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Energy savings due to daylight and artificial lighting integration in office buildings in hot climate

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Abstract
Reducing energy consumption while maintaining acceptable environmental quality in buildings has been a challenging task for building professionals. In office buildings, artificial lighting systems are a major consumer of energy and can significantly contribute to building cooling load. Furthermore, although reliable, artificial lighting does not necessarily provide the required quality of lighting. Significant improvement in lighting quality and energy consumption can be achieved by proper integration of daylight and artificial lighting. The objective of this study is to investigate the energy performance of office buildings resulting from daylight and artificial lighting integration in hot climates. A parametric analysis is conducted to find the impact of different window design parameters, including window area, height and glazing type, on building energy performance. Results have shown that as much as 35% reduction in lighting energy consumption and 13% reduction in total energy consumption can be obtained when proper daylighting and artificial lighting integration is achieved.

Keywords: Daylight integration; Window design; Energy efficiency.

1. Introduction

Demand for a better environmental quality in buildings is growing with the rising concern about occupants' health and productivity. At the same time, there is a genuine concern about rising energy consumption in buildings. Improvement in indoor environmental quality can be achieved through numerous means, but likely to require extra energy. When proper design and operational strategies are employed, significant improvement in indoor environmental quality can be achieved at the same or at reduced energy consumption.

The quality of indoor lighting is a crucial factor in determining the overall environmental quality in buildings. Daylight is considered to be the best source of light for its good color rendering and its quality that closely matches human visual response. Working for an extended time under artificial lighting is believed to be harmful to health. Conversely, daylight is believed to result in less stress and discomfort for occupants. Many research studies have demonstrated that daylight can help to maintain occupants' health and appropriate use of daylight decreases the occurrence of headaches, Seasonal Affective Disorder (SAD), and eyestrain [1]. Another important positive effect of daylight is improved mood which could result in increased job satisfaction, work involvement, motivation, organizational attachment, and lowered absenteeism [2]. The Reno Post Office in Nevada was refurbished in 1996 with the installation of indirect and better quality electric lighting. Reports from the first 20 weeks in the new building showed productivity increasing more than 8% and leveling to 6% [3]. Using an open office layout with integrated daylighting in their offices in Sunnyvale, California in 1983, Lockheed Martin designers successfully increased interaction among their engineers. This increase helped improving contract productivity by 15%. Lockheed officials believe that the higher productivity levels pertaining to daylighting helped them win a $1.5 billion defense contract. VeriFone, Inc., built a new daylit Worldwide Distribution Center Located near Los Angeles, California, and reported increased productivity of more than 5% a year and a half after they started using their new building. In addition, there was an increase in the total product output by 25% to 28% [2].

Despite of the clear advantage of daylighting, artificial lighting is an attractive alternative to architects who believe that they have total control over interior lighting levels. This has resulted in increasingly less than a desirable environmental quality, but more importantly, in unnecessary increase in energy consumption represented by the amount of electric energy consumed by artificial lighting and the increased cooling energy due to the additional heat gain from artificial lighting.

By properly integrating daylight with artificial lighting, the required lighting control and the quality of the indoor visual environment can be attained. At the same time, significant reduction in lighting and cooling energy can be achieved due to reduced dependence on artificial lighting. It is evident that energy savings resulting from daylight utilization may not only lower electric lighting expenditure and reduce peak electrical demands, but will also decrease cooling energy consumption and potentially reduce the size of air conditioning plants [4].

Many studies have investigated the impact of daylight integration on energy consumption. In 2002, Bodart evaluated the impact of lighting energy savings on global energy consumption in office buildings. It was concluded that the potential of global primary energy savings (heating, cooling, humidification, and lighting) by taking into account the daylight availability is around 40% for the glazing usually used in office buildings in Belgium. These savings could grow up to 50% for high performance glazing [5]. Ghisi and Tinker [6] presented a methodology to determine the potential for energy savings on lighting when there is daylight integration with the artificial lighting system. The energy analysis work was performed using the Visual DOE program for the climatic conditions of Leeds, in the UK, and Florianopolis, in Brazil. It was observed that the potential for energy savings on lighting ranged from 10.8% to 44.0% in Leeds and between 20.6% and 86.2% in Florianopolis. Krarti et al. [7] analyzed the effects on artificial lighting savings of building geometry, window area, window type, and perimeter area for four US locations when daylight is utilized. Energy savings due to daylighting integration with artificial lighting can reach 70% of the lighting energy consumption. Field measurements were conducted for a fully air conditioned open plan office using a photoelectric dimming system. The estimated annual saving was 365 kWh, representing a 33% reduction in energy use for electric lighting under the dimming control in the office [8].

In Saudi Arabia, according to the official report of the year 2007 [9], energy consumption in building sectors reached about 76% with about 11% allocated to commercial buildings including office buildings as shown in Figure 1. Office buildings, because of their functional and environmental requirements, have special characteristics compared to other buildings. They are required to provide better environmental quality to enhance occupants' productivity and performance, but at the same time consuming a large proportion of the total energy to maintain lighting requirements and visual comfort. As much as 20% of the total energy consumed by an office building goes to lighting [10]. Therefore, it is obvious that office buildings have great potential for energy savings and enhanced indoor environmental quality when daylight is integrated with artificial lighting. The objective of this study is to investigate energy savings potentials resulting from daylight and artificial lighting integration in an office building located in a hot climate represented by Dhahran, Saudi Arabia. As window’s characteristics may positively or negatively affect energy savings due to integration, the impact of influencing characteristics is investigated through parametric analysis.

2. Methodology

A theoretical modeling approach is utilized to investigate potential energy savings due to daylight and artificial lighting integration in office buildings under the specified climatic conditions. The research methodology consists of three main phases as illustrated in Figure 2. First, a base model is formulated based on the commonly practiced designs and operational characteristics as revealed from survey questionnaire on selected local design offices and interviews of building operators as well as relevant standards and logic judgment. The model is comprised of a thermal model and a lighting model, which are simulated under the selected climatic conditions using a simulation tool that integrates energy and daylight analysis. Then, the formulated model is verified through a comparison of base model initial results with available simulation or measured data acquired for similar building type under similar climatic conditions. In the third phase, building energy performance due to daylight integration on energy savings and the impact of glazing type and window configuration are investigated.

