

Chapter 2

Daylighting

Abstract Solar energy directly provides illumination (lux) inside a building without any additional heat (thermal energy) source, unlike artificial lighting, and saves the use of conventional (fossil) fuels. This can be treated as one method to conserve available fossil fuels.

Keywords Daylight factor • Daylight models • Sky component • Internally reflected components • Externally reflected components

2.1 Introduction

Daylighting is the general practice of having vertical windows and openings in a wall exposed to incoming solar radiation to receive natural light inside the room during the day time. The reflective surfaces outside the building can also provide effective internal lighting through an opening in the wall. This process of having natural light inside a room is known as **daylight harvesting**.

Windows in an exposed wall are the most common way to allow daylight into a living space as shown in Fig. 2.1. The amount of solar radiation (daylight in *lux*) available on the vertical window ($\beta = 90^\circ$) and with any orientation for known γ (wall azimuth angle) can be evaluated as discussed in Chap. 1. This means that the window selectively allows for direct and diffuse sunlight for different hours and days of the year. Different manufacturing technologies and process treatments improve the transmissivity of the glass, which in turn increases the amount solar radiation transmitted from the window.

A **clerestory window** is a band of narrow windows placed at the top of a high wall as shown in Fig. 2.2. The solar radiation transmitted from the clerestory windows illuminate the interior walls. Radiations falling on interior walls are further reflected to the living space. Light obtained using this method provides more diffuse radiation, which reduces shadow formation.

Daylight obtained using the concept of a skylight is very simple. These concepts are widely used in residential, community, and commercial buildings. Greater use



Fig. 2.1 Window fitted in the exposed walls of a room for daylighting

Fig. 2.2 View of a clerestory window



of daylighting ensures less use of artificial light, thus saving significant nonrenewable (electrical) energy. Hence, this concept is cost-effective and environment friendly.

2.2 History of Daylighting

Architectural design of building for daylight was an art and science for harnessing the visible portion of the solar spectrum into the built environment. Our historical buildings exhibit good daylight uses. Daylighting has important advantages such as creating psychological visual comfort in a living space [1]. It also reduces electrical energy consumption kWh for artificial lights [2]. This consequently reduces the sensible heat gain associated with artificial lights. Hence, the cooling requirement of the building decreases due to the provision of natural daylight. The **daylight coefficient concept** offers a more effective way of computing indoor daylight

illuminance in lux [3]. Similarly, Joshi et al. [4] gave a brief review on different mathematical models for the estimation of daylight in buildings.

Reddy and Manish [5] modeled the variation of global solar radiation with space and time using an artificial neural network (ANN) model. The validation results and comparison of ANN model with other models showed that the ANN model is more suitable compared with other classical regression models for predicting global solar radiation. Solar radiation for any place and weather condition (Sect. 1.2.6) can be predicted using an ANN model.

In modern architecture, daylighting is an inescapable concept used for meeting the visual needs and thermal comfort of the occupants and ensuring energy-efficient buildings [6]. Daylighting concepts provide maximum possible natural light to the occupant, which is strongly needed for visual as well as mental comfort. The openings provided for daylighting through a window also visually connect occupants to the outside environment, which confers a positive psychological effect.

The high consumption of electricity in buildings for many applications, viz., cooling, heating, illumination, etc., is directly or indirectly related to pollution and global warming due to the electricity produced mainly from conventional fuels [7]. In the US, energy consumption is almost 14 % of total energy required in residential applications as shown in Fig. 2.3. The lighting contribution is approximately 11 % of building energy consumption [8] as shown in Fig. 2.4.

Approximately 20–40 % of the total energy consumption of the building is due to lighting; hence, it is a prime source of carbon emission in buildings [9, 10]. Various researchers and architects have proved that the daylighting is also a good solution for illumination in buildings (through windows, skylights, wind tunnel, etc.) and for saving electrical energy based on fossil fuels during the daytime.

Daylight is the visible part of solar radiation as perceived by the human eye. It is composed of a spectral power distribution (SPD) of electromagnetic radiation in the

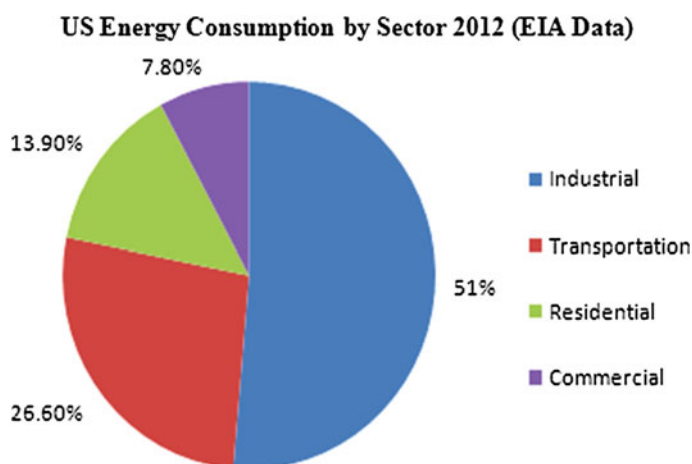


Fig. 2.3 Energy consumption by different sectors

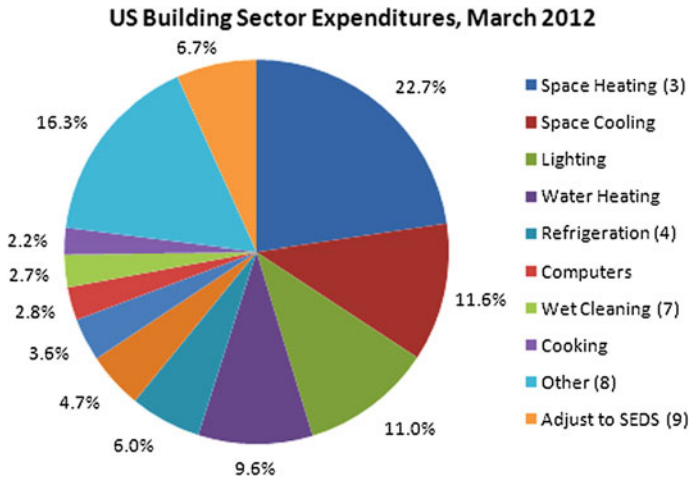


Fig. 2.4 Energy consumption by building equipment

visible wavelength range (0.38–0.78 μm) of solar radiation [11]. Daylight is one of the cheapest and efficient ways of using solar energy in buildings. Architects and building designers are also concerned about energy conservation in buildings due to the use of daylight [12]. It is reported that daylighting improves student performance and health in schools [11] because natural light gives more comfort and is beneficial for human health. With smart control systems, the use of conventional lighting can be considerably reduced and even eliminated inside a community center or office building. Daylight proportion can vary due to the structure of the house or building because the position, direction, and area of the windows play major factor in influencing the amount of natural light inside a room of a house.

Nevertheless, arrangements made for daylighting have direct and indirect impacts on the heating and cooling loads of building [13]. The optimization of daylight has been studied by many researchers [14–16]. The effects of daylighting optimization on thermal loads are also presented in the literature [17]. Some material-based optimization solutions with innovative approaches for lighting energy savings have also been reported [18–20].

The approach adopted for the optimization of daylighting inside a building must be as universal as much as possible so that it can be applicable to most of the building [21]. For the prediction of daylighting, building-simulation software [22] can be used. The annual variation in the availability of daylight at any place is important, particularly for daylight optimization for the annual performance of building [23, 24]. Stokes et al. [25] presented a simple model for the estimation of daylight throughout the year. The existing building can be retrofitted for the inclusion of daylighting concepts; a study regarding the economic analysis of retrofits has been performed by Mahlia et al. [26]. The amount of daylight inside a building strongly depends on the building design and the materials used for the openings for daylighting. Orientation of the living space with respect to light source, geometry of the

living space, optical properties of interior surfaces of the living space, obstructions outside the room, and optical characteristics of glazing play a major role in harnessing daylight [27]. The daylight coefficient for complex fenestration has been examined, and it was concluded that the daylight coefficient does not depend on luminance distribution in the sky [28, 29]. The illuminance level from natural light has been estimated by Rosa et al. [30] for overcast sky conditions.

2.3 Components of Daylighting (Natural Light)

2.3.1 Daylight Factor (DF)

The estimation of illuminance inside a living space can be predicted by an expression for the daylight factor, which is given by

$$DF = SC + ERC + IRC \quad (2.1)$$

where SC, ERC, and IRC are the sky, external, and internal reflection components falling on a building as shown in Fig. 2.5a. The sky component (SC) is the sum of beam and diffuse solar radiation coming from the Sun and the external (ERC) and internal (IRC) reflection components that are only beam/direct solar radiation coming from the Sun due to its direction.

