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Calculating the effect of external shading on the solar heat gain coefficient of windows

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Abstract

Current prescriptive building codes have limited ways to account for the effect of solar shading, such as overhangs and awnings, on window solar heat gains. We propose two new indicators, the adjusted Solar Heat Gain Coefficient (aSHGC) which accounts for external shading while calculating the SHGC of a window, and a weighted SHGC ($SHGC_w$) which provides a seasonal SHGC weighted by solar intensity. We demonstrate a method to calculate these indices using existing tools combined with additional calculations. The method is demonstrated by calculating the effect of an awning on a clear double glazing in New Delhi.

Introduction

Fenestration is an integral component of façades. Architects have used fenestration and façade design to express socio-cultural context over time. The second half of the 20th century and the initial years of the 21st century have experienced a proliferation of architectural expressions. Glass has played a significant role in defining the aesthetics during this period. The use of glass has also led to the use of various façade elements as solar protection. The effectiveness of solar protection has gained attention in the context of energy efficient building design. Providing external shade on a building façade and especially on fenestration containing glass is one of the most commonly adopted strategies to provide solar protection.

Voluntary green building rating programs and mandatory building energy codes define different approaches of evaluating building energy performance. The prescriptive performance path and the whole building performance path are two most commonly used methods to evaluate building energy performance (*Energy Conservation Building Code 2007*, 2008). The prescriptive compliance path provides a specific performance value for each building component, while the whole building performance (WBP) path determines energy performance of buildings based on energy use intensity or energy performance index measured considering energy consumption of building per unit floor area over the period of one year. Whole building performance simulation tools are necessary to show compliance using the WBP path.

The building energy performance community has well understood the effect of external solar shading on fenestration. Existing literature suggests ("Chapter 15 Fenestration," 2009; Kaftan & Marsh, 2005) that there is a difference between the amount of heat gained by an indoor space through fenestration having an external shade as compared to a fenestration not having an external shade. For the ease of communication this paper uses 'adjusted solar heat gain coefficient' (aSHGC) to indicate solar gain by a fenestration in the presence of an external shade. Whole building performance simulation tools ("EnergyPlus," 2016) are capable of calculating energy consumption of buildings with external shades. However, these tools do not provide output indicating aSHGC specifically for each window. Awnshade developed by Florida Solar Energy Centre (Mccluney, 1998; McCluney, 1986) provides shading benefit calculations for 145 pre-defined angles. While this approach is appropriate for comparison of shading types, this tool does not provide location specific shading calculations. An online shading tool by Sustainable by Design (Gronbeck, 2016) provides guidance on simple overhang design and annual analysis of shading percentage. However, the tool only allows for simple rectangular overhangs and does not calculate the aSHGC.

The prescriptive compliance path mentioned in some energy code documents does provide a 'M-Factor' multiplier to determine aSHGC (*Energy Conservation Building Code 2007*, 2008, "GRIHA Manual," 2010). For external horizontal shades, the M-factor takes the following two dimensions in account (i) vertical distance between bottom of window and bottom of overhang and (ii) horizontal distance from the edge of the fenestration and the outside edge of the overhang. The M-factor values are location specific and are prescribed for a range of locations and orientations of fenestration. Such prescriptive values are limited in terms of their accuracy and only apply to a limited range of external shade designs and environmental parameters.

A survey of existing techniques indicate that the methodology to evaluate the effect of external shading devices is well-established (Etzion, 1992; Kaftan & Marsh, 2005; McCluney, 1986; Olgyay, Olgyay, & others, 1976; Saleh & Narang, 1988). Instead of developing an entirely new algorithm to calculate the impact of shading, this research focuses on developing extensions of existing tools to calculate the aSHGC.