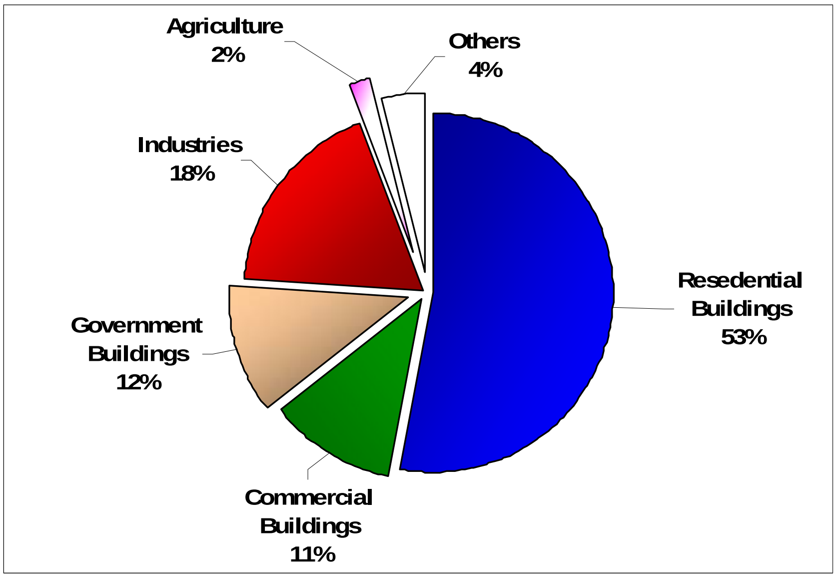

Figure 1. Distribution of sold energy all over Saudi Arabia in 2007 [9]

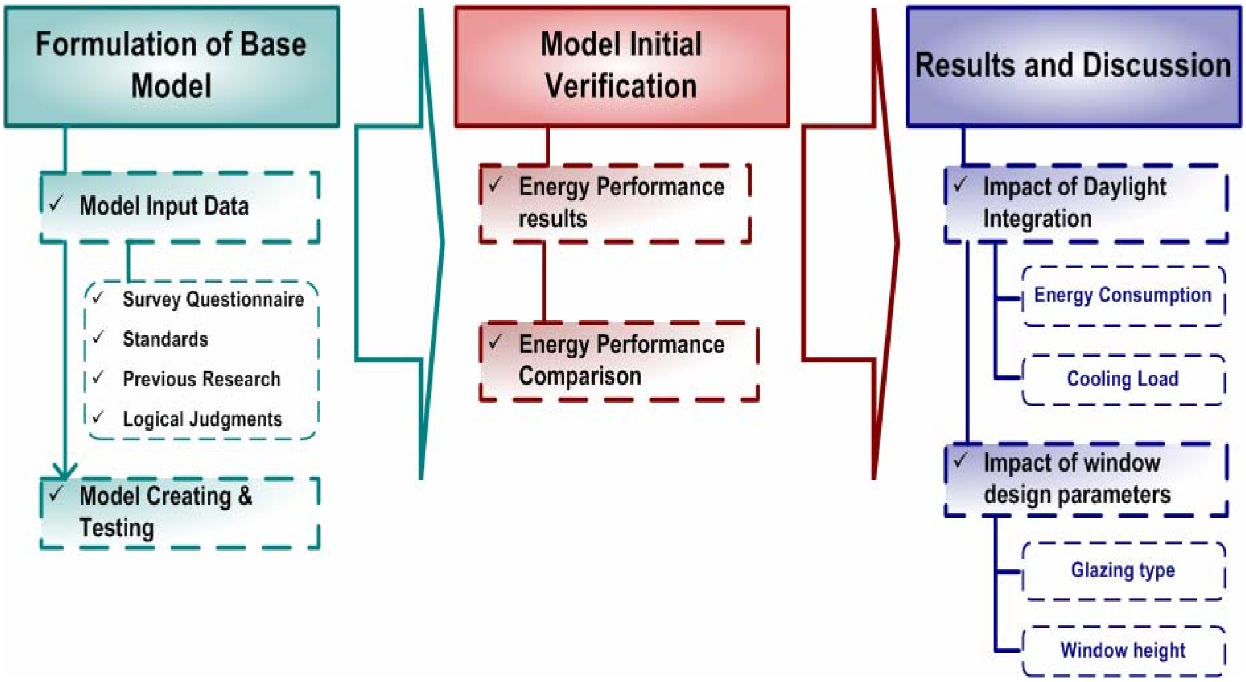

Figure 2. Flow chart of research methodology

2.1 The simulation tool

Considering the objectives and scope of the study, the energy analysis program VisualDOE is utilized in this work since it implements the daylight calculations from DOE-2, therefore, making it possible to evaluate the integration of daylight with artificial lighting system. Furthermore, the program has been widely validated for accuracy and consistency and offers a great capability for simulating a wide range of design features and energy conservation measures, including the integration of daylight with artificial light. The program also provides the ability for rapid development of energy simulations, reducing the time required to build a DOE-2 model.

2.2 Modeled climatic conditions

The modeled climatic conditions are of Dhahran, Saudi Arabia (Lat. 26°17'N, Long. 50°09'E, Alt. and 17 m above sea level). Its climate is characterized by being hot and humid in summer, and cool in winter with a total average annual rainfall of about 80 mm (during the winter) [11]. Temperatures can rise to more than 50 °C in the summer, coupled with extreme humidity (85-100%). Dhahran holds the record for the highest dew point ever recorded in the world. On July 8th, 2003 the dew point was 35 °C. The air temperature at the time was 42 °C giving a heat index of 78 °C. It also holds the record for the highest temperature recorded in the country (51 °C). In winter, the temperature rarely falls below 2 °C or 3 °C. The variable annual heating degree days at 20.5 °C base temperature are 426 and the variable annual cooling degree days at 20.5 °C base temperature are 2371 [12].

3. Formulation of base model

The base model is formulated to simulate the intended building type both in terms of physical and thermal characteristics. The model is developed to represent an office building based on data obtained from a survey questionnaire conducted to cover selected consultant offices in Dhahran area. Since questionnaire surveys are limited by respondents' input and understanding, it is possible to encounter missing or inaccurate information that is incompatible with normal practices. In order to complete model formulation, certain assumptions were made based on standards, previous research, and logical professional judgment.