The daylight factor (DF) is a guideline to determine the quantitative suitability (characteristic) of daylight in a particular room (work space) in terms of illuminance (lux). Based on this, there can be some changes in the design of the working space through the size of the windows.

2.3.2 Daylight Factor Due to Sky Components

The daylight factor due to the sky component (SC) is a ratio of inside illuminance, L_i (lux), on the horizontal work plane and outside diffuse illuminance, L_o (lux), on a horizontal surface.

$$SC = \frac{L_i}{L_o} \quad (2.2a)$$

In terms of percentage, it is expressed as follows:

$$SC = \frac{L_i}{L_o} \times 100 \quad (2.2b)$$

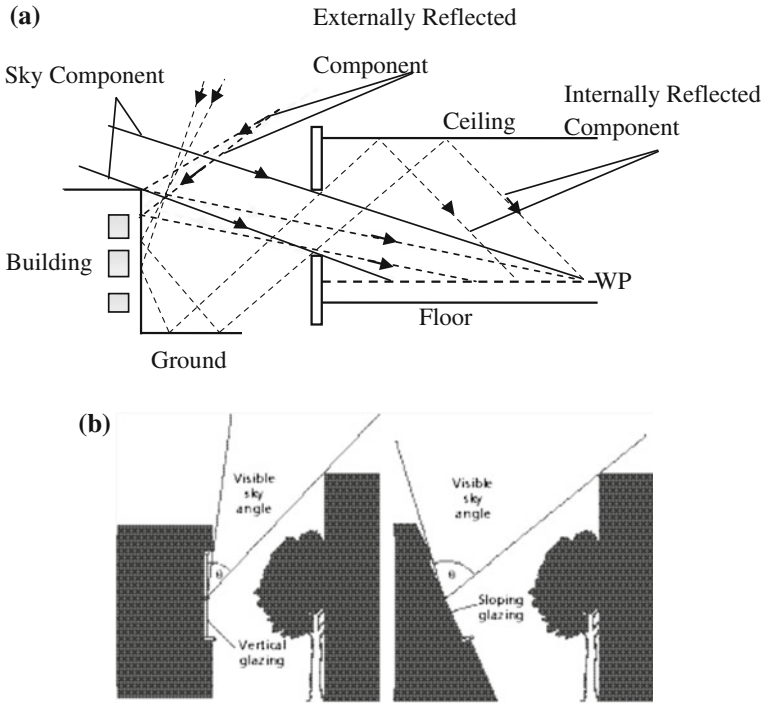


Fig. 2.5 **a** Different components of the daylight factor. **b** Obstruction and visible sky angle

The daylight factor for a skylight integrated with a vertical window in a building at ground level was developed by Chartered Institute of Building Services Engineers (CIBSE) [10] as follows:

$$SC = \left[\frac{L_i}{L_o} \right] = \left[\frac{\tau \times A_w \times \theta \times O_F \times M}{A \times (1 - R^2)} \right] \quad (2.3)$$

Equation (2.3) is applicable to CIE overcast conditions (completely cloudless conditions, weather condition 'a' as described in Chap. 1). Furthermore, the Chartered Institute of Building Services Engineers (CIBSE) is denoted SC by DF because they have not considered external (REC) and internal (IRC) reflection components falling on a building where:

- τ is the transmittance of window materials ($\tau = 0.8$, and 0.7 for single- and double-glazed clear glass, respectively). This also depends on the thickness of the window materials. The numerical value of τ decreases with an increase in the thickness of the window materials.
- A_w is the area a window in m^2 , which is inversely proportional to τ .

- θ is the visible-sky angle as shown in Fig. 2.5b, which is approximately written as,

$$\theta = 90 - \text{Obstruction angle} \quad (2.4)$$

The previous equation is valid for a window without an above-situated overhang. If there is no obstruction, then $\theta = 90^\circ$. The values of θ for different obstruction angle are given below:

Obstruction angle (degree)	0	20	40	60	80	90
θ (degree)	90	70	50	30	20	0

- R is the area-weighted average reflectance ($R = 0.6$ for a white wall, 0.5 for a medium-white wall, and 0.4 for a dark wall). High reflectance confers a double benefit, namely, (i) an increase in daylight factor and (ii) improvement in the distribution of daylight.
- A is the total area of the interior surfaces (including ceiling, floor, walls, and windows).
- M is the maintenance factor, which is generally considered to be <0.88 .
- O_F is the orientation factor for glazing ($0.77 \leq O_F \leq 1.20$). For a vertical window facing north–south, the value of O_F is 0.77 and 1.20 , respectively; otherwise $O_F = 1$ for a vertical east–west window.

The various parameters in Eq. (2.3) were tabulated with their numerical values for skylight components (SC) in an experimental dome-shaped mud house for a working place at the centre of the floor at IIT Delhi (Fig. 2.6) in Table 2.1. The left-hand side of Fig. 2.6 is a view of the sky component at the top of the mud house in a conical shape, and the right-hand side is the view of the central table as a working place. The conical shape at the top of the dome has been considered equivalent to a vertical window. In this case, an external reflection component (ERC) falling on the building can be neglected.

Equation (2.3) was modified by Chel et al. [31] by considering the effect of height (of a workplace from the floor of mud house) and the time of day ω , Eq. (1.9b). The modified daylight factor for the sky component (SC) is given as follows:

$$\text{SC} = \left[\frac{L_i}{L_o} \right] \times 100 = \left[\frac{\tau \times M \times A_w \times \theta \times O_F}{A_t \times (1 - R_f^2)} \right] \times \left(1 + \frac{h}{H} \right)^m (\cos \theta_z)^n \quad (2.5a)$$

where h , the vertical height of the table in the workplace above the floor surface inside the skylight-integrated living space (dome structure); H is the central height of the dome and M ($0.5 \leq M \leq 0.9$) is the correction factor for glazing due to dust, etc. In this case too, Chel et al. [31] also did not consider the external (REC) and internal (IRC) reflection components falling on the building because DF is replaced by SC.



Fig. 2.6 Skylight components (SC) in experimental dome-shaped mud house for working place at the centre of floor at IIT Delhi

Table 2.1 Parametric values considered for daylight-factor evaluation

Sr. no.	Parameter	Value	Sr. no.	Parameter	Value
1	Total area of room surfaces in large dome (A_t , m^2)	80	8	Total area of room surfaces in small dome (A_t , m^2)	25
2	Floor area of large dome (A_f , m^2)	26	9	Floor area of small dome (A_f , m^2)	5
3	Transmittance of glazing (τ)	0.8	10	Vertical angle of visible sky from horizon (θ , degrees)	90
4	Correction factor for glazing due to poor maintenance/dust ($0.5 \leq M \leq 0.9$)	0.6	11	Vertical height of work plane above floor surface (h , m) [0, 0.75, 1.5 m]	0, 0.75, 1.5
5	Orientation factor for glazing ($0.97 \leq O_F \leq 1.55$)	1	12	Average reflectance of all room surfaces ($0 \leq R_f \leq 1$)	0.3
6	Total area of glazing (A_g , m^2) for large dome	2.6	13	Total area of glazing (A_g , m^2) for small dome	1.5
7	Ballast factor (B_F)	0.9	14	Artificial light luminous efficacy (ϵ , lm/W) (CFL lamp)	40

Equation (2.5a) needs further modification for vertical windows with reference to Fig. 2.1 as follows:

$$SC = \left[\frac{L_i}{L_o} \right] = \left[\frac{\tau \times A_w \times \theta \times M \times O_F}{A_t \times (1 - R_f^2)} \right] \times \left(1 + \frac{h}{d} \right)^m (\cos \theta_i)^n \quad (2.5b)$$

where h , the mid-height of the window, and d is normal distance from the window and

$$\cos \theta_i = \sin \varphi \cos \gamma \cos \delta \cos \omega + \cos \delta \sin \omega \sin \gamma - \sin \delta \cos \varphi \cos \gamma$$

The above equation, obtained from Eq. (1.10) for $\beta = 90^\circ$ (vertical windows) takes care of orientation (γ), Table 1.3, and the shading effect due to a nearby building/obstruction. The values of γ for east-, south-, west-, and north-facing windows can be considered as -90° , 0° , 90° , and $\pm 180^\circ$, respectively. For a south-facing vertical window $\beta = 90^\circ$ and $\gamma = 0^\circ$, and then the form of Eq. (2.5) is the same as Eq. (2.4).

Equation (2.5b) is currently modified because Eq. (2.3) developed by CIBSE [10] was expressed as a fraction and not as a percentage.

The constants ' m ' and ' n ' are determined by regression method using experimental values of inside and outside luminance.

