Ideal Toplighting Glazing Area for Daylighting Quality and Energy Saving in Buildings

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ABSTRACT

Careful design and selection of daylighting systems can greatly help in reducing not only artificial lighting use, but also decrease cooling energy consumption and, therefore, potential for downsizing air-conditioning systems. This paper aims to evaluate the energy performance of two types of top-light daylighting systems due to the integration of daylight together with artificial lighting in an existing examination hall in University Kebangsaan Malaysia, based on a hot and humid climate. Computer simulation models have been created for building case study (base case) and the two types of top-light daylighting designs for building energy performance evaluation using the VisualDOE 4.0 building energy simulation program. The finding revealed that daylighting through top-light systems is a very beneficial design strategy in reducing annual lighting energy consumption and the overall total annual energy consumption. The results from this study also provides architects, designers and researchers with useful information and better understanding of the application of daylighting in academic buildings in a hot and humid climate, and will promote effective daylighting designs for energy efficiency for similar facilities located in similar climates.

Keyword: Daylight Quality; Energy Savings on Lighting; Toplighting Glazing Area; Energy simulation

1. INTRODUCTION

People have become more conscious of the interaction between buildings, energy, and the environment. There has also been a growing concern among architects and building designers on energy consumption in buildings and its likely adverse affect on the environment [1, 2]. As a point of reference in the United States, commercial buildings consume more than one-third of the nation's primary energy. Electrical lighting is estimated to account for 25–40% of the total electrical energy consumption [3]. Over the last three decades, several studies have been carried out to reduce electricity use associated with artificial lighting. These studies indicated that daylighting can offer a cost-effective alternative to electrical lighting for commercial and institutional buildings. Through the use of daylighting controllers, daylighting can reduce and even eliminate the use of electrical lighting required to provide sufficient illuminance levels inside building spaces. Simulation analysis as well as field-monitoring studies have reported that daylighting controls can result in significant lighting energy savings ranging from 30% to 77% [4-7]. Moreover, daylighting offers a lighting source that most closely matches human visual response and provides more pleasant and attractive indoor environment. It is reported that daylighting improves student performance and health in schools [8]. However, surveys have shown that daylighting control strategies are not commonly incorporated in commercial buildings [1-3, 8, 9].

The Malaysia sky has a lot of potential for daylighting applications due to the high daylight availability. According to a study conducted by S. Chirarattananon et al (2002), during office hours (8:00am-16:00pm), global, beam, and diffuse illuminance are typically at more than 20 Klux for Thailand sky [10]. Only a 2.5% daylight factor is needed then for the interior illuminance to reach 500 lux, which is the recommended illuminance level for academic buildings use[11]. Moreover, the study found that the differences of the illuminance availability between each month are small, as compared with those of locations far from the equator. The efficacy of daylight is also high at about 105-115 lumen/watt [12]. Furthwemore, the sky type of Bangkok, as studied by S. Chirarattananon et al. (2003), is 40% cloudy sky, 40% intermediate, and 20% clear sky [12]. Kuala Lumpur sky type is not much different from Bangkok sky type since both cites have tropical climate.

Malaysia, which is in a hot and humid climate, has a high potential for energy savings resulting from the use of daylighting because of daylight availability. However, heat gain is a major concern in this type of climate. Therefore, the ideal top-lighting system designs for this tropical region should perform well without adding excessive heat gain to the space.

The objective of this study is to evaluate the impact of top-light daylighting systems on energy performance in an academic hall building. In addition, the study presents useful information and better insights on the relationship between top-lighting shapes, glazing types, top-light area, spacing-to-ceiling height ratio, building orientations, and their impacts on the artificial lighting and total energy consumption. The impacts of these parameters are investigated based on hot and humid climate typical to the city of Kuala Lumpur, Malaysia. VisualDOE 4.0, a whole building energy simulation tool, is utilazed to determine the impact of top-light daylighting systems on artificial lighting and total energy consumption for an academic hall building.

2. METHODOLOGY

2.1. LOCATION AND CLIMATE

The case study academic hall building investigated in this study is located in the University Kebangsaan Malaysia, Malaysia (Latitude 3^0.12' North, Longitude -101^0.6' East, Alt. 25m), which is situated 25 km from the city of Kuala Lumpur. Malaysia has uniform temperature throughout the year. The annual variation is less than 2^0C except for the east coast areas of Peninsular Malaysia which are often affected by cold surges originating from Siberia during the northeast monsoon. Even there, the annual variation is less than 3^0C. Malaysia has high humidity. The mean monthly relative humidity is between 70 to 90%, varying from place to place and from month to month. Rainfall is high and the total annual rainfall of around 2600 millimetres, which is above the global average, but considered normal for an equatorial region. The sky type of Malaysia is 40% cloudy sky, 40% intermediate, and 20% clear sky [12].