The modeled building is a square in shape with four perimeter zones and an internal zone as shown in Figure 3. The building covers 484 m^2 with 22 m long on each principal orientation. The perimeter zones depth was selected to be 7 m based on a study that stated that daylight within a building will be significant within about twice the room height of a windowed façade [13]. Two lighting sensors were located; the first one controlling 50% of the lighting at 2.0 m away from the window wall and the second one controlling 30% of the lighting at 5.0 m away from the window wall. The main model characteristics are described in Table 1.

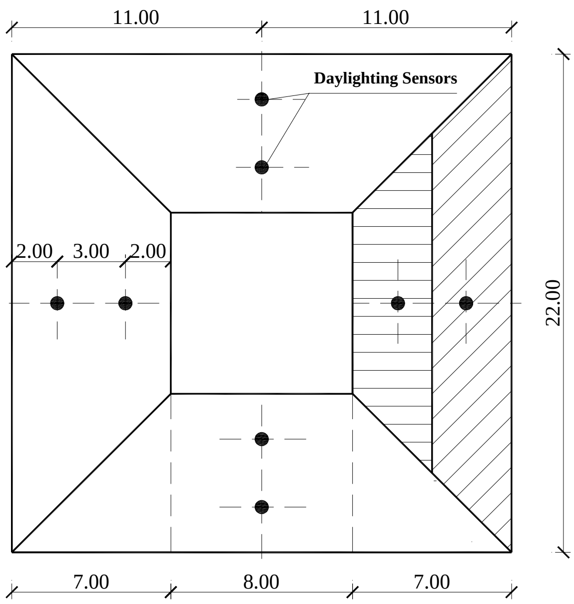

Figure 3. Schematic layout of the office building base case

Given that the developed model represents a baseline for investigating energy saving potentials associated with daylight and artificial lighting integration, it is important, as a first step, to check the reliability and accuracy of the formulated model in predicting the energy performance. This can be carried out by comparing model prediction with available simulation or measurement data obtained for similar building type subject to similar climatic conditions. Simulation results show that the total energy consumption of the modeled building is about 2960 kWh/m^2/year. Cooling consumes the major part which represents about 53% of the total consumed energy. The lighting and equipment consume about 23% and 24% respectively as illustrated in Figure 4. Comparing these results with relevant and similar data from literature shown in Table 2 reveals that model predictions of energy consumption and distribution are comparable to those predicted for office buildings in other locations with similar climate. The model is consequently judged as a reasonably accurate and reliable tool for predicting energy performance of office buildings.

Table 1. The main characteristics of the office building base case

Office Building	**Description**
Location	Dhahran, Saudi Arabia
Plan Shape	Square
Number of floors	10
Clear Floor Height	3.6 m
U-Value: Exterior Walls	0.53 $W/m^2.^0C$
Roof	0.61 $W/m^2.^0C$
Interior Floor	0.94 $W/m^2.^0C$
Ground Floor	0.51 $W/m^2.^0C$
solar absorptance	0.5 for external walls and the roof
Occupancy Density	15 m^2/person [14]
Lighting Power Density (LPD)	22 W/m^2 [15] & [16]
Equipment Power Density (EPD)	15 W/m^2 [17]
Infiltration	0.5 ACH (building with average tightness)

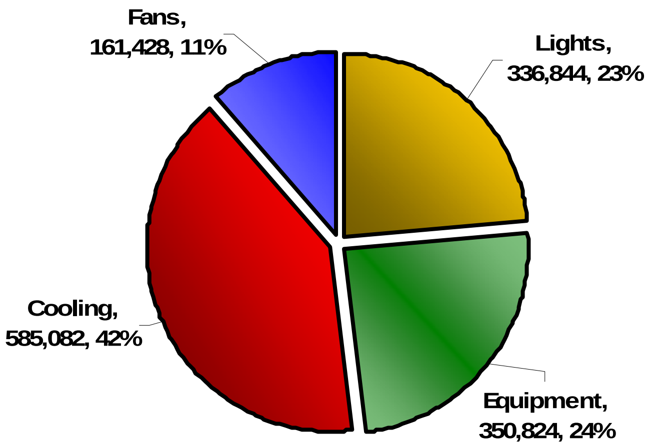

Figure 4. Building energy consumption of the building base case

Table 2. Energy consumption end-use comparisons

Location	Energy End-Use (%)			Ref.
	Cooling	Lighting	Others	
ASEAN Cont.	61.1%	22.5%	15.5%	[15]
USA	30%	35%	35%	[15]
Hong Kong	NA	20-30%	NA	[18]
Egypt	NA	36%	NA	[19]
Saudi Arabia	60%	20%	20%	[10]
Base Case	53%	23%	24%	Simulated

4. Results and discussions

To investigate the impact of artificial lighting and daylight integration on magnitude and pattern of reduction in lighting and cooling energy, the energy performance of the modeled building is compared and analyzed for various window's characteristics and integration schemes. A comparison between the magnitudes of energy consumption both with and without daylight integration is shown in Figure 5. It can be seen that a significant reduction is achieved for the major energy consumption components. The bulk of energy reduction is obtained in lighting energy with about 35%. This is an indication of the high potential of daylight to compensate for artificial lighting when properly integrated. Additionally, a reduction of 9% is obtained for the cooling energy. This reduction in cooling energy is a byproduct of reduction in heat gain and consequently the associated cooling load due to artificial lighting. The combined effect of daylight integration has resulted in a total reduction of about 13% of the total building energy consumption, which is a significant reduction that can be directly reflected on the cost of energy.