Theory

The Solar Heat Gain Coefficient (SHGC) is a common metric for characterizing the amount of solar gain that enters through a building component. It is most relevant for non-opaque parts of the building envelope such as windows and skylights. It is defined as the ratio of the incident solar radiation and the heat gain through the building component due to this solar gain. The incident solar radiation can be broadly separated into direct beam radiation and diffuse radiation. This diffuse radiation can come from the sky or diffuse reflections from the ground or other exterior objects such as exterior shading devices or other buildings. The solar radiation that strikes a building component is either transmitted, reflected or absorbed. The heat gain into the building can be separated into transmitted solar radiation (direct and diffuse short-wave radiation) and a fraction of the absorbed radiation that enters into the space, the so called 'inward flowing fraction'. This inward flowing fraction depends also on the inside and outside conditions such as temperature, air speed and long wave radiative environment. The definition of SHGC is:

$$SHGC = T_{sol} + A_{sol} * N \tag{1}$$

Where Tsol is the total transmitted solar, Asol is the absorbed solar fraction and N is the inward flowing fraction.

This SHGC depends on the incident angle of the solar radiation in relation to the building component, because the transmittance, reflectance and absorptance properties often change with the angle of incidence (aoi).

For comparative and rating purposes the most commonly used angle of incidence for calculating the SHGC of unshaded glazing systems is zero degrees, which equates to normal incidence. Typical windows are mounted vertical, which means that the sun would be at the horizon to be incident at normal incidence. The solar intensity while the sun is at the horizon is typically quite low. The variation in SHGC between zero degrees and ~45 degrees is fairly small for most glass types, but decreases rapidly at higher incidence angles. See Figure 1 for the effect of angle of incidence on SHGC for a common double glazed configuration.

The SHGC is often calculated as a single static value at a point in time with a set of standardized inside and outside conditions and direction of incident radiation (NFRC 2014). . In this paper $SHGC_{NFRC}$ denotes the SHGC for a glazing system calculated under standard SHGC conditions. Using a single SHGC value to characterize a building component like a window is appropriate when used to compare and rate different windows by themselves

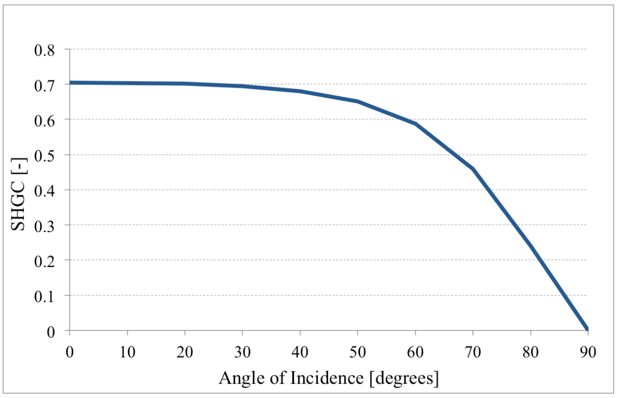

Figure 1: Solar Heat Gain Coefficient for a clear double glazing as a function of angle of incidence under NFRC standard conditions with direct only incident radiation

Whole building annual energy simulation tools like EnergyPlus cannot calculate the SHGC of a window. This is due to the fact that the solar energy transmitted through a window (direct and diffuse radiation and the inward flowing fraction of the absorbed energy) interacts with the surfaces inside the building, and cannot be separated out. Berkeley Lab WINDOW (2016) was designed to calculate window indices like SHGC and U-value and is used by rating organizations like NFRC to calculate SHGC values.

The addition of an external shading element such as an overhang or fin can reduce the amount of solar radiation that reaches a window. This shading element affects both the direct radiation from the sun and the diffuse radiation from the sky. Depending on the geometry it might even affect the amount of reflected diffuse solar radiation that a window receives from the ground.

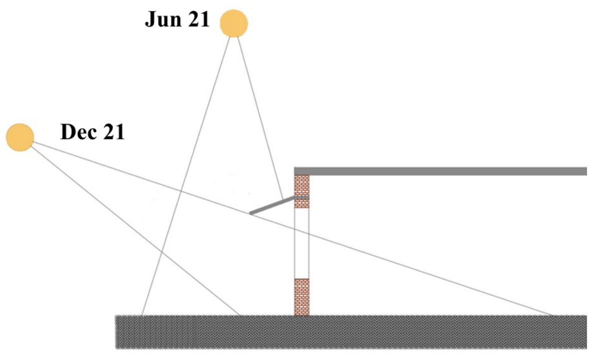

Figure 2: Effect of an awning on solar shading in the summer and winter.

