

SKYLIGHT DESIGN PERFORMANCE EVALUATION METHOD DEVELOPMENT WITH THERMAL AND DAYLIGHT SIMULATION

Xianou Li, Frederick Wong, and Yihan Li
Arup International Consultants (Shanghai) Co Ltd

ABSTRACT

This paper presents a methodology for optimizing skylight design with the considerations of thermal comfort, daylight availability and energy performance by integrated daylight and thermal simulation. Dynamic thermal modelling programmed *IES<VE>* and daylight simulation engine *Radiance* are used as simulation tools to study energy performance of a shopping mall atrium with a skylight on the roof top located in Hangzhou, China. The sensitivity of design options, such as skylight types, shading devices and glass configuration selection etc., on lighting and cooling energies are compared based on the simulation results. Separated roof light design with double low-e glazing is with the best energy performance. Energy performance comparison chart (S-chart) for skylight design option evaluation is then developed based on the simulation results for this study. This chart can be used as a fast check tool to guide energy efficient skylight design and to support a quick design assessment for designers in various design stages.

INTRODUCTION

Atrium skylight design is popular in shopping malls not only supplement spatial connection and aesthetic value of building to attract shopper, which can also work as a buffer between inner and outer environments to enhance building environment by maximizing daylight penetration in the building core. However, poorly designed skylight may cause problems of glare and excessive solar heat gains which will lead to occupant thermal dissatisfaction and more energy consumption happened to maintain a conditioned environment. Common strategies of reducing skylight area, installing shading devices and solar control glass etc. are ways to prevent the risk of overheating and glare, while at the same time most of these design alternatives may result in reduced daylight penetration and increased artificial lighting use. Besides, the influence of these design strategies to cooling load reduction and artificial lighting energy increasing are complex and interrelated, if strategies are integrated together. A sophisticated method is demanded to heighten efficiency and cost effectiveness of design process to overcome the complexity by simplified analysing sequence

particularly in early design phase for scheme comparison.

In this paper, one fast check method on design performance was developed. The performance of an atrium with a rectangle skylight in a shopping mall in Hangzhou, China was firstly studied as an example to verify building environmental condition and balance between impacts to cooling and lighting energies, and follow up studies were conducted to check sensitivity of various design options related to climate conditions as well. It will be easier and faster to determine the trade-off effects caused by design alternatives referring to generated energy performance chart and to optimize skylight design.

METHODOLOGY

The impacts of design alternatives to energy performance mainly are the HVAC energy consumption to maintain indoor thermal comfort and daylight-linked artificial lighting energy from changed daylight availability. From the viewpoint of energy saving, it will be reasonable to evaluate design performance depends on the total energy consumption (the sum of artificial lighting and HVAC energy).

Dynamic thermal modelling technique is widely used in building heating/cooling load and internal thermal comfort analysis, which is also a common technique on building performance assessment adapted in high-performance building and green building certification codes. In this study, dynamic thermal simulation programme *IES<VE>* was used to analyse atrium thermal environment and to calculate the cooling load by taking into account the schedule and nature of each heat gains, such as internal gains and solar heat gains.

There are several factors that will impact the occupant thermal comfort which are metabolic rate, clothing insulation, air temperature, radiant temperature, air speed and humidity. Occupant dissatisfaction from high mean radiant temperature in summer should be paid attention in the case of skylight design. The relatively high mean radiant temperature could come from direct solar radiation and also radiation of neighbouring high temperature air. Shading devices and solar insulation glazing can help reduce the impacts from radiation. Besides,

reducing zone air temperature is another way to improve thermal sensation but will make extra energy consumption for mechanical system. In this study, the annual cooling load calculation for each design alternative was based on constant thermal comfort with reducing thermal zone air temperature if necessary. Associated cooling energy to maintain the air temperature was calculated with assumed total HVAC system efficiency. Since the circulation spaces in the study are located in the core of the shopping mall, cooling load exists all year round and no heating command will happen even in winter. So heating energy will not be taken into account in the study.