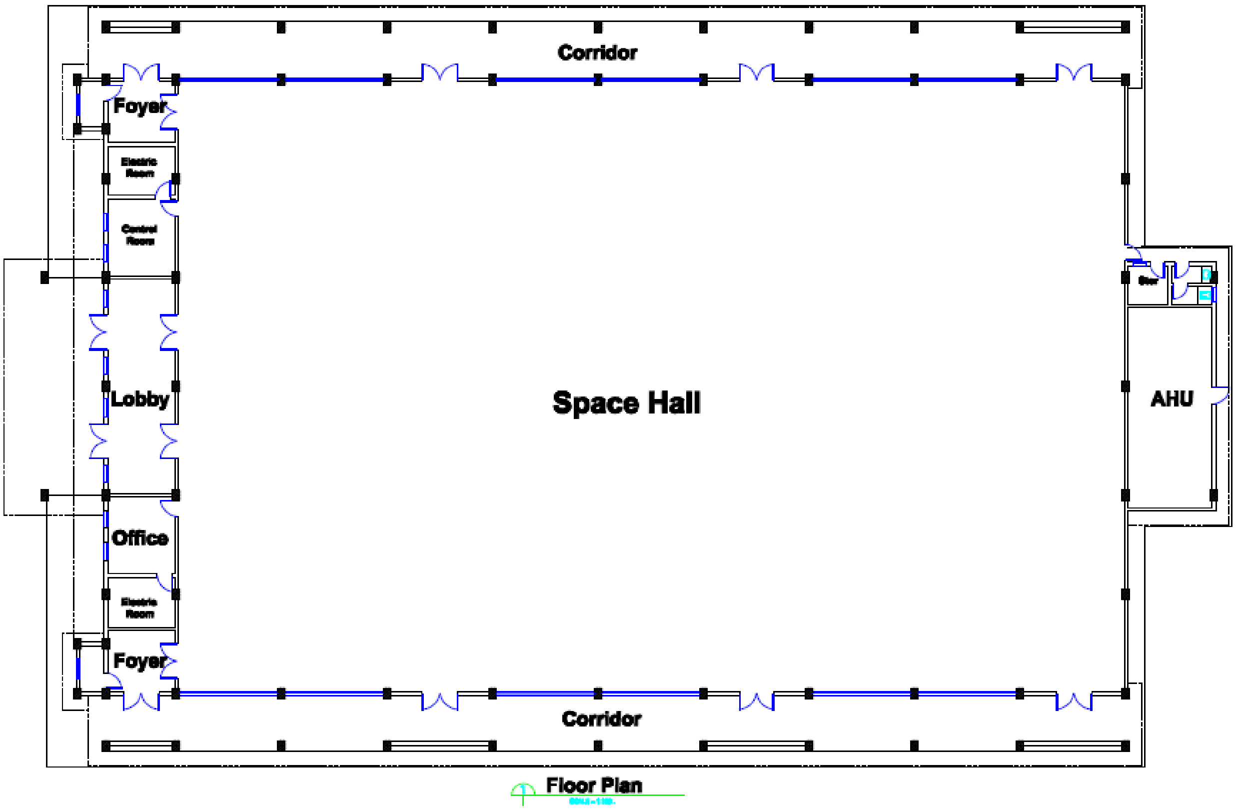
2.2. CASE STUDY BUILDING DESCRIPTION

The examinations hall building has a total 1890 square meters. The hall building has exterior wall structure, with 151 mm thick brick wall with cement, 15 mm plaster and paint on both sides. The roofing is built-up type with metal roof installation deck equivalent 0.48 mm thick, colored, 50 mm thick fiberglass insulation and 1 layer of chicken wire mesh. The floor is a lightweight 4” concrete slab construction with 20 mm terrazzo tile with cement in corridors and space hall. The entire building is single story and the front faces south. A floor plan of the hall building used and east and west elevations are presented in Figure 1.