Figure 2 shows the effectiveness of external shading on solar penetration. In this example the low sun angle on December 21st allows the sunlight to illuminate approximately 2/3 of the window and penetrate into the space. On June 21st however no direct sun is striking the window or entering the space.

We can quantify the effect that the shade is having on the SHGC of the window by calculating the SHGC of the window without shades and the aSHGC with external shades in place.

$$SHGC_{unshaded} = \frac{Q_{unshaded}}{I_{dir+diff,unshaded}} \quad (2)$$

$$aSHGC_{shaded} = \frac{Q_{shaded}}{I_{dir+diff,unshaded}} \quad (3)$$

Where $Q_{unshaded}$ is the amount of solar energy transmitted through the window due to the incident solar radiation without a shade. $I_{dir+diff,unshaded}$ is the total amount of solar radiation that is incident on the window without the presence of an external shade. Of note is that the aSHGC value is calculated with the unshaded incident solar radiation. This is the key aspect in calculating the adjusted SHGC (aSHGC) value, which indicates the SHGC of the window with a shade present.

The SHGC varies for each hour of the year due to climatic conditions. In this paper we introduce the concept of a weighted SHGC value that provides one number which represents a collection of static SHGC calculations throughout a time period.

We can calculate a specific SHGC for each hour of the year taking into account the specific solar angle, diffuse and direct intensity, outside temperature and wind speed conditions, orientation, shading and building geometry. The climatic conditions are based on a Typical Meteorological Year (TMY3) file for a location.

To obtain a representative SHGC over a certain period, we can weight these hourly SHGC values by the total solar radiation (direct and diffuse) that the surface received during that hour as shown in equation (4). This method ensures that the SHGC during an hour with low solar intensity on the surface carries less weight than a SHGC during an hour with higher intensity.

This method allows us to create seasonal or annual weighted SHGC indices, by applying the weighting over a certain time period. For example Mar 22 - Sep 21 for summer (in the northern hemisphere) with higher sun angles, and Sep 22 - Mar 21 for winter with lower sun angles. Weighted SHGC values will be denoted in this paper by $SHGC_w$.

$$SHGC_w = \frac{\sum_{t=1}^{8760} SHGC_t * I_t}{\sum_{t=1}^{8760} I_t} \quad (4)$$

Where I_t is the combined diffuse and direct radiation that is incident on the window at timestep t, and $SHGC_t$ is the SHGC at timestep t. 8760 is the number of hours in a year.

Methodology

Combined direct and diffuse radiation

To properly account for the effect of external shading on the solar heat gain coefficient of glazing systems, we are using incident solar radiation that is comprised of direct beam (ie specular radiation directly coming from the sun or specularly reflected) and diffuse radiation from the sky, or reflected of the ground or other surfaces.

The Berkeley Lab WINDOW tool only uses direct solar transmittance and reflectance to calculate the SHGC and solar transmittance of a glazing system for a specific incident angle. WINDOW can calculate diffuse (ie non direct) optical properties by calculating the properties at various angles and performing a hemispheric integration (Finlayson 1993). This assumes the diffuse incoming radiation follows a lambertian distribution. WINDOW cannot calculate the combined effect of direct and diffuse radiation.

To calculate the combined total effect of direct and diffuse radiation in WINDOW we use a special pre-calculation step. This pre-calculation is possible because optical properties such as transmittance and absorptance are independent of intensity. This is not true for thermal properties like heat transfer coefficients and temperatures. If for example 25 W is absorbed in a glass pane due to diffuse radiation and 100 W due to direct radiation, then we can combine these two numbers and use 125 W in the calculation of the overall heat balance of this glazing system when it is irradiated by direct and diffuse radiation. If however there is a 2 K increase in temperature in a glass layer due to 25 W of absorbed radiation and a 6 K increase in temperature due to 100W of absorbed direct radiation, then we can not assume that the temperature increase in that glass layer is 8 K due to a combination of the direct and diffuse radiation because of the nonlinearity of the thermal calculations.