After taking the log of both side of Eq. (2.5), one gets

$$\ln \left[\frac{L_i}{L_o} \right] = [n \times \ln(\cos \theta_i)] + \left[m \times \ln \left(1 + \frac{h}{d} \right) + \ln \left[\frac{\tau \times A_w \times \theta \times M \times O_F}{A_t \times (1 - R_f^2)} \right] \right] \quad (2.6)$$

The previous equation is a linear equation and can be rewritten as:

$$y = m'x + c \quad (2.7)$$

where $y = \ln \left[\frac{L_i}{L_o} \right]$, $x = \ln(\cos \theta_i)$ and $c = \left[m \times \ln \left(1 + \frac{h}{d} \right) + \ln \left[\frac{\tau \times A_w \times \theta \times M \times O_F}{A_t \times (1 - R_f^2)} \right] \right]$

Here, $m' = n$ = slope of line and c = intercept of line on y axis

or

$$m = \frac{\left[c - \ln \left[\frac{\tau \times A_w \times \theta \times M \times O_F}{A_t \times (1 - R_f^2)} \right] \right]}{\ln \left(1 + \frac{h}{d} \right)} \quad \text{and} \quad m' = n \quad (2.8)$$

After knowing ' m ' and ' n ', the inside luminance (L_i) in lux can be obtained for the given outside luminance by using Eq. (2.5b).

Sudan et al. [42] further modified the model developed by Chel et al. [31] by considering the effect of tilt, location (latitude), orientation of the window, and position of a point of interest inside the living space:

$$DF = \left(\frac{L_i}{L_o} \right) \times 100 = \left[\frac{\tau \times A_g \times M \times \theta}{A_t \times (1 - R^2)} \right] \times \left[1 + \frac{L}{2l} (\cos \theta_w) \right]^q \times (1 + \cos \theta_i) \quad (2.8a)$$

where θ_w is the angle between a line connecting point of interest with the centre of the window and the perpendicular axis from the window directing inside the room. The term $(L/2l) \cos \theta_w$ gives the three-dimensional variation of DF. The value of $\cos \theta_w$ can be given in terms of length, width, and height of the point of interest from the centre of the window. After substitution, Eq. (2.8a) becomes

$$DF = \left(\frac{L_i}{L_o} \right) \times 100 = \left[\frac{\tau \times A_g \times M \times \theta}{A_t \times (1 - R^2)} \right] \times \left[1 + \frac{L}{2} \left(\frac{1}{\sqrt{l^2 + h_{cw}^2 + w^2}} \right) \right]^q \times (1 + \cos \theta_i) \quad (2.8b)$$

where, L , l , and w are the total length of a room, perpendicular length of a given point from the window (m), and perpendicular length of a given point from the perpendicular axis along the width axis of the wall window (m), respectively. The unknown constant q , known as model exponent in Eq. (2.8a), can be found by regression method using the experimental data as follows:

$$q = \frac{\ln \left[\frac{DF \times A_t \times (1 - R^2)}{(1 + \cos \theta_i) \times \tau \times A_g \times M \times \theta} \right]}{\ln \left[1 + \frac{L}{2} \left(\frac{1}{\sqrt{l^2 + h_{cw}^2 + w^2}} \right) \right]} \quad (2.8c)$$

2.3.3 Daylight Factor Due to External Reflection Components (ERC)

External reflection components (ERC) will be zero if the building is not surrounded by any outside obstruction as shown in Fig. 2.6. In the presence of any outside obstruction, there will be a non-zero ERC value. To obtain this value, one can use the following expression for a window with inclination of β for an overcast sky,

$$ERC = 0.2 \times \left(\frac{1 + \cos \beta}{2} \right) \times SC \quad (2.9a)$$

For any inclination (β), the factor 0.20 is incorporated, which is generally considered equivalent to the reflection coefficient of the surrounding.

$$\text{For a vertical window, } (\beta = 90^\circ), \quad \text{ERC} = 0.1 \text{ SC} \quad (2.9b)$$

2.3.4 Daylight Factor Due to Internal Reflection Components (IRC)

For vertical window, the average internal reflection (IRC) is determined using the following formula:

$$\text{IRC} = \frac{\tau \times A_w}{A(1 - R)} [\text{CR}_{\text{fw}} + 5R_{\text{cw}}] \quad (2.10)$$

Here, R_{fw} is the weighted reflectance due to floor and lower height (from the centre of window) of the window; R_{cw} is the weighted reflectance due to the ceiling and upper height (from the centre of window) of the window; and τ , A_w , A , and R are the same as defined in Eq. (2.3), for a dome-type mud-house construction, $R_{\text{cw}} > R_{\text{fw}}$. Due to the poor reflectance of the floor, it may be slightly higher.

The coefficient 'C' of Eq. (2.10) can be expressed as follows [10, 33]:

$$C = \left[40 - \frac{\text{angle of obstruction}}{2} \right] \quad (2.10a)$$

$$= \left[40 - \frac{\arctan\left\{\left(\frac{h_1 - h_2}{2}\right)/d\right\}}{2} \right] \quad (2.10b)$$

$$= \frac{\theta}{2} - 5 \quad (2.10c)$$

where θ is given by Eq. (2.4).

Furthermore, the value of C for a different obstruction angle is also given in Table 2.2 [32].

The weighted reflectance can be obtained as

$$R_w = \frac{\sum_{i=1}^n A_i R_i}{\sum_{i=1}^n A_i} \quad (2.11)$$

Table 2.2 The values of coefficient 'C'

Obstruction angle	0	10	20	30	40	50	60	70	80
Coefficient 'C'	39	35	31	25	20	14	10	7	5

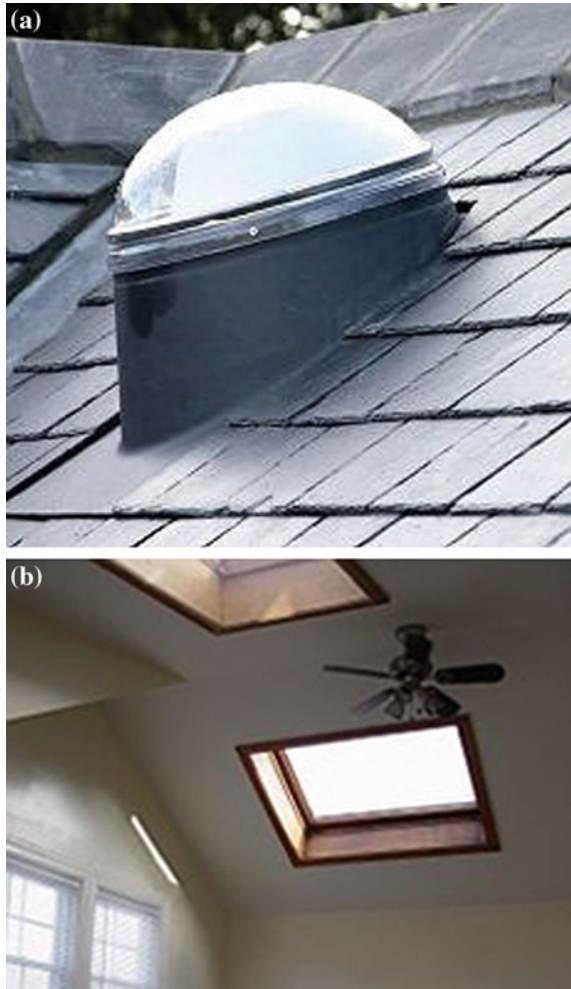
2.4 Different Concept of Daylighting

Generally, most conventional buildings have vertical windows in walls depending on the availability of solar flux on the wall. However, there are many other concepts to have natural daylight in a living space. These are as follows:

2.4.1 *Modern Sky Light*

Skylights are a light-transmitting fenestration from outside a building into a building living space through the roof as shown in Fig. 2.7a. It can be fixed or

Fig. 2.7 **a** View of skylight on inclined roof of a building.
b A pair of skylights installed in a cathedral ceiling



operable (for ventilation) glazing area on the roof of a building. Unit skylights and the sloped glazing in the centre of the roof are used to convey abundant daylight or top lighting into a living space. A skylight, if operable, can also serve for ventilating fresh air inside the building able.

The structure to be installed (fixed or operable) on a skylight opening is termed “unit skylight.” It is made from transparent glass or plastic (fixed with frame) in different shapes and sizes as per the building requirement.

2.4.2 Solar Pipe (SP)/Light Tube

Solar pipes/light tubes have less surface area exposed for heat transfer; therefore, the use of solar pipes reduces heat transfer from the outside environment. In addition, they provide light on a focused area (Fig. 2.8) of interior space of a building.