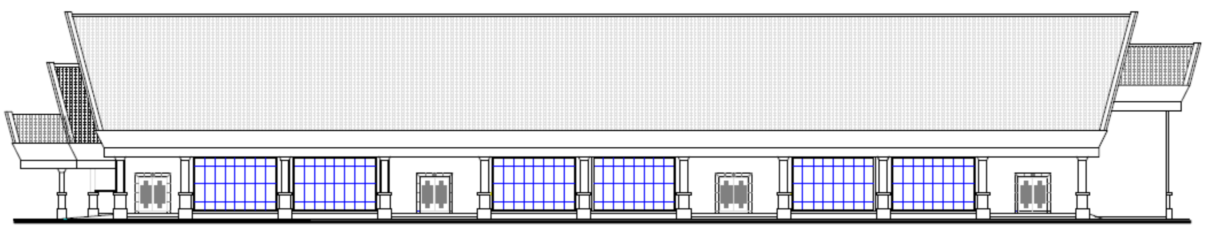
2.3. ENERGY ANALYSIS

The VisualDOE 4.0 building energy and daylighting analysis program was used to carry out the energy analysis for the case study. The selected tool was VisualDOE 4.0, which is a commercial version with a graphic interface developed by Eley Associates [13] that utilizes the DOE-2.1E calculating engine but works with the WINDOWS® operation system. The DOE-2.1E code has the ability to simulate a wide variety of potential energy conservation measures in buildings and it has been widely validated by comparing its results with thermal and energy use measurements on actual buildings [14]. DOE-2.1E has undergone validation by Los Alamos National Laboratory, LBL and at various US and international institutions to show that the program is sufficiently accurate in energy prediction. Validation gives users confidence that the DOE-2 results are reliable for building energy analysis [15]. The Kuala Lumpur hourly weather data is used with the VisualDOE 4.0 software for this study.

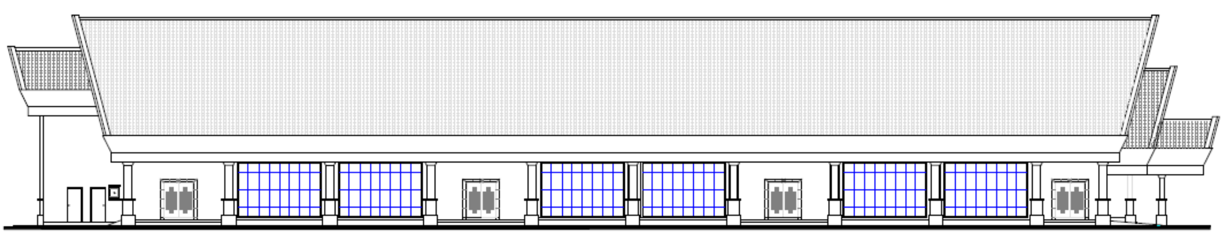
For the proposed study, an examination hall building in the Universiti Kebangsaan Malaysia has been selected as a base case and the characteristics of the building were needed as input data. The data were obtained from the Department of Development Management of the university which covers official statistics about the existing hall building. Inspection of the site and the selected building was done. All the relevant electrical and mechanical as built drawings, hourly weather data for 2010 and 2011, operation schedules, occupant’s density, lighting density and mechanical systems information were procured. The measured electric energy consumption (utility bills) for the selected building of the past two years was also obtained. As-built drawings to gather information about the thermal zoning was reviewed. A computer simulation model in the VisualDOE4.0 energy simulation program based on the hourly weather data of Kuala Lumpur was created. The base hall building and its HVAC equipment information and the measured energy consumption were described. The measure energy consumption for the selected building was compared with the simulated results for similar time and weather conditions. The characteristics of building, HVAC system, and operating conditions for the simulated examination hall single story building are displayed in Table 1 and 2. The weekday and weekend schedules for occupancy, infiltration, lighting, air-conditioning, and equipment are illustrated in Table 3.



Floor plan of base case examination hall



East Elevation



West Elevation

Fig1. Floor plan and east and west elevations of the case study UKM examination hall

Table 1. Main characteristics of the base case study UKM examination hall building