We can pre-calculate the optical properties such as angular and hemispheric transmittance through a glazing system (for example a double glazing system) and angular and hemispheric absorptance of the solar energy in each layer. This is independent of climate, intensity and orientation. Once we have these pre-calculated optical properties, we can calculate the total transmittance and absorptance by adding together the components for direct and diffuse, weighted by solar intensity:

$$\tau_{dir+diff} = \frac{(\tau_\theta * I_{dir,\theta}) + (\tau_{hem} * I_{diff})}{I_{dir} + I_{diff}} \quad (5)$$

$$\alpha_{dir+diff,n} = \frac{(\alpha_{\theta,n} * I_{dir,\theta}) + (\alpha_{hem,n} * I_{diff})}{I_{dir} + I_{diff}} \quad (6)$$

Where τ is the solar transmittance of the glazing system, θ denotes a specific incident angle and τ_{hem} is the hemispheric solar transmittance. $\alpha_{hem,n}$ is the absorptance in layer n of the glazing system for hemispheric incident radiation. I indicates solar irradiance in W/m^2. We can use $\tau_{dir+diff}$ and $\alpha_{dir+diff,n}$ and $I_{dir} + I_{diff}$ in the thermal algorithms of Berkeley Lab WINDOW to calculate the SHGC for a glazing system that is irradiated with direct and diffuse solar radiation.

Adjusted SHGC calculations

The SHGC for a glazing consisting of two panes of 6 mm clear uncoated glass (IGDB ID #103) with 12mm air fill is shown under various conditions in Table 1.

The standard SHGC value is for direct sunlight striking the glazing system at normal incidence (ie perpendicular to the glass). No diffuse radiation from the sky or the ground was taken into account for this calculation. When we calculate the SHGC at other angles of incidence for this same glazing under standard NFRC conditions, we get the results as shown in Table 1. From these angular results we can also obtain a hemispheric transmittance, which in this case is $SHGC_{NFRC,hem}$ = 0.61. The angle of incidence (aoi) in Table 1 is for the direct beam radiation only. Diffuse radiation is assumed to have a lambertian distribution.

Table 1: SHGC for a south facing double clear glazing under various conditions.

Date noon	aoi	Cond.	Rad. type	SHGC	Comment
	0	NFRC	Dir. only	0.70	Rated value
	hem	NFRC	Dir. only	0.61	
Jun 21	85	TMY3 -Delhi	Dir. only	0.12	
Jun 21	85	TMY3 -Delhi	Dir.+ Diff.	0.57	
Jun 21	85	TMY3 -Delhi	Dir.+ Diff.	0.46	600 mm overhang
Dec 21	39	TMY3 -Delhi	Dir. only	0.71	
Dec 21	39	TMY3 -Delhi	Dir.+ Diff.	0.69	
Dec 21	39	TMY3 -Delhi	Dir.+ Diff.	0.55	600 mm overhang

As we can see in Table 1, the SHGC coefficient can vary widely from its standard rated value, depending on the angle of the incoming sun, inclusion of diffuse radiation and the use of shading. Because the sun is very high in the sky on June 21st at noon (summer solstice) the SHGC for direct only radiation is very low (0.12) because of the high incidence angle, but as we add in diffuse sky radiation, the SHGC increases to 0.57, because the hemispheric SHGC for diffuse radiation is much higher ($SHGC_{NFRC,hem}$=0.61). On December 21st we see a much smaller difference between the case with only direct radiation (0.71) compared to the case with direct and diffuse radiation (0.69). The reason is that the sun is at a lower altitude in December. This results in more direct radiation striking the window at a lower incidence angle. The diffuse component is relatively small and only has a limited effect on the overall SHGC.