Internal daylight availability is related with building geometry, fenestration and local climate conditions. *Radiance* simulation engine was used for daylight analysis in this study to generate daylight factor maps to present internal daylight levels. Daylight Factor is a ratio of the diffused illuminance of indoor area to simultaneous unobstructed outdoor illuminance. The key advantages of the daylight factor are its simplicity, and its ability to quantify daylight penetration under the average minimum daylighting conditions; since no DF requirements for corridors underneath skylight can be found in China daylighting design standard (GB 50033 – 2001), daylight factor of 2 was referred to in this study. And the artificial lighting control zones were designed according to the boundary of this level. In this study, spaces with daylight factor equals to 2 and more were considered as daylight available area. To reflect the influence of building geometry design to indoor daylight availability, daylight available area ratio was defined as below:

$$\text{Daylight available area ratio} = \frac{\text{indoor area with DF} \geq 2}{\text{Indoor daylight sensible area}} \quad (1)$$

Besides the building geometry design, sunlight condition is another key element for indoor daylight availability. For most climate data in China, hourly outdoor horizontal illuminance is not available. With reasonable luminous efficacy of daylight (Paul J. Littlefair, 1985), hourly outdoor horizontal illuminance for Hangzhou was generated from direct and diffuse solar radiation data. Based on the annual illuminance data and calculated DF above, indoor annual daylight hours with more than 100 lux within daylight control boundary can be easily achieved. In this case, illuminance of 100 lux was considered as the acceptable daylight level for circulation space, under which artificial lighting can be turned off.

With the number of daylight available area ratio and annual hours with enough daylight illuminance, annual artificial lighting energy consumption with lighting control system can be achieved.

Then, to verify the effects of design strategies to daylight-linked artificial lighting energy, cooling

energy and total energy, three energy impact factors were defined, as shown below in equations (2)-(4).

$$\text{Lighting energy impact factor} = \frac{\text{Lighting energy change of a given strategy}}{\text{Lighting energy of base design case}} \quad (2)$$

$$\text{Cooling energy impact factor} = \frac{\text{Cooling energy change of a given strategy}}{\text{Cooling energy of base design case}} \quad (3)$$

$$\text{Total energy changing rate} = \frac{\text{Total energy change of a given strategy}}{\text{Total energy of base design case}} \quad (4)$$

With all information achieved above, energy performance comparison chart reflecting the trade off relationship between artificial lighting energy and cooling system energy consumption following design alternatives would be developed from the calculated energy impact factors.

MODEL DESCRIPTION AND ASSUMPTIONS

A 3D model of the shopping mall was built in IES<VE> as shown in Figure 1. It has five stories above ground and a rectangular atrium in the centre part covered by a skylight. The internal spaces were divided into 6 main zones, which are corridor (void adjoining circulation spaces), atrium, spaces under skylight, void, ceiling (considering effects of bulkhead to daylight) and retail, in which the atrium and adjoining circulation spaces are defined with more details in the model since the skylight has a much bigger impact on these spaces. Considering the over heat locations may change with the solar altitude and azimuth by time, the spaces were also zoned by positions. The total public area is 4564 m².

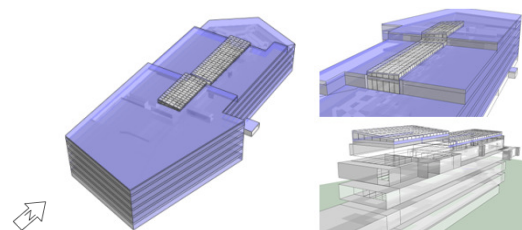


Figure 1 Base design model as in IES<VE>

The building fabric (opaque surfaces) thermal attributes were defined based on the requirements from the Design Standard for Energy Efficient Public Building (GB-50189-2005). And the U-value, S.C. value and visual light transmittance of the skylight glazing used in the base design case were 1.66, 0.324 and 0.64 (double low-e). Heat gains in the atrium and adjoining spaces can be sensible and latent, and mostly come from occupants, lighting and equipment. The magnitude and types of these casual gains are specified individually for each zone referring to the general mechanical system design for commercial

spaces. In this model, atrium, corridors, retail spaces were designed with thermal control, and the temperature set-points for heating and cooling simulation were 20 degree C and 25 degree C separately. Profiles of plant operation (lighting, equipment, occupancy and AC system profile) were defined by assuming the business hour is from 8:00 to 22:00 all year round.