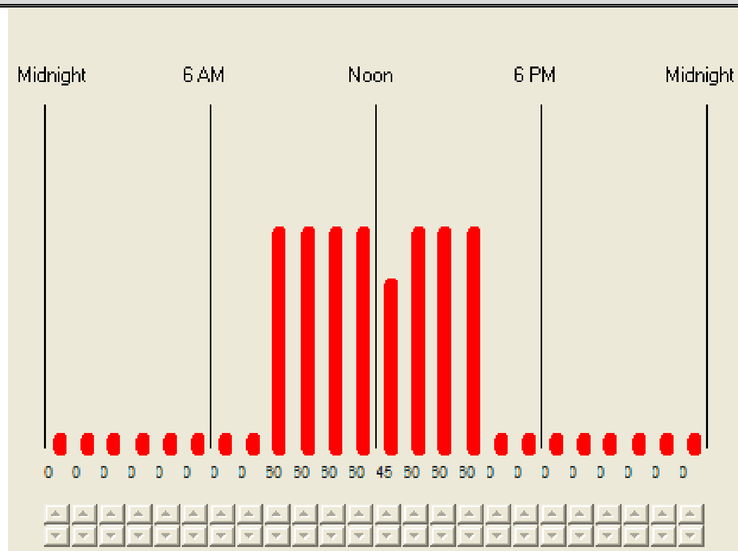
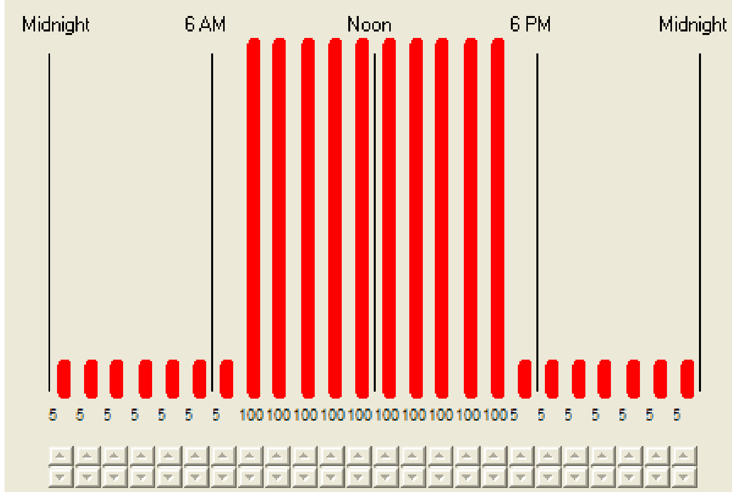
Component	Description
Location	Kuala Lumpur (Lat. 3^{0}.12' N, Long -101^{0}.6' East, Alt. 25m)
Plan Shape	Rectangular
Number of floors	One Story Building
Window-Wall-Ratio	27.8% Estimate from the actual data
North WWR	0.0%
Non-North WWR	34.6%
Construction Date	2004 From the actual data
Floor-to-Roof Height	6.5 m From the actual data
Floor-to-Ceiling Height	6 m From the actual data
Floor Dimension	54 x 35 m From the actual data
Gross Floor Area	1890 m^2 Estimate from the actual data
Number of Zones	One zone From the actual data
Zone Type	Conditioned From the actual data
Number of People (maximum)	630 students From the actual data
Lighting Type	Holophane Crystal Glo. 400 Watt From the actual data
Light-to-space	1 DOE-2 reference manual
Exterior Wall Structure	151 mm thick. Brick wall with cement 15 mm plaster and paint on both sides Calculated U-Value = 2.19 $W/m^2.^0C$
Roof Structure	Metal roof installation deck equivalent 0.48 mm thick, colored 50 mm thick. fiber glass insulation 1 layer of chicken wire mesh Calculated U-Value = 0.6 $W/m^2.^0C$
Ground Floor Structure	1 00mm concrete slabs 20mm terrazzo tile with cement Waterproof layer Calculated U-Value = 1.21$W/m^2.^0C$
Window Glazing Structure	Single Bronze 6mm Visible Transmittance = 0.534 Shading Coefficient (SC) = 0.71 Solar Heat Gain Coefficient (SHGC) = 0.61 Calculated U-Value = 6.14 $W/m^2.^0C$
Solar Absorbance	0.5 for external walls and 0.5 for the roof
Surface Reflectance	80% for the ceiling, 50% for the walls and 20% for the floor
Occupant Density	4.6 m^2/person From the actual data
Lighting Power Density LPD	15.1 W/m^2 From the actual data
Equip. Power Density EPD	1.1 W/m^2 Approximate Value
Infiltration (Air-changes/hour)	0.5 ACH Average tightness Building DOE-2 reference
Operation Hours	Weekdays from 07:30 AM to 05:30 PM

Table 2. Characteristics of the HVAC system of the base case UKM examination hall

Characteristics	System Description
System Type	Tow Packaged Single Zone System
Cooling Design Temp. (°C)	24 °C Estimate from the actual data

Heating Design Temp. (°C)	21 °C Estimate from the actual data
Cooling Only	Available year round
Ventilation	10 l/s (ASHRAE 62, 1999)
Weather File	Kuala Lumpur weather file available from the DOE-2 website

Table 3. Typical weekday and weekend schedule for occupancy, lighting, equipment, outside air, infiltration, and fan used in the simulations

Schedule	Schedule Description	Weekdays
Occupancy	60% during occupied period, 0 % for unoccupied period, weekends and holidays	
Lighting	100 % during Occupied period and 5 % for unoccupied period, weekends and holidays	