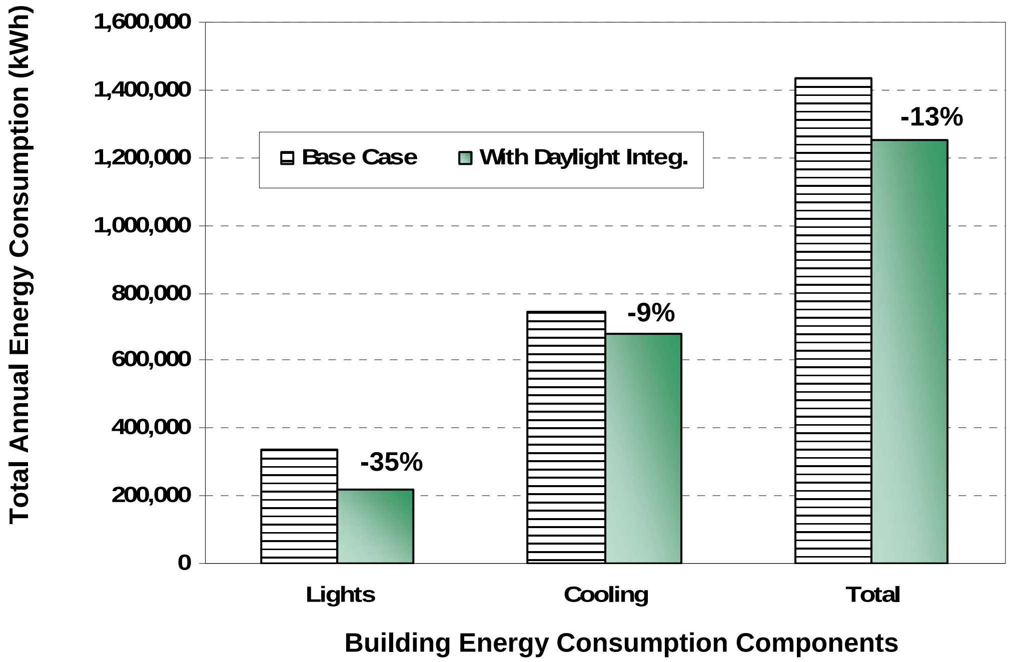

Figure 5. Impact of daylight integration on the building energy consumption

Although the introduction of daylight and its integration with artificial daylight has been shown to improve building energy performance, it should be recognized, however, that window's physical, thermal and visual characteristics are important in determining the net contribution of daylight integration to the overall energy performance. Increasing the window's area or selecting a window with high light transmittance will introduce more daylight, but at the same time can introduce a significant amount of additional heat gain resulting in more cooling energy. Proper selection of window's characteristics is therefore required for better energy performance due to daylight and artificial light integration. The glazing type and the number of glazing layers are among the critical parameters that must be considered when designing windows for daylight. Four different glazing types were selected for investigation based on the commonly used types in the local area. Tinted glazing was not selected in this study because of its low lighting transmittance. Thermal and lighting characteristics of investigated glazing types are given in Table 3.

Figures 6 and 7 show the reduction in lighting energy associated with daylight integration for various types of windows at different window to wall ratios (WWR) and zone orientations. It can be noticed that significant reductions in lighting energy is achieved for all glazing types with a dramatic reduction in the lighting energy consumption when the window area is increased from 0% to 5%. Further increase in window's area (up to a WWR of 50%) results in a steady but limited decrease in energy consumption. The reduction in lighting energy consumption ranges from about 40% to 54% for all glazing types. The highest reduction in energy consumption is associated with the glazing type with the higher visible transmittance. This is because the amount of lighting transmitted into the space is higher resulting in a reduced artificial lighting usage. Furthermore, higher WWR results in reduced lighting energy consumption for all glazing types as higher glazing area will introduce more natural light to the space and hence less reliance on artificial lighting. The difference in lighting energy consumption among the different types of glazing decreases with higher WWR as the window's area becomes a predominant factor in determining reduction in lighting energy consumption. Similar lighting energy consumption behavior is obtained for the other zone orientations as indicated by the simulation results for the east zone shown in Figure 7.

Table 3. Glazing types used

Glazing Type	No: of panes	Visible Transmittance	Shading Coefficient (SC)	Solar Heat Gain Coefficient (SHGC)	U-Value $W/m^2.K$
Single Glazed Clear 6 mm **(Clr SG)**	1	0.88	0.95	0.81	6.17
Double glazed Clear 6/12/6 mm **(Clr DG)**	2	0.78	0.81	0.70	2.74
Double Glazed Clear Low-e 6/12/6 mm **(DG Low-e)**	2	0.74	0.65	0.56	1.78
Double Glazed Clear Heat Mirror 6/12/6 mm **(DG HM)**	2	0.53	0.40	0.34	2.02

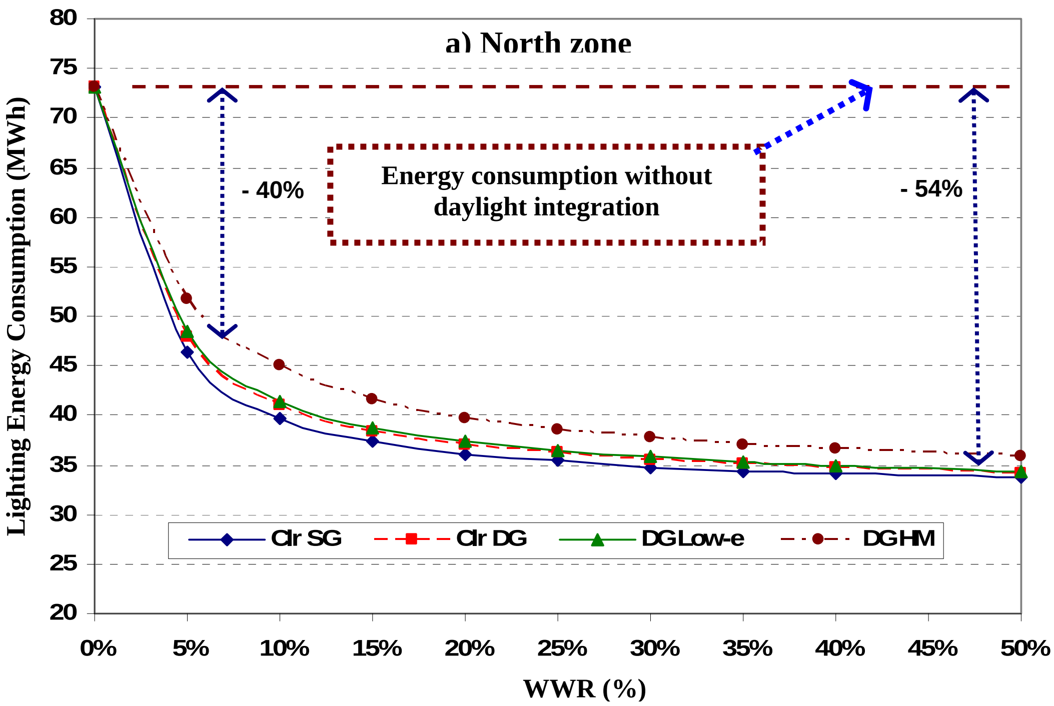

Figure 6. Lighting energy consumption variations with glazing area for different glazing types, (North zone)