Adding a 600 mm deep overhang above the window reduces the SHGC down to aSHGC=0.46 in June and aSHGC=0.55 in winter.

Implementation

The method described in this paper is based on using two existing tools (EnergyPlus 8.6 and Berkeley Lab WINDOW 7.5) combined with some custom calculations and post processing that were written in Python. EnergyPlus was used to determine the incident direct and diffuse radiation on a window surface with and without external shading. This takes advantage of the detailed validated calculations in EnergyPlus related to the modeling of radiation coming from the sun and sky and shadowing of building components.

1. The output from EnergyPlus is hourly (or sub-hourly timestep) diffuse and direct solar irradiance on the window, as well as the outside air temperature (which directly comes from the weatherfile used in EnergyPlus) and the exterior convective heat transfer coefficient (which is calculated by EnergyPlus based on the wind speed in the weatherfile).
2. The Python code calculates the combined transmittance and absorptance for the specific glazing system based on the data from EnergyPlus and the glazing optical data from Berkeley Lab WINDOW. This is done both for the case with and without external shading, for each timestep (hourly or sub-hourly).
3. The thermal calculation routines in Berkeley Lab WINDOW are called to calculate the SHGC based on the outside air temperature and heat transfer coefficient from step 1) and the glazing system transmittance and absorptance from step 2)
4. The Python code calculates a seasonal and annual $aSHGC_w$ that is weighted by the intensity at every timestep.

This approach in our opinion calculates the most accurate SHGC coefficient, but it is fairly slow. Only a small portion of the EnergyPlus results are used, which is not the most efficient use of EnergyPlus. EnergyPlus calculates many other results, such as energy consumption of the building, but those are not used in this method. For every timestep during hours when there is solar radiation the SHGC is calculated by Berkeley Lab WINDOW. This results in ~4500 SHGC calculations each for the case with the solar shading and without. It takes about 5 minutes to do these 4500 calculations on a 2.3 GHz Intel Core i7 laptop from 2013. The current calculations are performed on a single core. The calculations could be sped up by a factor of 6x-7x by using all cores on this laptop with 8 virtual cores. This method is very suitable for running in a parallel fashion, because there is no interdependence between the SHGC calculations for specific timesteps. The time used for pre- and post processing the data is negligible compared to the Berkeley Lab WINDOW simulations.

Sample application of the method

EnergyPlus was used to calculate the incident direct and diffuse solar radiation on one window located on one wall. The window dimensions are 1.2 m (width) X 1.5 (height). The wall is 3m tall and the window is centered on the wall, the window has no framing and only consists of a double clear glazing system. This is the identical glazing system that was used in Figure 1 and Table 1. EnergyPlus is not used to calculate the amount of solar transmitted through the window, or the heat transfer in the room, therefore the other building parameters are irrelevant. Berkeley Lab WINDOW assumes a room indoor air temperature of 25 °C. The $SHGC_{NFRC}$ for this glazing system is 0.70. An awning as shown in Figure 3 was modeled over the window.

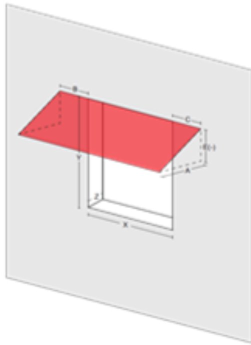

Figure 3: Awning geometry

Table 2: Effect on SHGC of a 1000 mm 20 degree awning in Delhi and Denver on a south facing double clear glazing

		Summer $SHGC_w$ Mar 22- Sep 21		**Winter $SHGC_w$ Sep 22 - March 21**		**Annual $SHGC_w$**	
City	**Rated $SHGC_{NFRC}$**	**Unshaded $SHGC_w$**	**Awning $aSHGC_w$**	**Unshaded $SHGC_w$**	**Awning $aSHGC_w$**	**Unshaded $SHGC_w$**	**Awning $aSHGC_w$**
Delhi	0.70	0.56	0.26 (-54%)	0.66	0.33 (-50%)	0.62	0.30 (-52%)
Denver	0.70	0.56	0.32 (-43%)	0.65	0.27 (-58%)	0.62	0.29 (-53%)