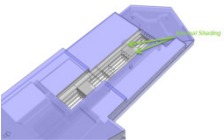
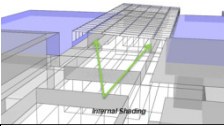
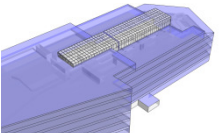
If the ratio of annual average energy used for space cooling to that used for fluid (water/air) transportation is 1.5 and the annual average COP of chillers is assumed to be 4, the total energy efficiency (COP_{total}) of the cooling system in the model could be considered as about 2.5. Generally, the number of total cooling energy efficiency changes with HVAC system configurations and local climate conditions. In this study, three efficiency steps 2.0, 2.5 and 3.0 were used to calculate the cooling energy consumption for each design options.

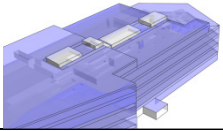
The visual light reflectance of solid surfaces of the building model in daylight simulations were assumed with typical values. The reflectance for floor, ceiling, internal partition and roof surfaces are 0.3, 0.8, 0.8 and 0.5. And in base case, the visual light transmittance of skylight glazing is 0.64. The lighting power density of corridors and atrium space is considered as $12W/m^2$.

Study scenarios for impact sensible study

Reducing skylight area, installing shading devices and solar control glass etc. are ways to prevent the risk of overheating and glare. In this paper, sensible study for impacts from four kinds of design options to total energy performance were conducted, including internal shading strategies (case 1&2), roof type (case 3), rooflight area (case 4) and glazing attributes (case 5 to 11) as summarised in Table 1 below.

Table 1 Design options summary

SHADING OPTIONS		
CASE	DESCRIPTION	
1	Horizontal shading	
2	Vertical shading	
3	Raised rooflight	

4	Separated rooflight with reduced rooflight area		
GLASS PERFORMANCE OPTIONS			
CASE	DESCRIPTION	VLТ	S.C.
5	Double low-e on clear glass	0.64	0.324
6	Single Low-e on clear glass	0.463	0.401
7	Double Low-e on clear glass	0.58	0.372
8	Single Low-e on green tinted glass	0.512	0.328
9	Double Low-e on Green tinted glass	0.489	0.299
10	Reflective coating on Green tinted Glass	0.434	0.385
11	Single Low-e on clear glass with 30% ceramic frit	0.354	0.28

RESULTS AND ANALYSIS

Daylight maps and lighting energy for design options

All the daylight factor (DF) maps of atrium and circulation spaces were generated from daylight simulation under standard CIE overcast sky. As shown in Figure 2, the daylight performance of the top two floors in base design case is quite good. And the daylight levels in most parts of 1st floor atrium space can achieve a DF of 2%, which means daylight performance can be considered as acceptable. The floor area in corridors and atrium spaces with DF of 2 is 2,058 m², 45% of the total public area.

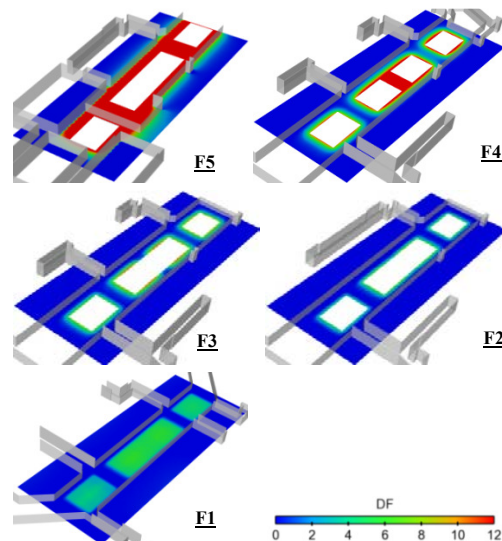


Figure 2 Daylight Factor (DF) maps for base design case

Daylight available area ratio for other design options can be found in Figure 3. Consider the total atrium and void adjoining corridor spaces as indoor daylight

sensible area, the daylight available area ratio will be from 32% to 45%; Compared with the base design case, separated rooflight with reduced skylight area will lower the daylight availability by 15%; the impacts from changing glass transmittance (from 0.64 to 0.43) will be about 5%. With 30% ceramic frit coverage, interior daylight availability will be lower.