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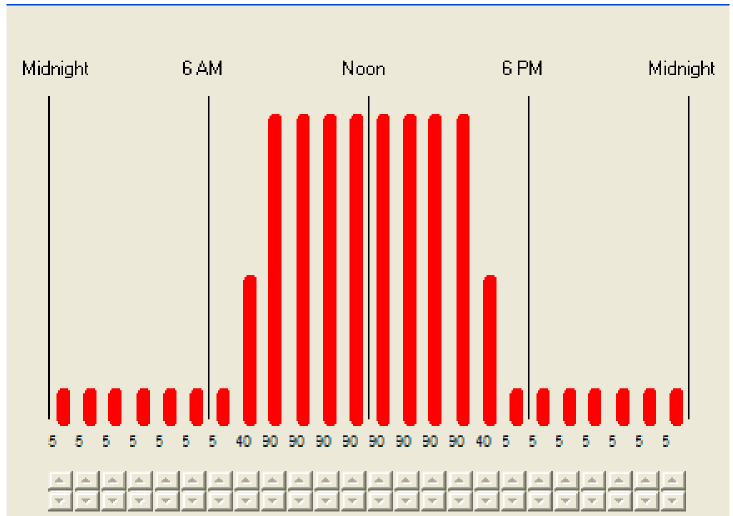
<td>90% occupied period , 5-10% during unoccupied period, weekends and holidays</td>
<td>
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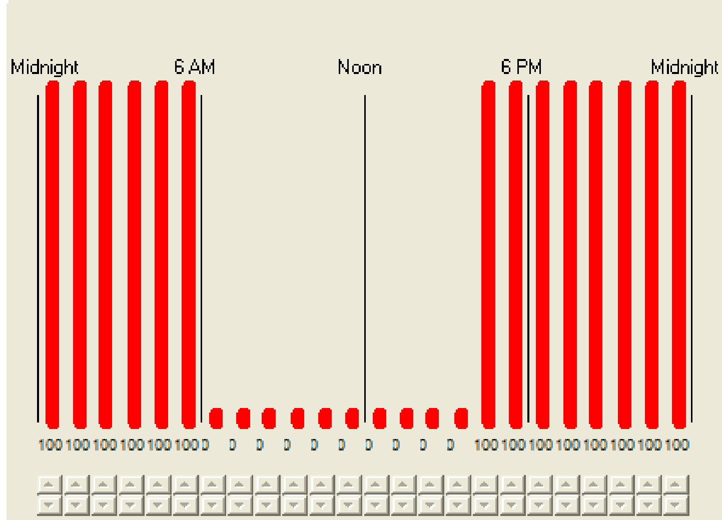
<td>Infiltration</td>
<td>0 % occupied period , 100% during unoccupied period, weekends and holidays</td>
<td>
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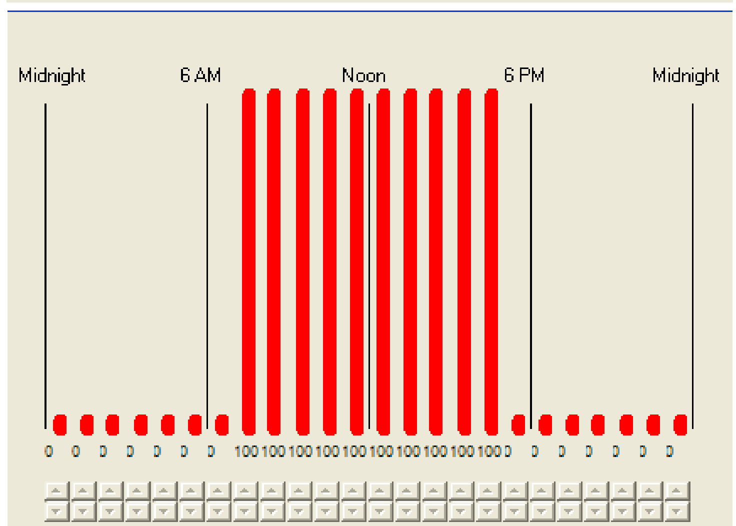
<td>Fan Profile</td>
<td>100% for occupied period and 0 % during unoccupied period, weekends and holidays</td>
<td>
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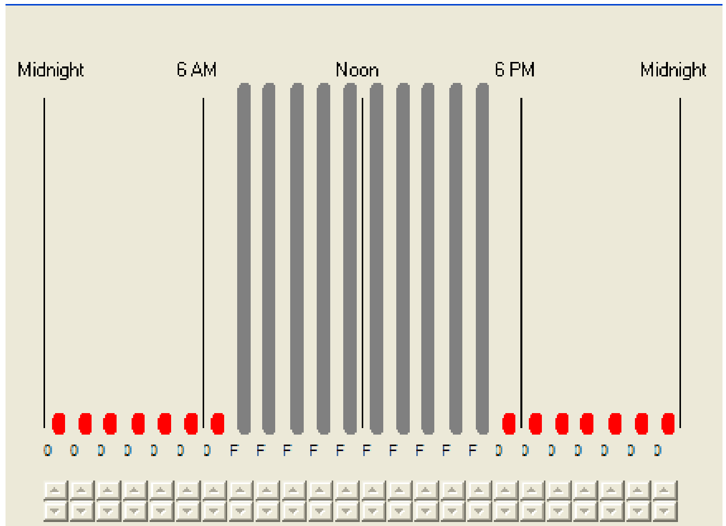
Outside Air	100% for occupied period and 0 % during unoccupied period, weekends and holidays.	