Reducing the magnitude of artificial lighting by utilizing daylight does not only result in reduced lighting energy, but additionally in less cooling energy due to decreased light-generated heat gain. At the same time, the introduction of daylight by increasing window's area or selecting a high transmittance glazing will introduce additional heat gain and cooling energy requirements. The combined impact of these factors will result in a unique change in total energy consumption. Figures 8 and 9 illustrate the impact of window's characteristics and area on total energy consumption with and without daylight integration with artificial lighting for different orientations. It can be seen that the total energy consumption steadily increases with the window's area but with different rates depending on the window's type and orientation due to different exposure and transmittance of solar heat. The heat mirror double glazed window compared to the single glazed window, for example, is associated with a reduced energy consumption of 46 kWh/m^2/year for the east zone, and 18 kWh/m^2/year for the north zone at 20% window-to-wall ratio. The difference becomes more pronounced as the window's area increases.

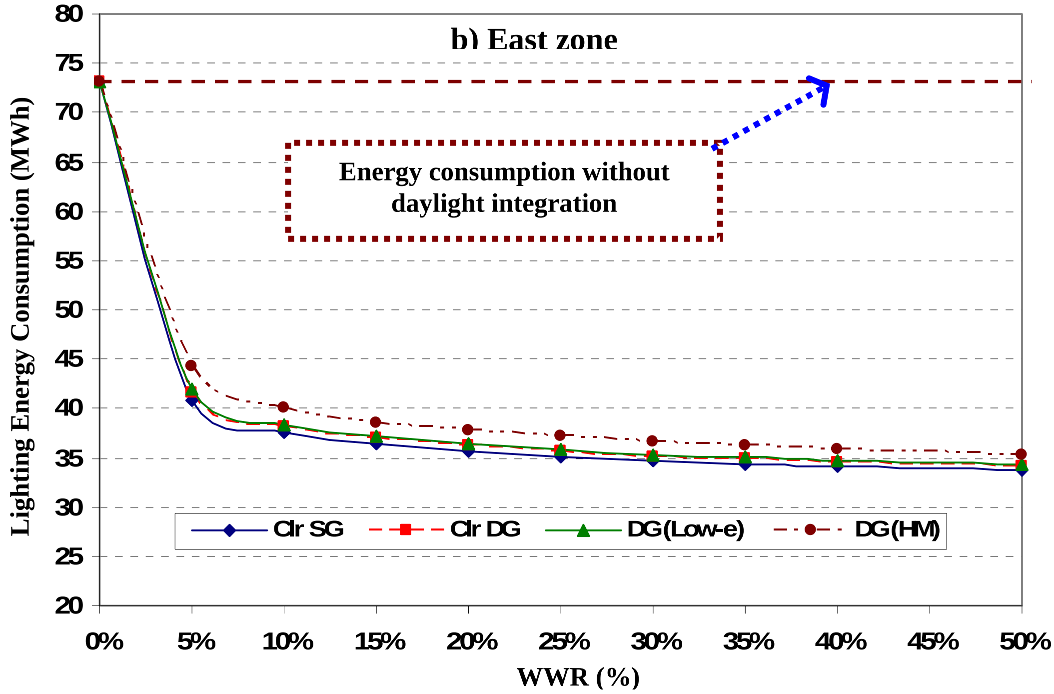

Figure 7. Lighting energy consumption variations with glazing area for different glazing types, (East zone)

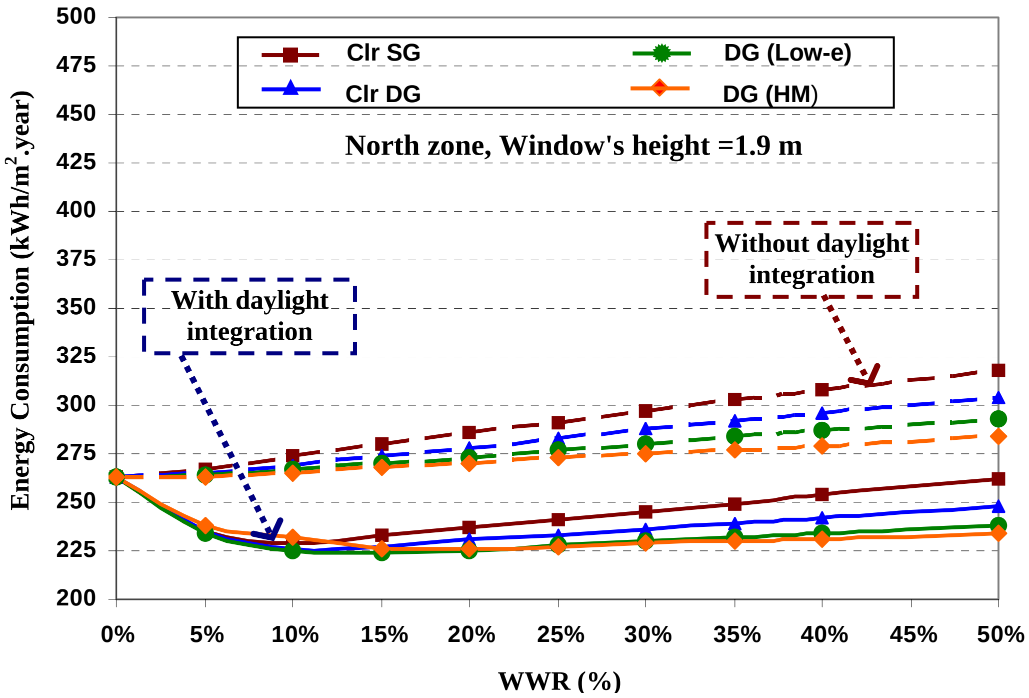

Figure 8. Variations of total energy consumption with glazing area due to daylight integration for various glazing types, (North zone)