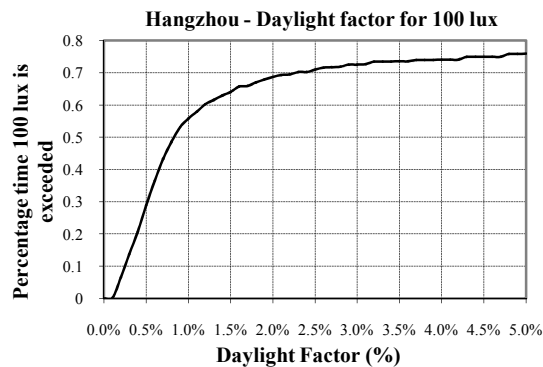


Figure 4 Percentile distribution of illuminance level with 2% DF

Percentile distribution of illuminance level with 2% DF was generated from Hangzhou climate data (EPW) as shown in Figure 4, from which it can be seen that on an annual basis, a DF of 2% means 100 lux for about 68.7% of the daylit hours, the illuminance level can reach or exceed 100 lux. The annual daylight hours in Hangzhou is 3798 hours.

With the number of daylight available area ratio and annual daylight available hours, annual artificial lighting energy for design options were calculated and can be found in Figure 5.

For base design case, in total public area, lighting energy without daylight control system will be 280 MWh/yr. Based on the simulation results and external illuminance condition, with lighting control system, almost 20% of lighting energy will be reduced (215 ~ 225 MWh/yr). For other design options, daylight-linked lighting energy will be increased with lower internal daylight levels. When the VLT value of glass decreases from 0.64 to 0.43, lighting energy impact factors changes linearly and from 0 to 1.75%. With 30% frit coverage, the reduced visual light transmittance will lower the daylight availability especially in the bottom level open spaces.

Thermal comfort conditions for circulation and bottom level open spaces

Circulation spaces in a shopping mall are where shoppers will not stay too long and usually walk through quickly. So these spaces were treated as moderate thermal environments in which PMV range of -1 to 1 is defined as acceptable (GB 50736-2012) as shown in Figure 6. There are six primary factors that will impact the thermal comfort which are metabolic rate, clothing insulation, air temperature, radiant temperature, air speed and humidity. To focus

on the impacts from air temperature and radiant temperature, other 4 primary factors were set as constant as shown in the table below.

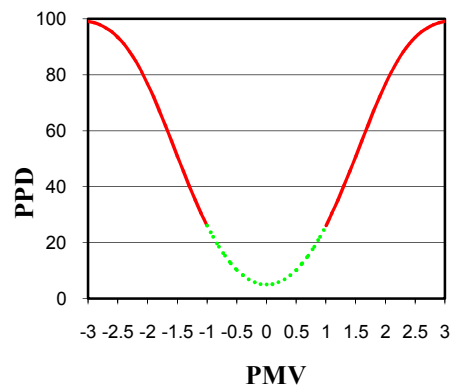


Figure 6 predicted percentage dissatisfied (PPD) as a function of predicted mean vote (PMV)

Table 2 Constant parameter inputs for PMV calculation

PARAMETER	VALUE
Clothing (clo)	0.69
Activity (met)	1.6
Air speed (m/s)	0.1
Relative Humidity (%)	55

With higher over heat possibility, corridors on level 5 and bottom open area are the critical area to achieve thermal comfort. In one run of the base design case, in peak cooling load day, when air temperature was set in 24C, the mean radiant temperature could achieve 29C. Following the calculation method described in ASHRAE 55-2004 (ANSI/ASHRAE Standard 55-2004), the PMV value equals to 1.2, under which people will feel a little warm. To achieve constant acceptable thermal environment for base design case, the conditioned air temperature will be reduced to 23C.

Shading devices can reduce captured solar radiation and in turn drop the mean radiant temperature to improve indoor thermal comfort. Besides, reducing conditioned air temperature is another way to improve thermal sensation but will make extra energy consumption for mechanical system. For design options stated in table 1, shading devices (Case 1, 2 and 4) and solar control glazing (Case 5 through 11) can both help prevent too much solar radiation and improve thermal comfort. However, from the simulation results, with these design options un-acceptable condition still existed for top level corridor spaces and sometimes for ground floor open space. Same as for base design case, reducing conditioned air temperature will be used to help maintain constant indoor thermal comfort.

Cooling energy for design options

Annual HVAC system cooling energy consumed in total public area (with $COP_{total}=2.5$) for design options can be found in *Figure 7*. As shown, the annual HVAC system cooling energy varies from 111 to 116 kWh/m² with design alternatives and is more sensitive to the internal shading design and skylight area than to shading performance of glass.