2.4.3 Semitransparent Solar Photovoltaic Lighting System (SSPLS)

In this case, a semitransparent photovoltaic (PV) (Sect. 4.4.1) module with a reasonable nonpacking factor (NPF) is considered. A set of semitransparent

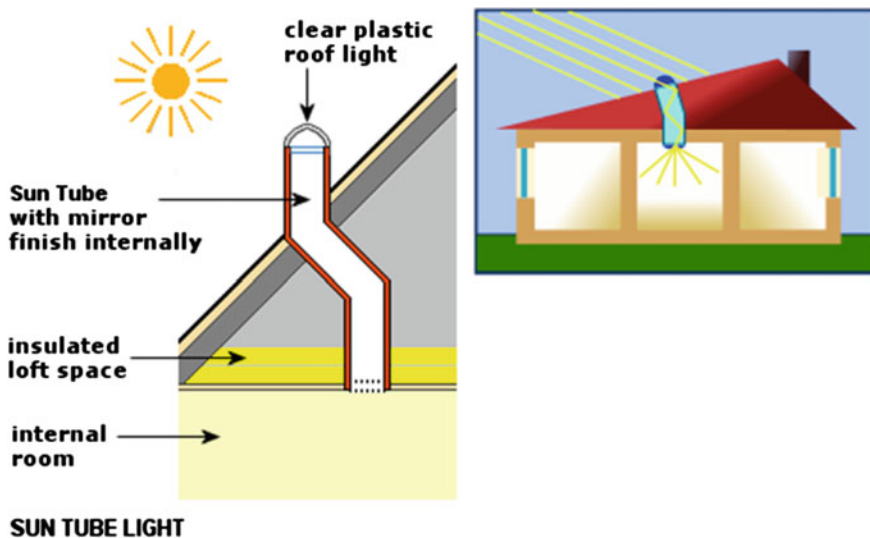


Fig. 2.8 View of solar pipe/light tube/tubular daylighting device (TDD)



Fig. 2.9 View of roof-integrated semitransparent photovoltaic (PV) module

photovoltaic (PV) modules connected in series and parallel combination is integrated with an inclined roof to receive the maximum solar radiation for daylighting and electrical power required by the building as shown in Fig. 2.9. There is a daylighting effect inside the building through the nonpacking area of the PV module. Such roof-integrated semitransparent photovoltaic (PV) modules also provided a greenhouse effect, which can be used for many applications such as

- (i) Daylighting
- (ii) Solar crop-drying
- (iii) Sun bath
- (iv) Electrical power

2.4.4 Light Shelves

Light shelves are an effective way to enhance the daylighting provided through windows on a wall exposed to incoming solar radiation. A highly reflective metal light shelf is attached to the outside of the window at the top as shown in Fig. 2.10. This arrangement with the window will protect direct solar radiation coming into the living space during summer season due to projection.

This arrangement is also referred as a “light shelf.” Solar radiation falling on a light shelf is reflected toward the ceiling of the living space; some radiation will be absorbed (responsible for heating of ceiling an undesirable situation in the summer), and the rest will be reflected back to the living space and illuminate the living area. In case of intense solar radiation, glare-control techniques are needed for proper daylighting.

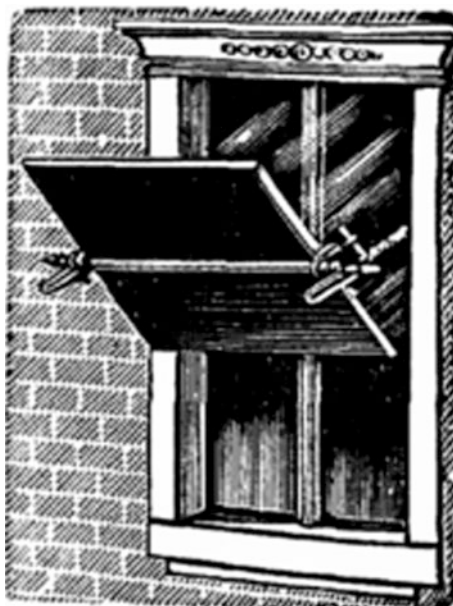


Fig. 2.10 View of light shelves integrated into a wall of a building

2.4.5 *Light Reflector*

Figure 2.11 shows the manually adjustable **light reflector**, which was mostly used in office buildings in past. Currently it is seldom used. The adjustment of the reflector depends on the season in order to have maximum daylighting into a living space.

Fig. 2.11 View of adjustable light reflector attached to an exposed window



2.4.6 Tubular Daylighting Devices (TDDs)

Tubular daylighting devices (TDDs) are devices that provide daylight through tubes integrated with walls or the roof of the building. These tubes collect daylight from a transparent dome structure mounted on them. TDDs can be a simple tube with a high reflective coating or filled with bundles of optical fibers. The daylight carried by TDDs is distributed using a diffuser assembly for the homogeneous distribution of light in a whole living area. These devices are promising techniques to provide daylighting in multistory residential and commercial buildings.

2.4.7 Sawtooth Roof

A **sawtooth roof** is very old concept used in old factories for using daylight inside the building. It is an arrangement of vertical glass opposite the exposed area of the roof. A sawtooth roof allows diffuse solar radiation. The prime disadvantage of these structures is that the exposed area increases unwanted thermal losses during winter seasons because it allows loss of thermal energy from the exposed glass.

2.4.8 Heliostats

A heliostat, as shown in Fig. 2.12, is a mirror that rotates with the motion of the Sun. The heliostat move in phase with the direction of the Sun and reflects solar radiation in a single direction. These advanced technology devices are used to shine the glazed portion of the building such as the window, a skylight (Fig. 2.7), and tight tubes (Fig. 2.8). The light received from these glazed portions is further used

Fig. 2.12 View of a heliostat mirror



to illuminate the interiors of a room. A heliostat is more energy efficient technique because it uses maximum available solar radiation throughout day.

2.4.9 Smart-Glass Window

The glazing window made of smart-glass materials is known as a smart-glass window. Smart-glass is a material that changes its optical properties significantly on application of a voltage to the material or by applying some mechanical treatment. These materials can behave as a transparent glass sheet or as a reflective surface or retro-reflective surface with a variation of voltage or mechanical treatment. Therefore, these materials can be tuned per the daylighting requirement inside the living space.

2.4.10 Fiber-Optic Concrete Wall (FOCW)

Fiber-optic concrete wall/translucent concrete wall, also known as a **light-transmitting concrete wall**, is made of enhanced light-transmitting building materials having compatibility with concrete. These materials are embedded with optical fiber cables as shown in Fig. 2.13. Solar radiation falls on the outer portion of the fiber-optic concrete wall and is captured by the optical fiber cables and transmitted to the inner space of the wall. The quantity and quality of the daylight in living space depend on the material as well as other structural properties of the optical fiber.

Light-transmitting concretes are mainly used on windows and the interior surface of walls. These materials are made by mixing fine-grain concrete (approximately 95 %) with optical fiber cables (approximately 5 %). After casting processes, these translucent concretes can be cut in the desired shape and sizes per

Fig. 2.13 View of translucent concrete wall at Expo Bau 2011, München/Germany



the building requirement using advanced machines. The mounting of translucent concrete structures on the façade and walls of the building must be performed in such a way that it results in a uniform distribution of day/artificial lighting inside living area.

2.4.11 Hybrid Solar Lighting (HSL)

Hybrid solar lighting was developed by the Oak Ridge National Laboratory (ORNL). This technology can eliminate the requirement for artificial light during day time. Hybrid solar-lighting system comprise a light-collector system mounted on the roof of building, optical fiber cables, and fluorescent lighting fixtures with transparent rods attached to optical fiber cables.

During evening hours, when the intensity of the sunlight decreases, fluorescent fixtures gradually turn on and maintain a nearly constant luminance level in the interior space. At night hours, the fluorescent lighting system is electronically operated. The cost of these systems is a major concern that must be addressed. In near future, hybrid solar lighting may become a promising technology for daylighting.

2.4.12 Solarium

A solarium is a glass house attached to a building having orientation toward either the south in northern hemisphere or the north in southern hemisphere to receive the maximum solar radiation. In this case, the partition opaque wall between the solarium and the building can have a provision of (i) glazed window (Fig. 2.1), (ii) smart glass window, and (iii) Fiber-optic concrete wall (FOCW), (Fig. 2.13) for daylighting. In addition to daylighting, the solarium can be used for many other applications such as (i) daylighting (ii), sun bath, and (iii) heating of the attached room, etc. There can be another application for producing electricity if glass materials are replaced by a semitransparent photovoltaic module as shown in Fig. 2.9.

