters in order to reduce energy consumption.

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