By integrating daylight with artificial lighting, increasing the window's area results initially in a noticeable reduction in total energy consumption for all types of windows, but no or limited additional reduction is obtained by further increase of area indicating a diminishing potential for energy savings due to daylight integration. Furthermore, beyond a certain window-to-wall ratio, depending on window's orientation, the reduction due to daylight integration is maintained almost the same while the total energy requirement follows a variant increasing trend similar to that in the absence of daylight integration indicating an increased heat gain and cooling energy requirements. For the north orientation, the window's area can be increased to as much as 15% for the double glazed heat mirror window and 10% for the clear single glazed window before an increasing trend in energy consumption occurs. Meanwhile, for the east zone, the double glazed heat mirror window area can only be increased to 10% and 5% for the single glazed window before an increasing trend in energy consumption occurs. These values set the upper limits of window-to-wall ratios at which minimum energy consumption is achieved for different window's types and orientations. Furthermore, it cab be concluded that for windows with less solar radiation transmittance (higher shading coefficient) and less light transmittance, the full potential for energy reduction due to daylight integration is recognized at larger areas. Furthermore, for orientations other than the north, which receive relatively higher amounts of solar radiation, the impact of window's type on the reduction of total energy consumption due to daylight integration is more recognizable at small window's area and becomes less pronounced with all types exhibiting the same level of reduction at larger areas. For the north zone which receives the least solar radiation, the clear single glazed window performs slightly better than other types as it allows more daylight but less solar radiation due to reduced exposure.

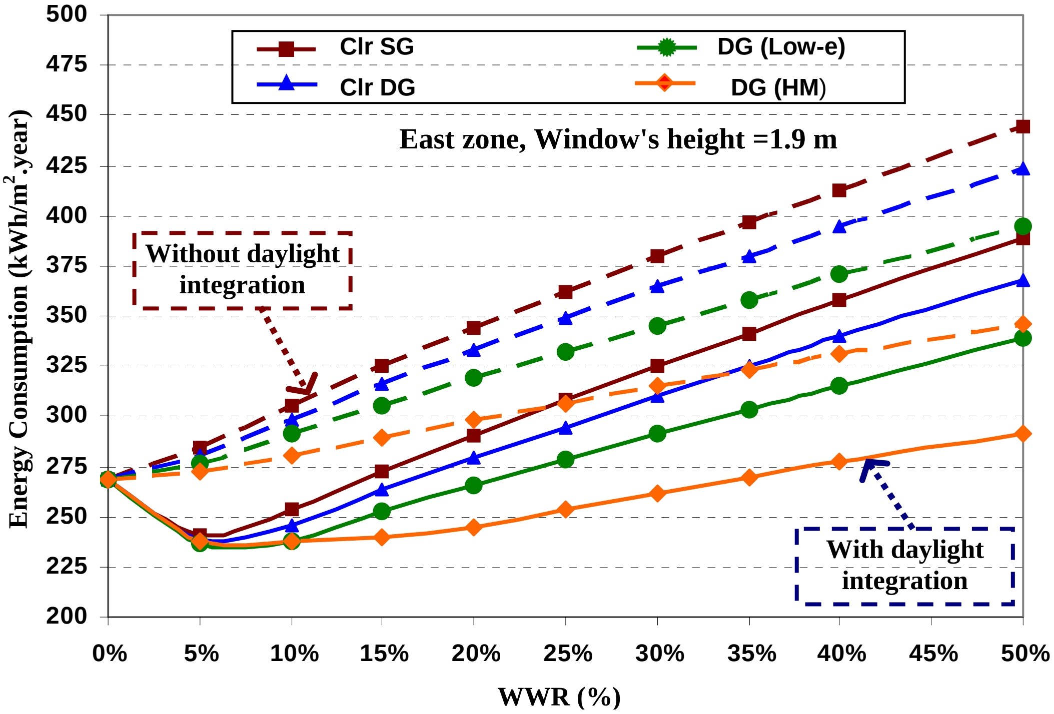

Figure 9. Variations of total energy consumption with glazing area due to daylight integration for various glazing types, (East zone)

Another important factor that may have a crucial influence on the impact of daylight integration on energy consumption is the height of window. Window's height is defined as the distance from the window sill to the window lintel. It is clear that the larger the window height, the greater the amount of light transmitted into the space. Window height also has a significant impact on the depth which light can reach in the space. The daylight penetration depth increases as the window height is increased. In this study, various window heights were examined starting from 1.20 m up to the ceiling height (2.60 m). Five different window heights were selected with an interval of 0.55 m to cover a wide range of possible window heights, as shown in Figure 10. Window sill is maintained at 1m for all simulated cases, as the influence of daylight is preferred at the work plane height (0.76 m) and can be ignored at a lower height. Results revealed that there is a recognizable influence of window height on the building energy performance.

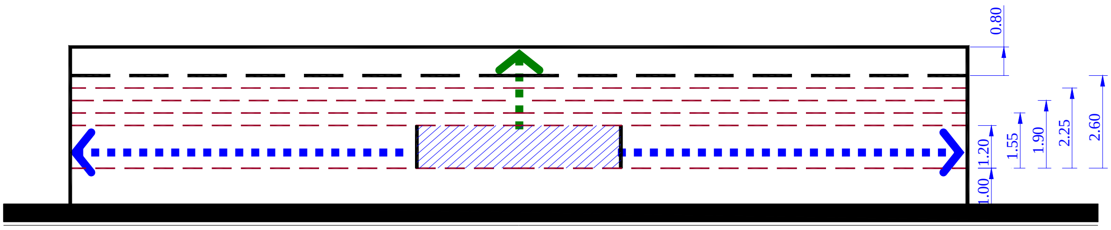

Figure 10. Investigated window configuration schemes

The impact of different window heights on lighting energy consumption when daylight is integrated with artificial lighting is illustrated in Figures 11 and 12 for different zone's orientations. It can be depicted that the impact of window's heights on the reduction of lighting energy consumption is generally more pronounced at lower window-to-wall ratio particularly for the north zone. This can be attributed to the high relevance of the window's height in determining the amount of transmitted daylight and the depth of its penetration when at small window's area. Meanwhile, the impact of window's height diminishes as the window's area increases beyond 40%. The maximum reduction in lighting energy consumption of about 53% is attained at window-to-wall ratio of about 70% for all window heights. Similar lighting energy consumption trends are obtained for the other principal zone orientations.