2.5 Experiments on Skylight for Natural Lighting for a Mud House: A Case Study [34]

2.5.1 Experimental Results

Most of the studies on skylights have been performed for houses with octagonal-pyramid and/or conical dome-shaped roofs. In the present case study, experiments have been performed for a mud house having an octagonal-shaped

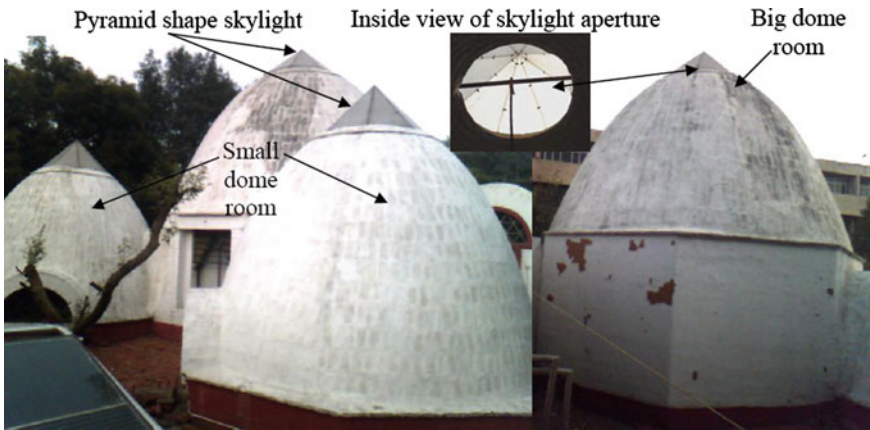


Fig. 2.14 Photograph of octagonal pyramid-shaped skylight for existing dome-shaped buildings: one large and two small-domes rooms

dome-structure roof as shown in Fig. 2.14. Hourly illuminance levels were recorded from 7 a.m. to 5 p.m. inside two rooms having different surface areas of skylight. The view of the large dome and the small dome are also shown in Fig. 2.14. The large dome with the skylight had a conference room with a conference table as shown in Fig. 2.6. Luxmeter (least count = 1 lx; accuracy $\pm 6\%$ of reading ± 1 minimum effective digit; range 0–999,000 lx) was used to record the hourly illuminance inside the rooms at the floor and planes >0.75 - and 1.5 -m heights from the floor. Hourly variations of global and diffuse radiations were also recorded using same luxmeter. A calibrated glass thermometer was used to measure the ambient air and room air temperature. Experimental observations inferred that the luminance levels inside the rooms were different at different heights from the floor surface. In addition, the luminance level was different for different times (winter or summer) of the year. However, only the results for winter (sun at low altitude) are shown in Fig. 2.15.

Figure 2.15a shows the hourly variation of outside illuminance in lux and solar flux in W/m^2 including the diffuse component for each case for a typical clear day in winter. It can be observed from this figure that $1 \text{ W/m}^2 \cong 100 \text{ lx}$. Furthermore, it should be noted that the ratio of diffuse to total radiation is <0.25 , which requires clear/blue-sky conditions (Sect. 1.2.6) for better daylighting.

The hourly illuminance inside the small and the large dome at a height of (i) 0 cm (floor) (ii) 75 cm from the floor and (iii) 150 cm from the floor is shown in Fig. 2.15b. It is observed that the level of illumination increases with height in the small as well as the large dome due to the decrease in distance between the skylight and the point of observation as expected. It can also be observed that the illumination level in the large dome has a lower value compared with that of the small

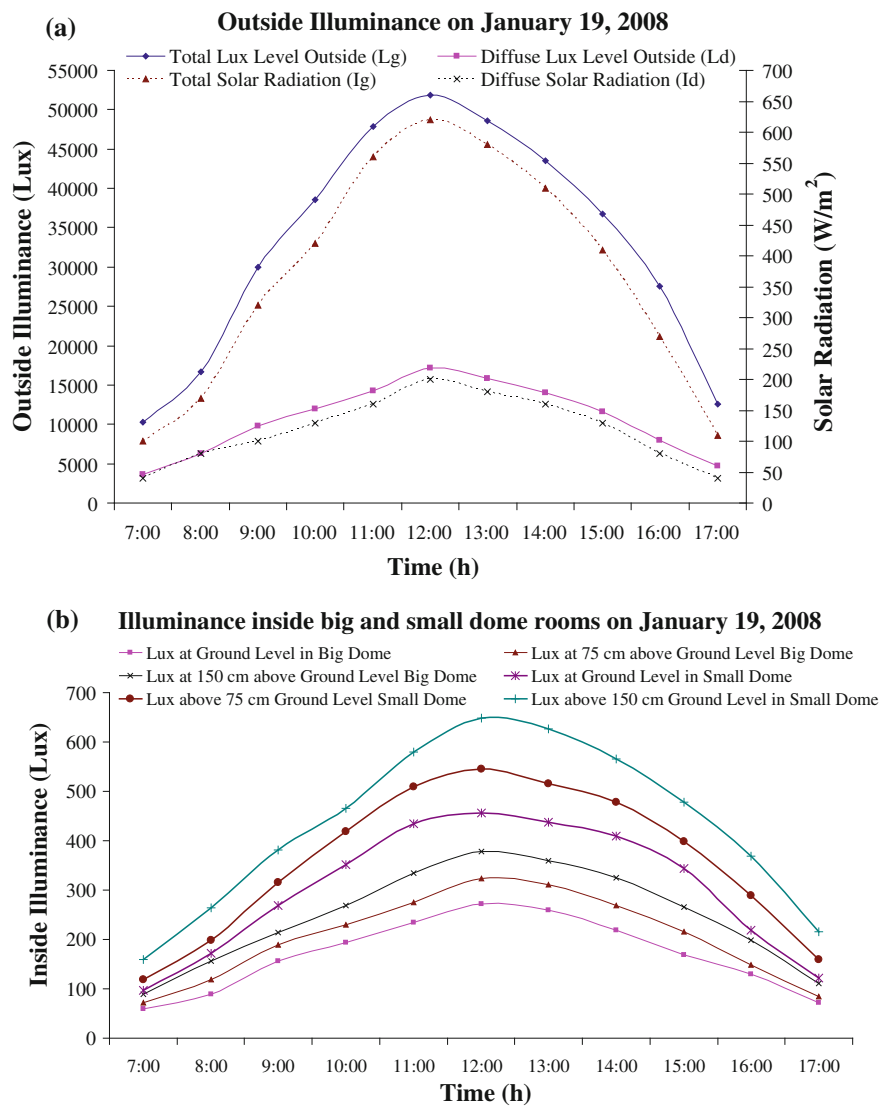


Fig. 2.15 **a** Outside illuminance at a horizontal surface on January 19, 2008. **b** Inside illuminance at three horizontal work planes on January 19, 2008

dome due to (i) the larger floor area and (ii) the larger distance between the skylight and the point of observation.

The dome-structure rooms in present study have been used for harnessing natural light inside an office building from a skylight. Various training programs,

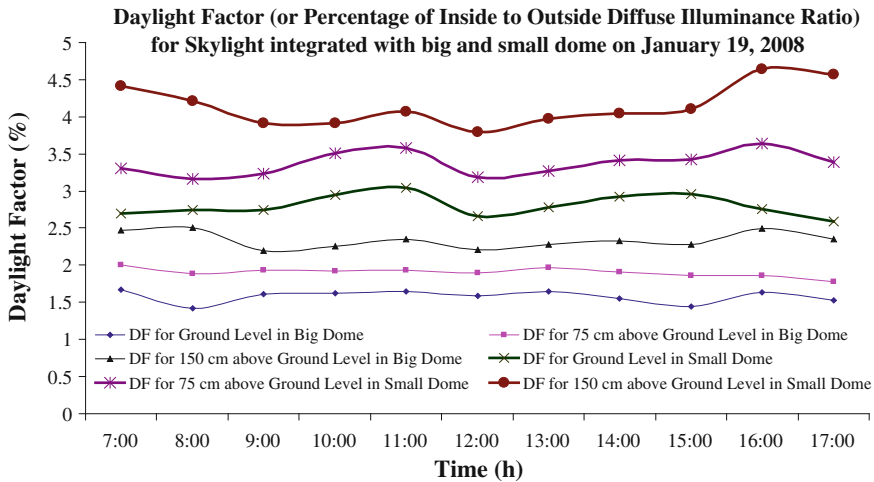


Fig. 2.16 Experimental daylight factor for the same building on January 19, 2008

seminars, and conferences have been performed at this site to show the practical utility of these structures under real operating conditions.

The illuminance level at the floor of the rooms varies from 100 to 250 lx for a large-domed room and 200 to 400 lx for a small-dome room (Fig. 2.15) in month of January. The illuminance levels inside the rooms were suitable for office (working hours) activities.

The experimental hourly values of the daylight factor (DF in %) due to skylight condition can be determined by using Eq. (2.2) in terms of percentage. The results are shown in Fig. 2.16.