Total impact factors and S-chart

Since the relationship between daylight and HVAC energy under design options is complex, it is difficult to generate a simple mathematical connection between them. To clarify the contradiction relationship and provide a fast check tool for architects and engineers to make scheme comparison and selection, energy performance comparison chart—*S-chart* was developed as shown in *Figure 9* based on the dynamic thermal and daylight simulation results. The energy impact factors for design options could be found in *Table 3* below.

Table 3 Energy impact factors for design options

	LIGHTING ENERGY IMPACT FACTORS	COOLING ENERGY IMPACT FACTORS	TOTAL ENERGY CHANGING RATE
Base case	0.00%	0.00%	0.00%
Horizontal shading	4.66%	-2.80%	-0.59%
Vertical shading	2.44%	-0.61%	0.29%
Raised rooflight	-0.11%	0.53%	0.34%
Separated rooflight modules	4.54%	-4.02%	-1.49%
Single low-e on clear	1.49%	0.44%	0.75%
Double low-e on clear	0.49%	0.34%	0.39%
Single low-e on green	1.05%	-0.42%	0.02%
Double low-e on green	1.23%	-0.78%	-0.19%
Reflective coating on green	1.75%	-0.25%	0.34%
Single low-e on clear with 30% frit	4.23%	-0.73%	0.74%
Single low-e on green with 30% frit	2.35%	-1.85%	-0.61%

The energy performance comparison chart summaries the resulting energy performance from the series of option runs for the atrium model built above. The x axis represents the lighting energy impacts of each design alternative, and the y axis represents the cooling energy impacts.

The red dot line indicates the energy neutral boundary, the slope of which is from the ratio of lighting energy to base case cooling energy. When the option dots locate on the left bottom part, it means that the design will have better energy performance than base case, and vice versa.

Since the impacts of lighting and cooling energy change to total energy is related with the ratio of the lighting to cooling energy, the neutral line will rotate with several criteria, such as climate conditions and mechanical system efficiency.

As shown in *Figure 8*, the neutral lines for total energy change rate with total cooling efficiency of 2.0 and 3.0 are also displayed in the S-chart. With lower cooling efficiency, the cooling energy required to meet internal thermal comfort will be increased, and also for the ratio of cooling energy to lighting energy. In this case the sensitive of lighting energy increasing is much lower than cooling energy reduction. As shown in the figure, more option dots will be under the slope of $COP_{total}=2.0$ neutral line, which means more design options will be available for a sustainable skylight design from the view point of energy performance. On the other side, when the cooling efficiency is lower, the sensitive of lighting energy will be increased. As a result, on the early skylight/building design stage, the impacts of each design option to energy performance can be predicted with the design scheme for HVAC system.

When the total cooling efficiency equals to 2.5, it can be seen that the total energy change rate for design options of horizontal shading and single low-e on green glass with 30% frit is nearly the same. In this case, the two design strategies can be compared from other considerations, such as aesthetics or economic impacts. Since the total energy performance is related with cooling energy efficiency as discussed in last paragraph, once the COP_{total} is increased, horizontal shading design will have higher priority than using frit glass in terms of total energy performance.

FURTHER WORK

The S-chart is currently capable of evaluating the design options for rectangle skylight located in Hangzhou China or neighbouring cities. As discussed above, the neutral line slope relies on the climate conditions and HVAC system efficiency for a specified geometry atrium design. Besides that, the scatters of each design options on S-chart will also have some changes if the building is built on other cities and with different skylight shape. In next step, studies on the S-chart generation in cities with distinct climate conditions and for different atrium geometries are very necessary. With these further works the S-chart for skylight energy performance can be more climate suitable and have wider usage.

CONCLUSION

A methodology for optimizing skylight design with the considerations of thermal comfort, daylight availability and energy performance by integrated daylight and thermal simulation was presented. Contradictions of design options on lighting and cooling energy performance were studied. For a rectangular shopping mall atrium with a skylight on the rooftop, separated modules skylight design with

double low-e glazing is the most energy efficient design strategy.

Skylight energy performance comparison chart (S-chart) was developed to show the sensibility of each design option to lighting and HVAC energy performance, together with the total energy performance under Hangzhou climate conditions. The skylight performance comparison chart (S-chart) can clearly indicate the complex relationship between daylighting and HVAC energy, and can be used as a fast check tool for design strategies selection on various design stages.