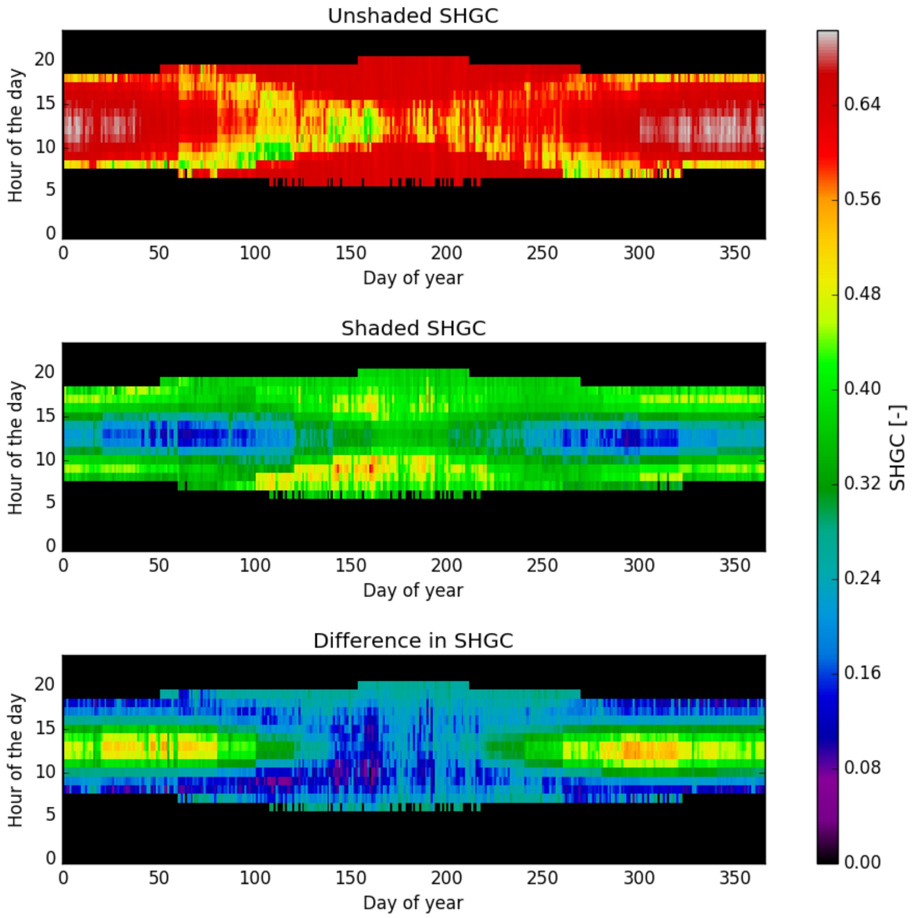

Figure 4: Annual graph of shaded, un-shaded and difference in SHGC for a south facing orientation with an awning in New Delhi, India.

The awning has a horizontal projected depth of 1000 mm. It extends 200mm on either side of the window, and has an angle of 20 degrees. For this sample application an awning was simulated in EnergyPlus. The adjusted SHGC methodology however is applicable to any shading device that can be simulated in EnergyPlus. The simulations were performed in New Delhi, India (latitude=28.6 degrees, $CDD_{18.3}$=2762, $HDD_{18.3}$=270) and Denver, USA (latitude=39.8 degrees, $CDD_{18.3}$=432, $HDD_{18.3}$=3301)

Table 2 shows the impact on $aSHGC_w$ of this awning added to a south facing vertical double clear glazing. The analysis was performed for two different climatic conditions. For all cases the $aSHGC_w$ is reduced by the addition of the awning.