From Fig. 2.16, one can conclude the following:

- (i) The daylight factor (DF) due to the skylight at top of small dome is maximum as expected.
- (ii) The daylight factor (DF) due to the skylight for a large dome has a lower value compared with a small dome.

For daylighting in a large-domed mud house, the size of the skylight system should be increased and optimized.

2.5.2 Modeling of the Skylight for a Dome-Shaped Mud House

Performances of the skylight in both rooms have been evaluated by comparing the luminance level inside the room with the diffuse solar radiation outside the room.

In this case study, the performance of skylight was evaluated from theoretical analysis as well as from experimental observation.

2.5.2.1 Total Luminous Flux, ϕ (Lumen)

According to Jenkins and Newborough [35] the total luminous flux, (ϕ (lumen) needed from an artificial (electrical) lighting system to produce the desired level of illuminance (L_i (Lux or lumen/m²)) on a horizontal working surface of area (A_s (m²)) is given as follows:

$$\phi = \left[\frac{L_i A_s}{U_F M_F} \right] \quad (2.12)$$

The use factor (U_F) is the fraction of light actually falling on the working area. Its value depends on the dimension of the living area and varies between 0.5 and 0.7 for office buildings; the maintenance factor, M_F , depends on the life and working condition of the light source, and it varies from 0.7 to 0.9. For the horizontal surface of area A_s (m²) and the measured illuminance level L_i , total luminous flux ϕ can be obtained using following relation:

$$\phi = [L_i \times A_s] \quad (2.13)$$

The electrical energy equivalent corresponding to total luminous flux (ϕ) can be found using Eq. (2.15). This equivalent electrical energy is the conservation of conventional energy due to the incorporation of a skylight in dome-shaped building. The recommended values of the illuminance level for various activities are listed in Table 2.3.

Table 2.3 Recommended illuminance for various activities

Activity	Illumination (lux, lm/m ²)
Public areas with dark surroundings	20–50
Simple orientation for short visits	50–100
Working areas where visual tasks are only occasionally performed	100–150
Warehouses, homes, theaters, archives	150
Easy office work, classes	250
Normal office work, pc work, study library, groceries, show rooms, laboratories	500
Supermarkets, mechanical workshops, office landscapes	750
Normal drawing work, detailed mechanical workshops, operation theatres	1000

2.5.2.2 Total Lighting Power, $P(W)$

Luminous efficacy ε_e (lm/W) is a measure of visible light produced by a light source. It is the ratio of **luminous flux** (ϕ) to **power** (P) and is mathematically expressed as

$$\varepsilon_e = (\text{lm/W}) = \phi/P \quad (2.14)$$

where ϕ can be obtained from Eq. (2.13). In the case of daylighting, power (P) is the solar radiation flux on the given area; for artificial light sources, power (P) is the electrical power consumed in a light source. In the case of daylighting, ε_e is also termed the “luminous efficacy” of solar radiation, and it is known as the luminous efficacy of the artificial source.

The luminous efficacy of an artificial source (electrical) reflects the ability of a source to convert electrical energy into visible light. The overall luminous efficacy depends on how efficiently the source generates electromagnetic radiation from electrical energy and to what degree the human eye is susceptible to the radiation emitted from the source. Luminous efficacy of solar radiation is a measure of visible light produced by electromagnetic radiation coming from the Sun.

The total electrical power savings $P(W)$ corresponding to the luminous flux for the measured illuminance level on a given horizontal surface can be obtained using the following equation [35]:

$$P(W) = \left[\frac{\phi}{B_F \times \varepsilon_e} \right] \quad (2.15)$$

where B_F is ballast factor.

Equation (2.15) can be used to evaluate the daily, monthly, and annual power consumed in kWh for a given illuminance.

Monthly and annual daylighting energy savings potential due to a skylight at the floor of large-domed mud house is shown in Fig. 2.17. It can be observed that the potential annual daylighting energy savings varies from 467 to 662 kWh. The average annual potential daylighting energy savings for a large-domed mud house is 564.5 kWh. The monthly energy savings in kWh is greater during the summer months (April–September) due to a high level of insolation. The monthly average energy savings in kWh is 70 during the summer months and 40.7 kWh during winter months. This indicates that the monthly average energy savings in kWh during the summer months 70 % higher than during the winter months (Fig. 2.18).

Similar trends were observed for a small-dome mud house. However, the potential annual daylighting energy savings varies from 169 to 239 kWh. Thus, the average annual potential daylighting energy savings for small-dome mud house is 204 kWh. It is also important to note that the average annual potential daylighting

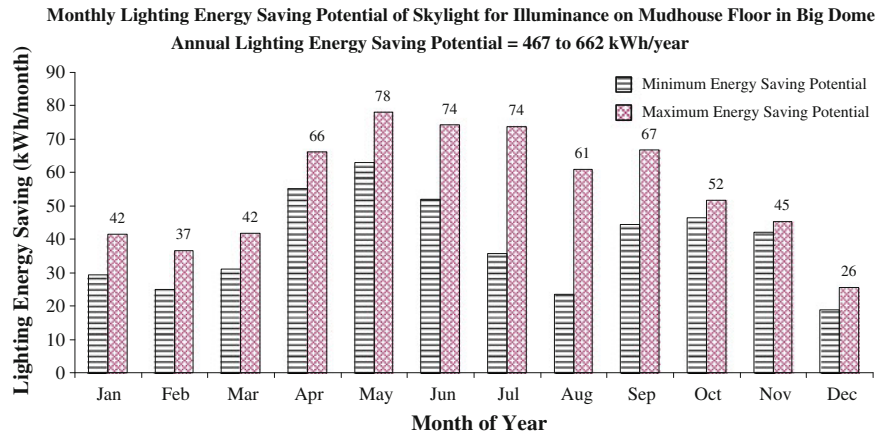


Fig. 2.17 Monthly lighting energy savings corresponding to illuminance at ground level inside room with a large-domed skylight

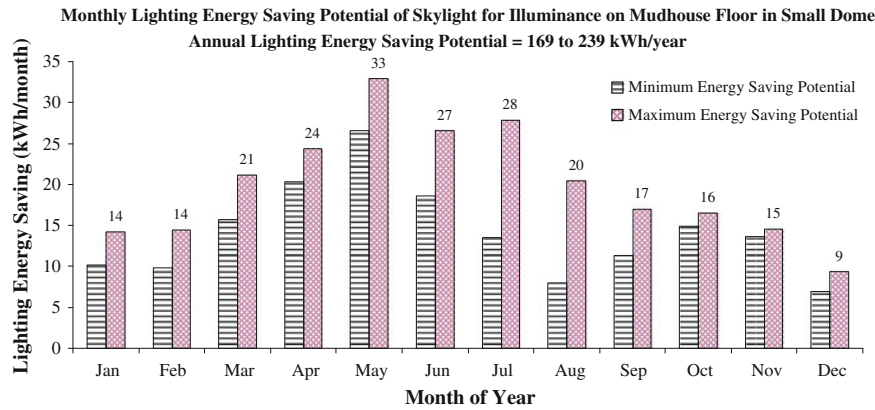


Fig. 2.18 Monthly lighting energy savings corresponding to illuminance at ground level inside a room with a small-domed skylight room

energy savings for a large-domed mud house is 177 % higher than the average annual potential daylighting energy savings for a small-dome mud house, which is in contrast to the illuminance parameter

Furthermore, the total annual potential daylighting energy savings in kWh for small-dome and large-domed mud houses were calculated for all weather conditions (type ‘a’ to type ‘d’, Sect. 1.2.6) for five different climatic condition in India, and the results are shown in Fig. 2.19. It is observed that the total annual daylighting energy savings in kWh for small-dome and large-domed mud houses for Srinagar is minimum due to the low level of insolation as well as sunshine hours.