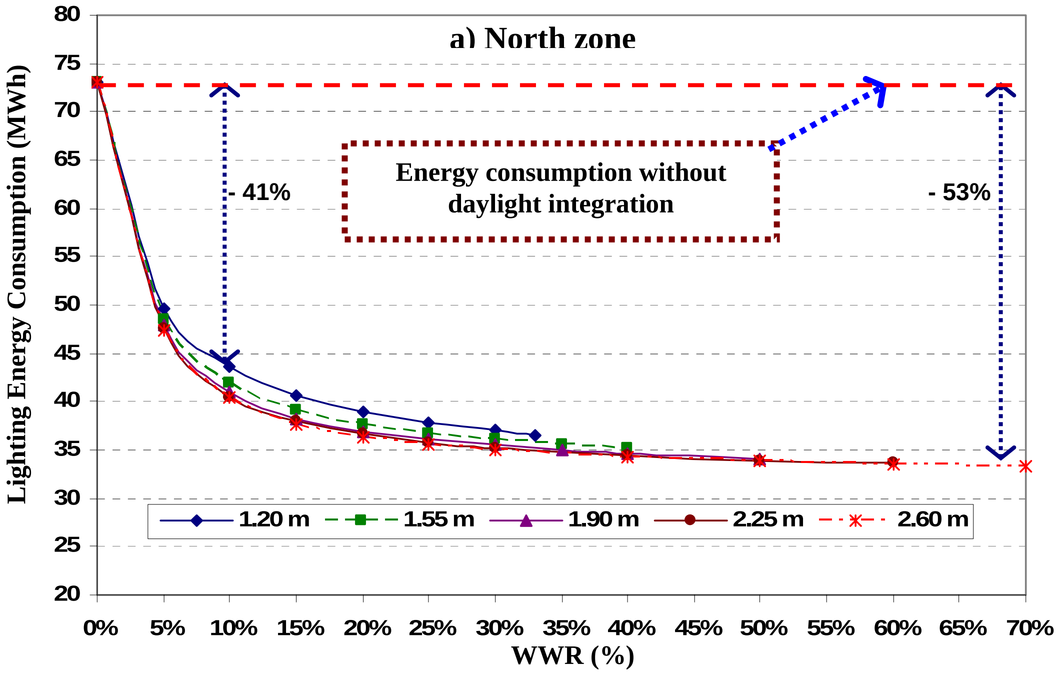

Figure 11. Lighting energy consumption variations with glazing area for various heights of a double glazed clear window, (North zone)

The influence of different window heights on the total building energy consumption for two principal zone orientations when a clear double glazed window is used is illustrated in Figures 13 and 14. Results showed that there are generally negligible variations in the building's total energy consumption with window's heights. The reduction in total energy consumption for the north zone, however, shows little dependence on window's height at lower window's area compared to other zones. A larger window height results in slightly lower total energy consumption at a glazing area of about 10%. This reduction in energy consumption can be explained by the decrease in lighting energy requirement due to increased daylight transmission at larger window's height.

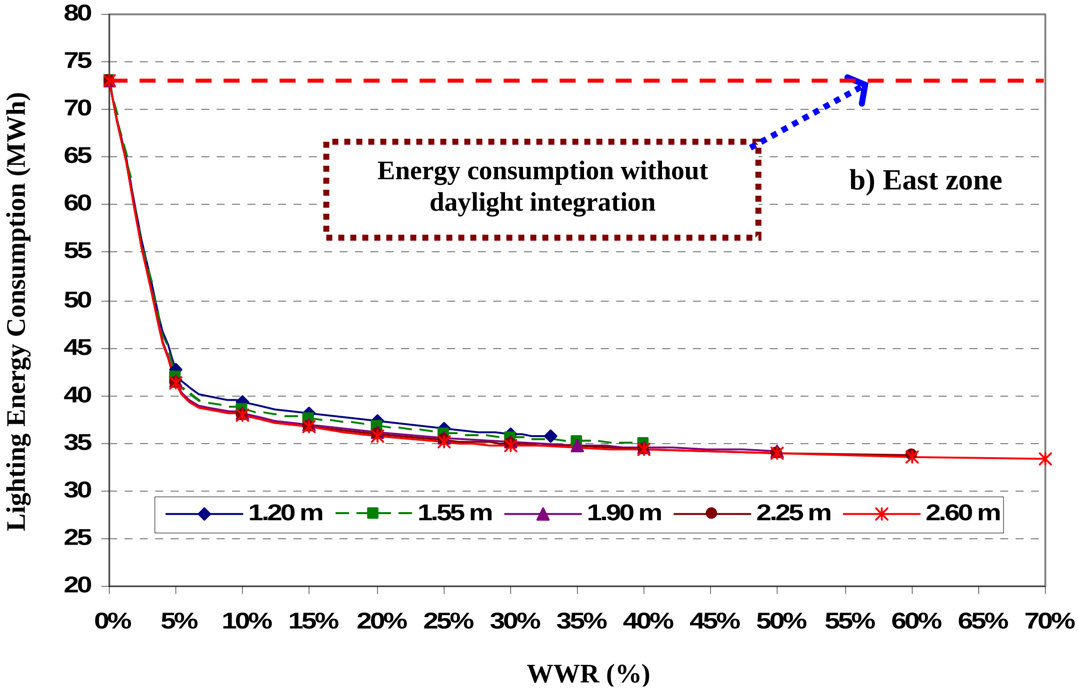

Figure 12. Lighting energy consumption variations with glazing area for various heights of a double-glazed clear window, (East zone)