3. RESULTS OF ENERGY ANALYSIS

The calculated annual energy consumption for the base case study hall building is about 295,356 kWh and the required annual cooling and lighting energy consumption is 79,033 kWh and 206847 kWh respectively. The distribution of the electrical end-use, calculated by the simulation program, for the base hall building is shown in Figure 2. It can be seen from the figure that the most important factors affecting the energy consumption of the building are the cooling about50.8%, lighting about 26.8%, HVAC fans about 19.2%, equipment 1.6% and domestic hot water about 1.6%. In addition, part of the cooling energy consumption is resulting from the associated sensible cooling load due to artificial lighting. Therefore, the lighting parameter was investigated to see the potential lighting energy reductions and associated lighting internal loads impacts of integrating artificial lighting with daylight admitted through skylights and saw-tooth daylighting systems. The effect of different types of glazed, different glazed area and for different orientations on the annual lighting energy saving was also evaluated in this analysis.

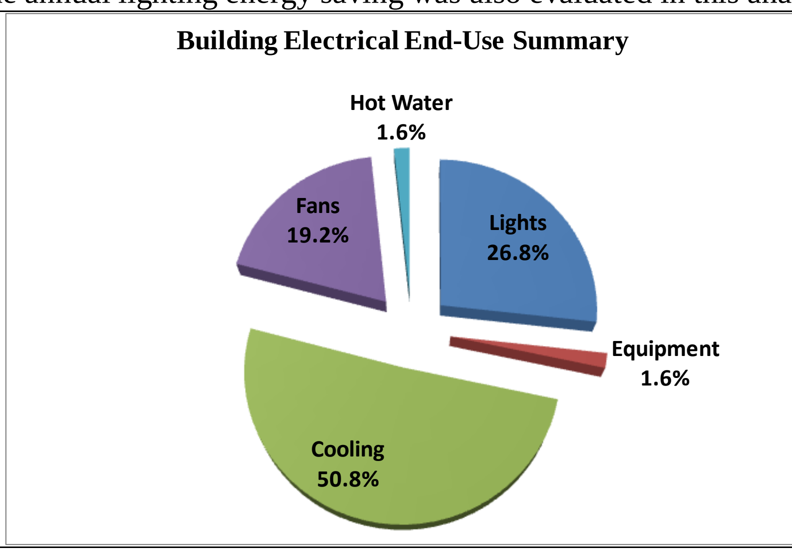


Figure 2. Electrical end-use summary for the base case examination hall building

The effect of the integrating top-light daylighting and artificial lighting on the annual lighting and total annual energy consumption of the base case hall building are shown in Figure 3. The results of the simulation study demonstrated that utilization of the daylighting in the base hall building results in reduction of the electric lighting consumption by about 70% and cooling energy needs by about 4.6% when compared to the base case hall building (without daylighting); and consequently, the total annual energy consumption is reduced by about 22%. Cooling is used to evacuate the internal loads, which are mainly due to artificial lighting. The utilization of the natural light implies a large reduction of all energy needs for the building (except equipment and hot water) when daylight-linked by automatic continuous dimming daylighting control systems.