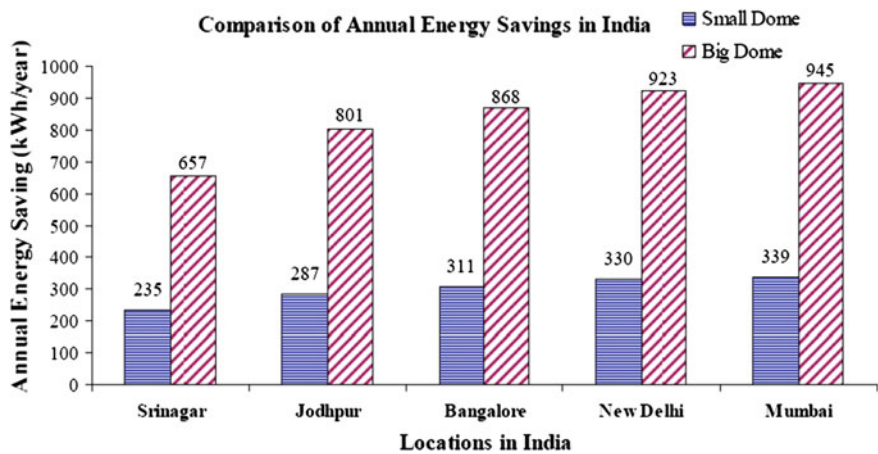


Fig. 2.19 Annual energy saving of skylight for small- and large-domed rooms in India, For $P_i = 5200$, $R = 4615/\text{year}$, $M = 2400/\text{year}$ and $n = 50$ years

2.5.3 Life-Cycle Cost Analysis for Skylight in the Mud House

A similar analysis was used to determine the cost investment for a skylight over the domed roof structures of the mud house. There were annual energy savings for large and small domes of 923 and 339 kWh/year, respectively, which equals the respective annual rate of returns (R) Rs. 4615/year and Rs. 1695/year, respectively, with a unit energy savings cost of Rs. 5/kWh in India. There were total investments in skylight transparent diffuse glass (P_i) for 2.6 m² a large dome of Rs. 5200 and Rs. 1200 for a 1.5 m² glass area for the skylight, including labor costs, for making a pyramid-shaped skylight. Life-cycle cost analyses were performed for this skylight for different rates of interest. The annual minor maintenance of the mud-house skylight (M) was considered as Rs. 2400 for cleaning the skylight four times per month at rate of Rs. 50 per washing and cleaning. The end-of-life salvage value of the skylight glass was neglected with a 50-year lifetime for a pyramid-shaped skylight. The payback period for different interest rates were determined as shown in Fig. 2.20.

It can be seen that the payback period at lower rate of interest is minimum (2.5 years) as per expectation. Energy matrices of a building by using the day-lighting concept have also been studied by Sudan and Tiwari [36].

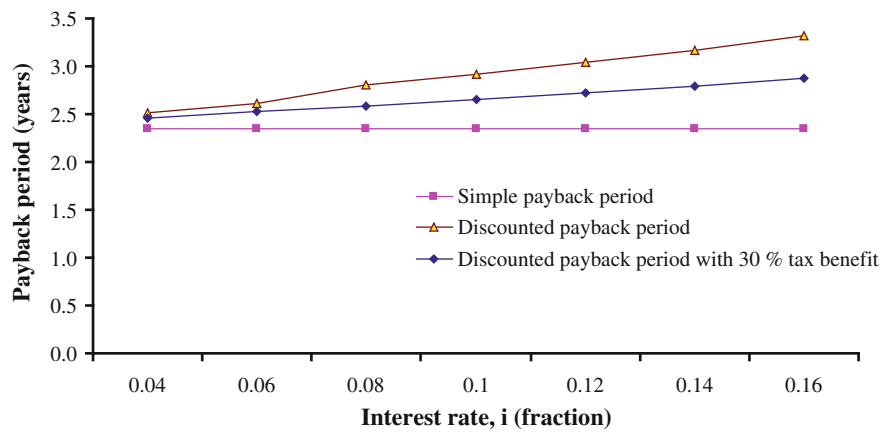


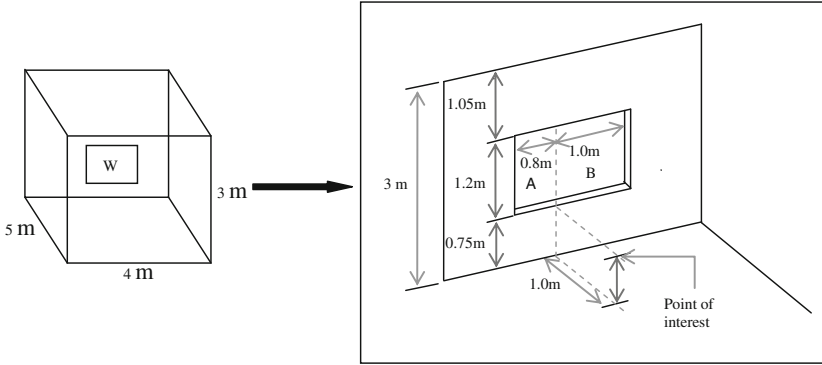
Fig. 2.20 Payback period, with interest rates, for investment in large-domed skylight

Solved Examples

Example 2.1 Calculate the sky components of the configuration given below for the following parameters by using The Building Research Establishment (BRE) Table 2.4:

Table 2.4 The BRE table for vertical glazed rectangular windows

h/d ratio <div>↓</div>	Obstruction angle (degree)	h = height of window head above working plane; W = width of window to one side of normal; d = distance from window											
		W/d ratio →											
		0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	2.0	∞	
	8	0.1	0.02	0.03	0.04	0.05	0.05	0.06	0.06	0.06	0.07	0.08	
	11	0.2	0.06	0.11	0.14	0.20	0.21	0.22	0.22	0.22	0.23	0.24	
	17	0.3	0.14	0.26	0.34	0.42	0.47	0.49	0.50	0.50	0.51	0.53	
	22	0.4	0.25	0.45	0.62	0.75	0.89	0.92	0.95	0.95	0.96	0.98	
	27	0.5	0.39	0.70	0.97	1.10	1.30	1.40	1.40	1.40	1.50	1.50	
	31	0.6	0.53	0.98	1.30	1.60	1.80	1.90	1.90	2.00	2.00	2.10	
	35	0.7	0.68	1.30	1.70	2.10	2.30	2.50	2.50	2.60	2.60	2.80	
	40	0.8	0.83	1.60	2.20	2.60	2.90	3.10	3.20	3.30	3.30	3.31	
	42	0.9	0.99	1.90	2.60	3.10	3.40	3.70	3.80	3.90	4.00	4.20	
	45	1.0	1.10	2.20	3.00	3.60	4.00	4.30	4.50	4.60	4.70	5.00	
	48	1.1	1.30	2.50	3.40	4.10	4.60	4.90	5.10	5.30	5.40	5.70	
	50	1.2	1.40	2.70	3.80	4.50	5.00	5.40	5.70	5.90	6.10	6.30	
	52	1.3	1.50	2.90	4.10	4.90	5.50	5.90	6.20	6.40	6.70	7.00	
	54	1.4	1.60	3.20	4.40	5.20	5.90	6.40	6.70	7.00	7.30	7.60	
	56	1.5	1.70	3.30	4.60	5.60	6.20	6.80	7.10	7.40	7.80	8.10	
	63	2.0	2.0	4.0	5.6	6.7	7.5	8.3	8.7	9.1	9.7	10.3	
	90	∞	2.5	4.9	6.9	8.4	9.6	10.7	11.6	12.2	13.0	15.0	



$h_1 = 1.95 \text{ m}$, $h_2 = 0.75 \text{ m}$, $W_1 = 0.8 \text{ m}$, $W_2 = 1 \text{ m}$ and $d = 1 \text{ m}$.

Solution

Sky component for window A (SC_1):

$$\frac{\text{Height of window}}{\text{Distance of point of interest from window}} = \frac{h_2 - h_1}{d} = \frac{1.95 - 0.75}{1} = 1.2$$

and

$$\frac{\text{Width of window}}{\text{Distance of point of interest from window}} = \frac{W_1}{d} = \frac{0.8}{1} = 0.8$$

Using Table 2.4, the sky component for window A (SC_1) for 1.2 (y-axis) and 0.8 (x-axis) can be written as $SC_1 = 4.5$

Sky component for window B (SC_2):

$$\frac{\text{Height of window}}{\text{Distance of point of interest from window}} = \frac{h_2 - h_1}{d} = \frac{1.95 - 0.75}{1} = 1.2$$

and

$$\frac{\text{Width of window}}{\text{Distance of point of interest from window}} = \frac{W_2}{d} = \frac{1}{1} = 1$$

Using Table 2.4, the sky component for window B (SC_2) for 1.2 (y-axis) and 1 (x-axis) can be written as $SC_2 = 5.0$.

Thus, the total sky component is given as $SC = SC_1 + SC_2 = 4.5 + 5.0 = 9.5 \%$.

Example 2.2 Evaluate the sky component of Example 2.1 if a half portion of window A and window B is obstructed.

Solution

The sky component for the lower half of window A:

$$\frac{\text{Height of half window}}{\text{Distance of point of interest from window}} = \frac{(h_2 - h_1)/2}{d} = \frac{0.6}{1} = 0.6$$

Using Table 2.4.

The sky component for the half lower portion of window A for 0.6 (same y-axis) and 1 (same x-axis) = 1.6.

Similarly,

The sky component for the half lower portion of window B for 0.6 (y-axis) and 0.8 (same x-axis) = 1.8.

The sky component for the half upper portion of windows A and B = 9.5 – 1.6 – 1.8 = 6.1 %.

Example 2.3 Calculate the externally reflected component (ERC) of Example 2.2.