ACKNOWLEDGEMENT

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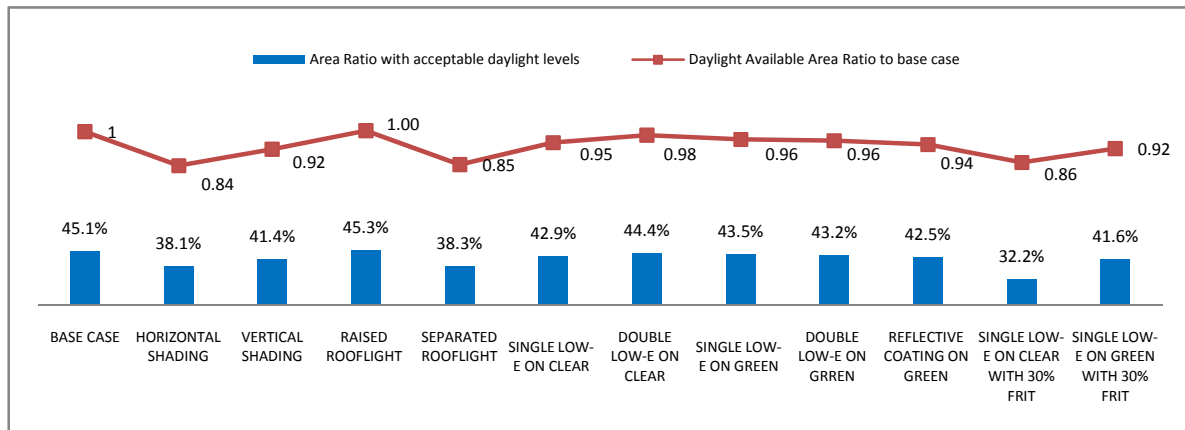