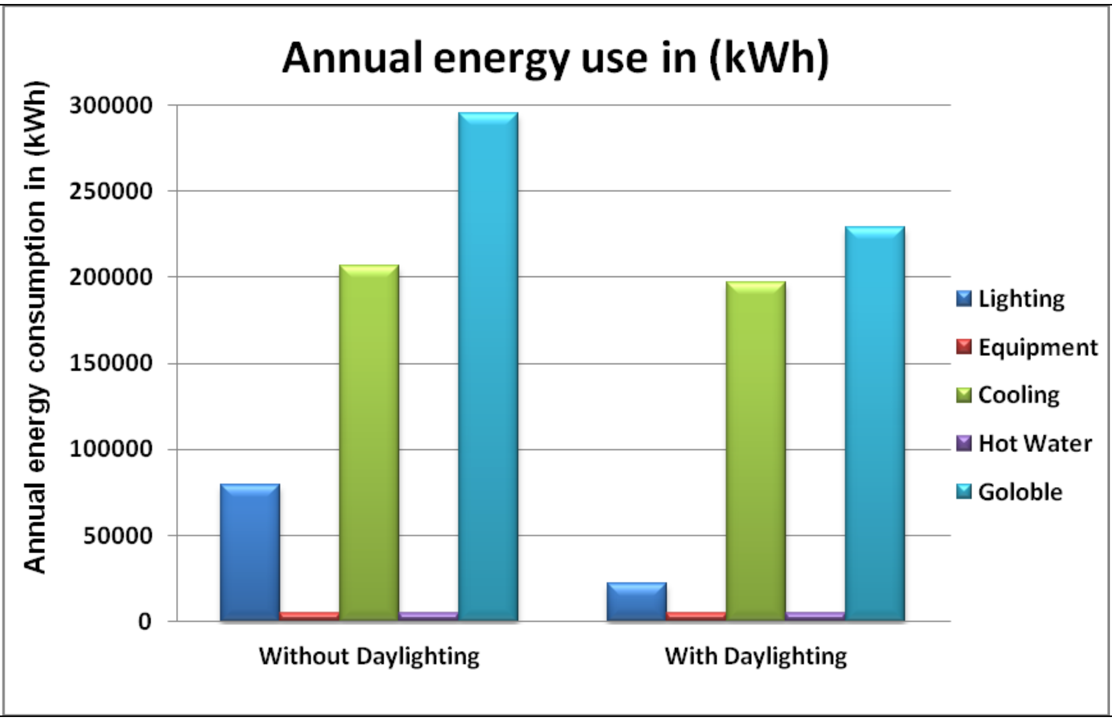


Figure 3. Total annual energy use in (kWh)

The effect of the glazing area on the building energy consumption was also considered. Increasing the glazing area of the top-lighting system from 0% to 5% reduces the lighting energy consumption by 70% and the total energy consumption by 22% compared to that of the base hall building, as shown in Table 5, but this has insignificant effect on the cooling energy consumption. A simulation run for the base case hall building was also made for second type of top-lighting system (saw-tooth) instead of the roof without top-lighting system. It is observed from the table that the saw-tooth system reduce the lighting energy consumption by 71.9%. The corresponding reduction in the cooling energy consumption is 19.3 %.

Table 5.Effect of Glazing-to-Roof Ratio on the energy consumption for the base case hall Building

GRR		Annual building energy consumption (kWh)			
		Lighting	Cooling	Total	Energy savings %
Base case without daylighting		79,033	206,847	295,356	-------
Skylights	**5%**	23,753	197,242	230,471	-21.97
	10%	20,942	219,453	249,871	-15.4
	15%	20,860	227,100	257,436	-12.8
	20%	20,120	241,736	271,332	-8.1
	25%	19,759	256,449	285,684	-3.3
	30%	19,408	197,242	302,637	2.5
	35%	19,256	219,453	318,418	7.8
	40%	19,082	227,100	333,684	12.97
	45%	18,929	241,736	350,729	18.75
	50%	18,823	256,449	363,909	23.2
Saw-tooth	**5%**	25,133	206,516	241,125	-18.4
	10%	20,723	251,587	281,786	-4.6
	15%	19,778	297,639	326,893	10.7
	20%	19,201	341,335	370,012	25.3
	25%	18,992	379,485	407,953	38.1
	30%	18,821	423,126	451,423	52.8
	35%	18,778	462,008	490,262	65.9
	40%	19,488	479,037	508,001	71.9
	45%	19,404	521,613	550,493	86.3
	50%	18,801	577,368	605,645	105

A simulation run was made for the examination hall building with two types of top-lighting systems, different types of glazing, different glazed area and different orientations to see the combined effect of the above parameters on lighting energy saving in terms of (kWh/m^2 yr). Results of the simulations are presented in Table 6 and 7 for skylights and saw-tooth. The energy savings is calculated for unit floor area. Annual energy savings is maximum when artificial lighting integrated with daylight for the whole year (8.00AM-5.00PM). As the lighting power density is 15.1 W/m^2 and the required lighting level is 300 lux, the maximum of energy saving to be 32.1 kWh/m^2 yr. For different glazing types and glazing area, the results showed that if the visible transmittance is high (e.g. 0.881 for single clear glass, 0.781 for double clear glass and 0.745 for double clear glass Low-e), the energy savings is highest, about 29.7 kWh/m^2 yr – 32.1 kWh/m^2 yr, and it remains almost same when glazed area is increased from 5% to 40%. But when the visible transmittance is low (0.531for double clear glass with heat mirror), the energy savings increases with the glazed area increases.

Effect of top-lighting glazed orientation on the energy savings, for the saw-tooth system, is shown in Table 7. The results showed that, when the visible transmittance is high lighting energy savings is almost same in all directions. When the visible transmittance is low (TV =0.531) lighting energy savings is maximum for north direction (32.1 kWh/m^2 yr) and it is lower for the other three directions (31.6 kWh/m^2 yr).