Solution

The sky component for the half lower portion of windows A and B = 1.6 + 1.8 = 3.4.

This sky component for the half lower portion of windows A and B is reflected from the obstruction back into building and can be evaluated from Eq. (2.9b) as

$$\text{ERC} = 0.1 \times 3.4 = 0.34$$

Example 2.4 Evaluate coefficient ‘C’ for obstruction angle of 0°, 40°, and 90° and compare the results of Table 2.3.

Solution

From Eq. (2.10a), we have

$$C = \left[40 - \frac{0}{2} \right] = 40$$

$$C = \left[40 - \frac{40}{2} \right] = 20$$

$$C = \left[40 - \frac{90}{2} \right] = -5$$

From Eq. (2.10c), we have

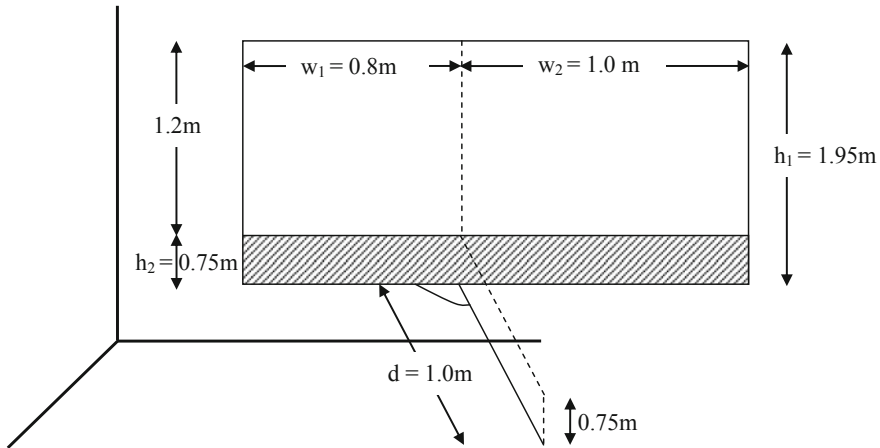
$$C = \frac{90}{2} - 5 = 40$$

$$C = \frac{50}{2} - 5 = 20$$

$$C = \frac{0}{2} - 5 = -5$$

This suggests that both equations give same results, but its validity is only for obstructions $<90^\circ$. The values of the calculated coefficient 'C' is nearly the same as reported in Table 2.3.

Example 2.5 Evaluate coefficient 'C' using Eq. (2.10b) for the following configuration.



Solution

From Eq. (2.10b), we have

$$= \left[40 - \frac{\arctan\left\{\left(\frac{h_1 - h_2}{2}\right)/d\right\}}{2} \right]$$

Here, $h_1 - h_2 = 1.2$ m and $d = 1$ m.

For the above values, we have

$$C = \left[40 - \frac{\arctan 0.6}{2} \right] = 40 - \frac{30.96}{2} \cong 24.52$$

In this case, the value of coefficient 'C' depends mainly on the size of window and the point of observation unlike in Example 2.4.

Example 2.6 Evaluate the internally reflected component of a house having dimensions of 5 m \times 4 m \times 3 m with a window configuration of the same as in Example 2.1.

Solution

$$\text{Window area } (W) = \text{width} \times \text{height} = 1.8 \text{ m} \times 1.2 \text{ m} = 2.16 \text{ m}^2;$$

$$\text{Ceiling area} = \text{Floor area} = 4 \times 5 = 20 \text{ m}^2;$$

Height between the floor and the mid-height window

$$= \text{mid-height window} + \text{sill} = 0.6 + 0.75 = 1.35 \text{ m}$$

Height between the ceiling and the mid-height window

$$= \text{mid-height window} + \text{above window} = 0.6 + 1.05 = 1.65 \text{ m}$$

Total area of the side walls = perimeter \times height

$$= (4 \times 3) \times 2 + (5 \times 3) \times 2 = 18 \text{ m} \times 3 \text{ m} = 54 \text{ m}^2$$

Total internal area of the roof/floor and walls (A)

$$= (4 \times 5) \times 2 + (4 \times 3) \times 2 + (5 \times 3) \times 2 = 94 \text{ m}^2$$

For various reflectance, namely, the ceiling (R_C) = 0.70, floor (R_F) = 0.20, window (R_{W1}) = 0.10, and the walls (R_W) = 0.50, the weighted average reflectance inside the building can be calculated by Eq. (2.11) as

$$R = \frac{20 \times 0.7 + 20 \times 0.2 + 2.16 \times 0.10 + (54 - 2.16) \times 0.5}{94} = 0.469$$

The weighted reflectance of the floor and part of the walls below the mid-height of the window wall (mid-height window + sill = 1.35 m), excluding the window, can also be calculated using Eq. (2.11) as

$$R_{fw} = \frac{[(5 + 5 + 4) \times 1.35] \times 0.5 + 20 \times 0.2}{[(5 + 5 + 4) \times 1.35] + 20} = 0.589$$

The weighted reflectance of the ceiling and part of the walls above the mid-height of the window wall (mid-height window + above = 1.65 m), excluding the window, can also be calculated by using Eq. (2.11) as

$$R_{cw} = \frac{[(5 + 5 + 4) \times 1.65] \times 0.5 + 20 \times 0.7}{[(5 + 5 + 4) \times 1.65] + 20} = 0.3$$

From Example 2.5, coefficient $C = 24.55$.

Now the internally reflected component (IRC) can be obtained from Eq. (2.10) by considering $\tau = 0.85$ as

$$\text{IRC} = \frac{0.85 \times 2.16[24.55 \times 0.589 + 5 \times 0.3]}{94 \times (1 - 0.469)} = 0.587$$

Objective Questions and Answers

- 2.1 The daylight factor consists of
(a) a sky component (b) an ERC (c) an IRC (d) all of these
Answer: (d)
- 2.2 The externally reflected component is zero for an obstruction angle of
(a) 90° (b) 0° (c) 45° (d) none of these
Answer: (a)
- 2.3 The externally reflected component is maximum for an obstruction angle of
(a) 90° (b) 0° (c) 45° (d) none of these
Answer: (b)
- 2.4 The sky component is zero for an obstruction angle of
(a) 90° (b) 0° (c) 45° (d) none of these
Answer: (a)
- 2.5 The sky component is maximum for obstruction angle of
(a) 90° (b) 0° (c) 45° (d) none
Answer: (b)
- 2.6 The internally reflected component (IRC) is maximum for a transmissivity of
(a) 0.6 (b) 0 (c) 0.45 (d) 0.90
Answer: (d)
- 2.7 The internally reflected component (IRC) is minimum for a transmittivity of
(a) 0.6 (b) 0.75 (c) 0.45 (d) 0.90
Answer: (c)
- 2.8 The internally reflected component (IRC) is maximum for internal walls of
(a) yellow paint (b) green paint (c) white paint (d) blue paint
Answer: (c)
- 2.9 The daylight factor is maximum for
(a) a dome-structure building, Fig. 2.6 (b) a vertical window
(c) an inclined window (d) none of these
Answer: (a)
- 2.10 Daylight provides
(a) an emission of CO_2 (b) a mitigation of CO_2
(c) energy conservation (d) none of these
Answer: (b) and (c)

- 2.11 Daylight provides
 (a) thermal heat (b) no thermal heat
 (c) electrical heat (d) none of these
 Answer: (b)

Problems

- 2.1 Calculate the sky components of a window having dimension of $4 \text{ m} \times 3 \text{ m}$ equal to the south wall area and a point of interest that is 2 m from the window.
 Hint: See Example 2.1.
- 2.2 Determine the effect of a point of interest from window on the sky components for Problem 2.1.
 Hint: Vary the point of interest (d) from 0.5 to 5 m at an interval of 0.5 m,
- 2.3 Evaluate the sky component of Problem 2.1 if a half portion of the south window is covered by an opaque curtain.
 Hint: Follow Example 2.2,
- 2.4 Calculate the externally reflected component (ERC) of Problem 2.3,
 Hint: Follow the procedure given in Example 2.3,
- 2.5 Calculate coefficient ' C ' using Eq. (2.10b) for different points of interest,
 Hint: See Example 2.5 and vary " d " from 1 to 5 m.
- 2.6 Evaluate the internally reflected component of a house having dimensions of $5 \text{ m} \times 4 \text{ m} \times 3 \text{ m}$ with a north wall as a window and a point of interest that is 1 m from the window.
 Hint: See Example 2.6,
- 2.7 Determine the effect of a point of interest on the internally reflected component (IRC) of Problem 2.6,
 Hint: Vary d from 1 to 5 m.
- 2.8 Calculate the daylight factor (DF) for Problems 2.1–2.6 for each case.
 Hint: Use Eq. (2.1).

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