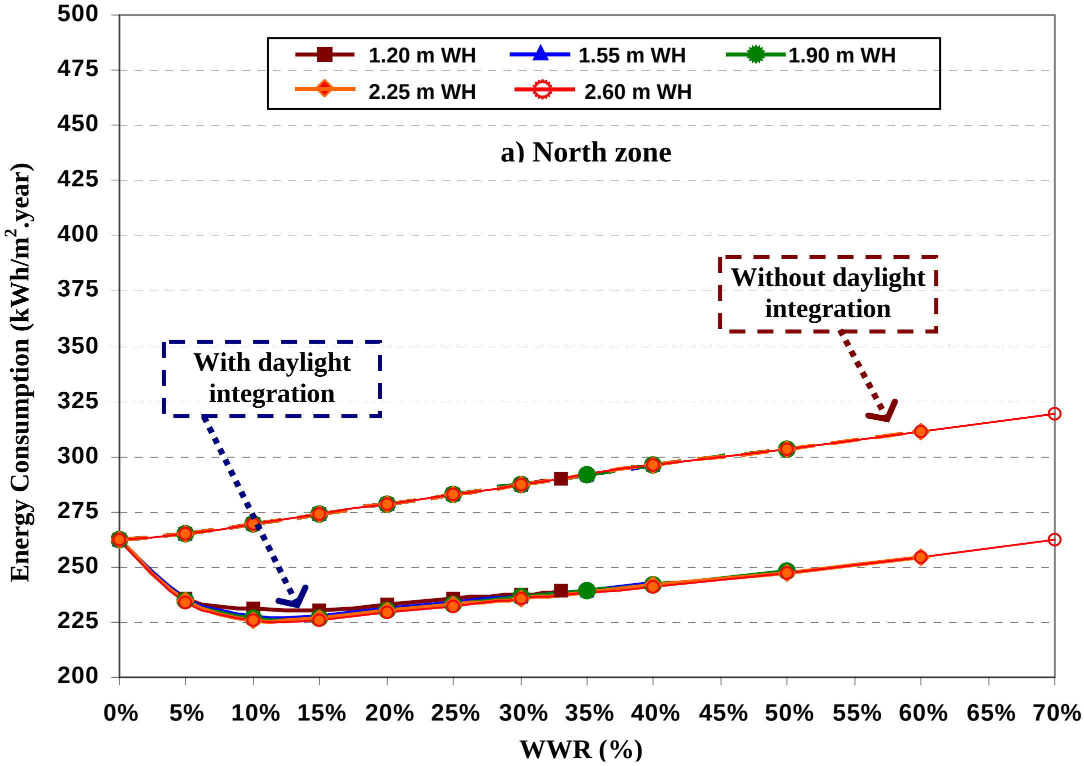

Figure 13. Total energy consumption for various window heights, double-glazed clear, North zone

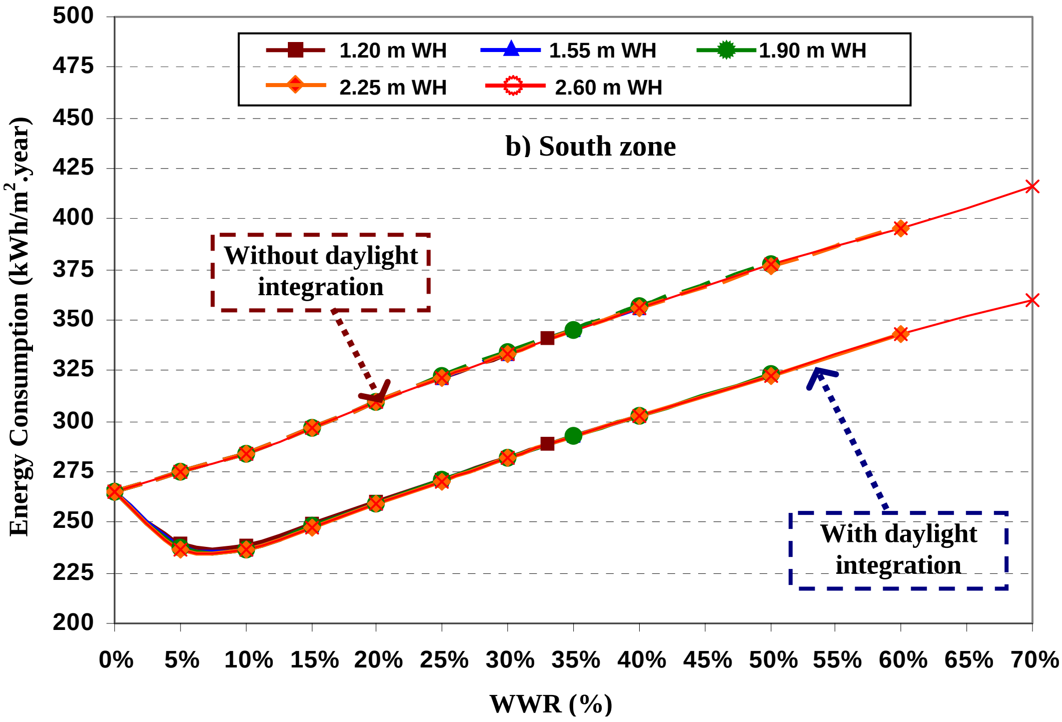

Figure 14. Total energy consumption for various window heights, double-glazed clear, South zone

5. Conclusion

Office buildings, particularly in hot climates, are major consumer of electric energy with lighting system accounting for a large proportion of the total energy consumption. Many strategies including the integration of daylight with artificial lighting through lighting controls can be used to contribute to energy conservation in office buildings. Energy savings due daylight integration will not only result in a lower lighting energy, but additionally in a reduced cooling energy and potentially a smaller air conditioning system.

The impact of daylight integration with artificial lighting on energy consumption in office buildings under hot climatic conditions was investigated. Results showed that a reduction of about 35% of the lighting energy and 13% reduction in the total energy can be achieved. Investigation of the impact of various types of glazing on lighting energy consumption when daylight integration is employed revealed that a significant reduction in energy consumption is obtained for all window's types with noticeable difference between the clear single glazed window and other types particularly at lower window-to-wall ratio. The highest reduction in lighting energy is obtained for the window with the higher light transmittance. On the other hand, the reduction in total energy which includes the cooling energy is found to be greatly influenced by the shading coefficient which determined the amount of solar heat gain. Lower total energy consumption can therefore be obtained at a lower shading coefficient value. Investigation of the impact of window's height on energy performance due to lighting integration revealed that at a small window's area, lower lighting energy consumption is obtained when a window height is increased. The impact of windows height diminishes as the window-to-wall ratio is increased. No significant impact of window's height on total energy consumption is observed. In general, it can be concluded that daylight integration with artificial lighting can significantly contribute to energy reduction in office buildings. This reduction can be enhanced when proper window's design is employed.

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