Table 6. **Skylights**: annual lighting energy saving for different types of glazed, different glazed area and for different orientations.

No	Glazing Type	Glazed area as percentage of roof area	Energy savings (kWh/m^2yr) for different orientations			
			North	South	East	West
1	Single Clear 6 mm V. T = 0.881 SC = 0.95 SHGC = 0.815 U-Value = 6.172W/m^2.^{0}C	5%	30.1	30.1	29.6	29.4
		10%	31.3	31.3	31.2	31
		20%	31.6	31.7	31.6	31.5
		30%	31.9	31.9	31.9	31.8
		40%	32.1	32.1	32	32
2	Double Clear 6/12/6 mm V. T = 0.781 SC = 0.81 SHGC = 0.698 U-Value = 2.742W/m^2.^{0}C	5%	29.8	29.7	29.3	28.9
		10%	31.1	31.1	30.9	30.7
		20%	31.5	31.5	31.4	31.3
		30%	31.8	31.8	31.7	31.7
		40%	31.9	31.9	31.9	31.9
3	Double Clear Low-e 6/12/6 mm V. T = 0.745 SC = 0.65 SHGC = 0.563 U-Value = 1.777W/m^2.^{0}C	5%	29.7	29.6	29.1	28.8
		10%	31.1	31	30.7	30.6
		20%	31.5	31.4	31.3	31.3
		30%	31.7	31.7	31.7	31.6
		40%	31.9	31.9	31.9	31.8
4	Double Clear Heat Mirror 6/12/6 mm V. T = 0.531 SC = 0.40 SHGC = 0.344 U-Value = 2.02W/m^2.^{0}C	5%	29.2	29.1	28.6	28.2
		10%	30.7	30.6	30.4	30.2
		20%	31.2	31.1	30.9	30.8
		30%	31.5	31.5	31.4	31.4
		40%	31.7	31.7	31.7	31.6

Table 7. **Saw-tooth**: annual lighting energy saving for different types of glazed, different glazed area and for different orientations.

No	Glazing Type	Glazed area as percentage of roof area	Energy savings (kWh/m^2yr) for different orientations			
			North	South	East	West
1	Single Clear 6 mm V. T = 0.881 SC = 0.95 SHGC = 0.815 U-Value = 6.172W/m^2.^{0}C	5%	28.5	30.1	29.7	29.4
		10%	30.8	31.3	31.2	31.0
		20%	31.6	31.7	31.6	31.6
		30%	31.9	31.9	31.8	31.9
		40%	32.1	32.1	32	32.0
2	Double Clear 6/12/6 mm V. T = 0.781 SC = 0.81 SHGC = 0.698 U-Value = 2.742W/m^2.^{0}C	5%	28.5	29.8	29.3	28.9
		10%	30.8	31.1	30.8	30.7
		20%	31.6	31.5	31.4	31.3
		30%	31.9	31.8	31.8	31.7
		40%	32.1	31.9	31.9	31.9
3	Double Clear Low-e 6/12/6 mm V. T = 0.745 SC = 0.65	5%	28.5	29.6	29.1	28.8
		10%	30.8	31	30.8	30.6
		20%	31.6	31.5	31.3	31.2
		30%	31.9	31.7	31.7	31.7

	SHGC = 0.563 U-Value = 1.777W/m^2.^{0}C	40%	32.1	31.9	31.9	31.9
4	Double Clear Heat Mirror 6/12/6 mm V. T = 0.531 SC = 0.40 SHGC = 0.344 U-Value = 2.02W/m^2.^{0}C	5%	28.5	28.6	28.6	28.2
		10%	30.8	30.2	30.4	30.2
		20%	31.6	30.6	31.0	30.8
		30%	31.9	31.2	31.4	31.4
		40%	32.1	31.4	31.7	31.6

4. CONCLUSIONS

The present study shows that the major parameters consuming the building energy are the cooling, lighting, equipments and hot water. The study also demonstrates the importance of taking into account the interaction between artificial lighting and air-conditioning systems. It was found that daylighting the base case hall building causes significant reduction in the lighting and cooling energy consumption and consequently reduction in the total energy consumption by about 22 %. The combined effect of the top-lighting shapes, glazing types, glazing area and top-lighting orientations causes significant reduction in the annual lighting energy consumption in terms of (kWh/m^2 yr). Saving in the annual lighting energy remains almost unaffected by its glazed area if its visible transmittance is high and it increases with the glazing area if glass visible transmittance is low. Top-light orientation does not affect the annual lighting energy savings if the glass visible transmittance is high (greater than 0.881) or low (less than 0.531). Finally, it is worth to mention that the gain from reducing the electrical energy consumption in artificial lighting and air conditioning systems of buildings is not only affecting the end users but also affecting the national economy.

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