Figure 4 shows an annual plot for the impact of this awning on a south facing window in New Delhi, India. The top plot shows the hourly SHGC of a window without any external shading features, the middle one shows the hourly SHGC of the window with the shade in place, and the bottom graph shows the difference between the two graphs above.

Discussion

The results from Table 2 show that the addition of an awning reduces the $aSHGC_{w,summer}$ by 54% in Delhi, but only 43% in Denver. During the winter season, the awning however has a larger reduction in Denver (58%) compared to Delhi (50%). Given the fact that Denver has a substantially higher number of Heating Degree Days ($HDD_{18,3}$=3301) compared to the Cooling Degree Days ($CDD_{18.3}$= 432) this awning might not be the best design for Denver, because it reduces the $aSHGC_w$ more during the winter than the summer. Usually a high SHGC during the winter season is beneficial in a heating dominated climate.

This visual representation of the hourly properties for a whole year can help identifying during which part of the year the shade is most effective. Figure 4 shows that the strongest reduction in SHGC is around day 50 (Feb 20th) and day 300 (Oct 27th).

Conclusion

The presented method uses two standard tools (EnergyPlus and Berkeley Lab WINDOW) to calculate a seasonal weighted adjusted SHGC which accounts for the effect of external shading. This method can be referenced by building codes to allow them to properly account for the effect of a shade on the SHGC of a window. The method can also be used by manufacturers of exterior shading devices to demonstrate the effectiveness of their products in various climates and configurations.

This method has been incorporated in the latest version of the COMFEN tool and a web-based calculator to help practitioners determine the effect of shading. The method can also be used to calculate a seasonal, orientation and location specific SHGC for an unshaded glazing.

Future research will focus on validating the method using existing tools. Even though a complete validation of the aSHGC method is difficult due to the limitations of existing tools, components such as the transmitted solar radiation can be compared against other tools.

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References

ASHRAE (2009). Chapter 15 Fenestration. In *ASHRAE Handbook, Fundamentals* (2009 SI Ed, p. 60). American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Berkeley Lab WINDOW (2016). Retrieved from: http://windows.lbl.gov/software/window

Energy Conservation Building Code 2007 (2008). India: Ministry of Power.

EnergyPlus. (2016). Denver, Colorado: Department of Energy. Retrieved from https://energyplus.net/

Etzion, Y. (1992). An improved solar shading design tool. *Building and Environment*, *27*(3), 297–303.

Finlayson, E. U., Arasteh, D. K., Huizenga, C., Rubin, and M. D., Reilly, M. S., (1993). "WINDOW 4.0: Documentation of Calculation Procedures." *LBL Report 33943*. Berkeley CA.

GRIHA Manual. (2010). New Delhi: TERI Press.

Gronbeck, C. (2016). No Title. Retrieved from http://www.susdesign.com/overhang_annual/index.php

Kaftan, E., & Marsh, A. (2005). Integrating the cellular method for shading design with a thermal simulation. *Passive and Low Energy Cooling for the Built Environment*, (May), 965–970.

Mccluney, R. (1998). Advanced Fenestration and Daylighting Systems. *Daylighting '98, an International Conference on Daylighting Technologies for Energy Efficiency in Buildings.*

McCluney, R. (1986). Awning shading and algorithm for window energy studies. In *ASHRAE Trans.; (United States)* (Vol. 92:1A).

NFRC (2014) *200* Procedure for Determining Fenestration Product Solar Heat Gain Coefficient and Visible Transmittance at Normal Incidence. Retrieved from http://www.nfrc.org

Olgyay, A., Olgyay, V., & others. (1976). *Solar control & shading devices*. Princeton University Press.

Saleh, A. M., & Narang, P. P. (1988). *Design of Sunshading Devices*. CSIRO Australia, Division of Building, Construction and Engineering.

2009 International energy conservation code, and ANSI/ASHRAE/IESNA standard 90.1-2007 energy standard for buildings except low-rise residential buildings. Washington, D.C. Atlanta, GA: International Code Council American Society of Heating, Refrigerating and Air-conditioning Engineers.