Figure 3 Daylight available area ratios for design options

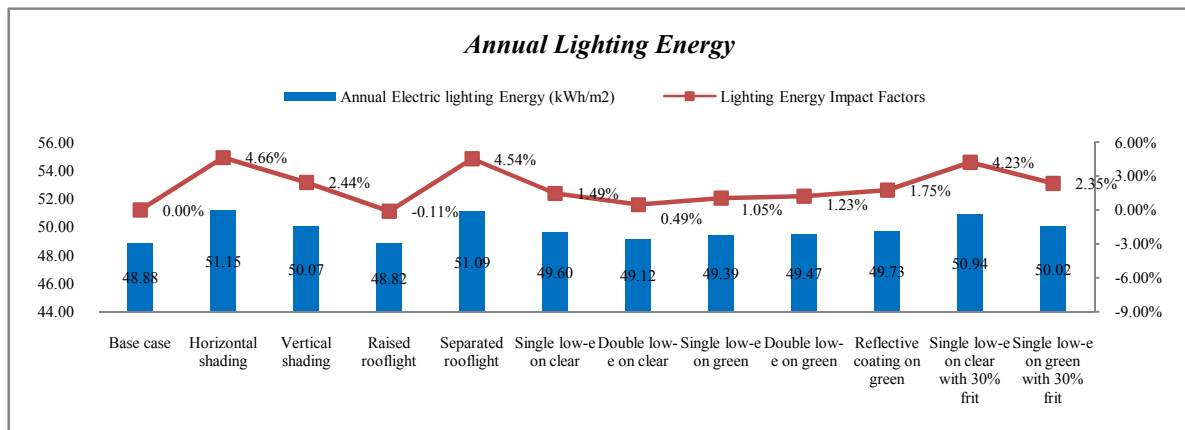


Figure 5 Annual electric lighting energy for design options

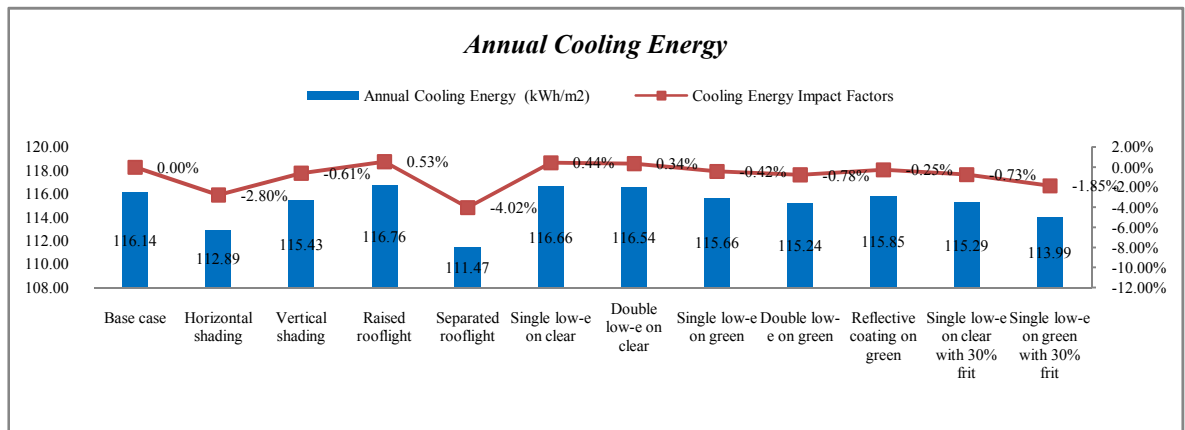


Figure 7 Annual cooling energy for design options (total cooling efficiency=2.5)

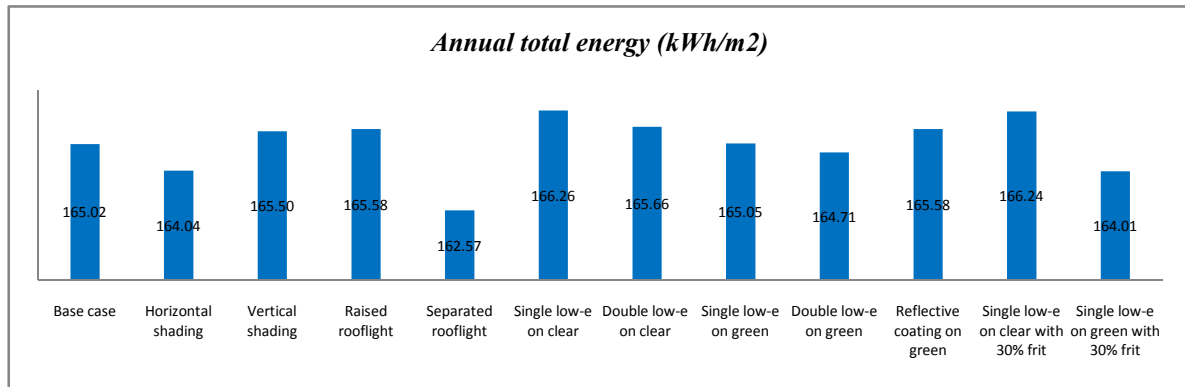


Figure 8 Annual total energy for design options

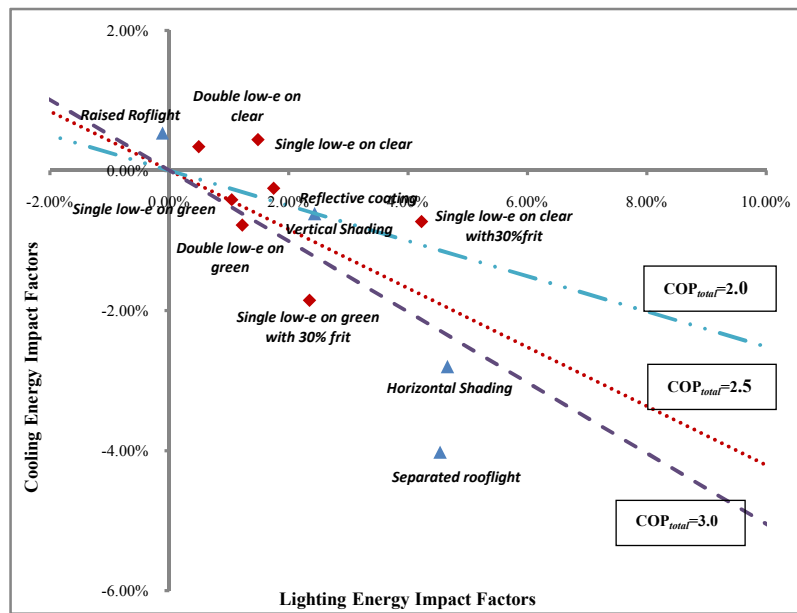


Figure 9 Energy performance comparison chart for design options (S-chart)