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Review Article

Review of Active and Passive Daylighting Technologies for Sustainable Building

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According to the International Energy Agency, nearly 20% of worldwide electricity is used up by lighting. This is equal to the total electricity nuclear power generates. Thus, it is needy to explore new technologies for direct use of sunlight via integrating daylight system to the building, which is cost-saving, environment-friendly, and a green solution rather than indirect conversion of electricity to lighting even from renewable sources. In this paper, we present a review on the existing technologies of daylighting systems up to date and how they can provide lighting in a building interior via collection and distribution of sunlight. Our review is a comprehensive study to embrace both passive daylighting system with stationary design and active daylighting system equipped with sun tracking. The economic feasibility, general challenges, and prospects of daylighting systems are also discussed to understand the existing problems that hinder the extensive deployment of daylighting systems. In conclusion, more research works are needed in improving the technological development of a daylighting system so that it is more affordable, environment-friendly, less energy-intensive, and easy to install and gives uniform illumination for the effective application in both commercial building and residential houses.

1. Introduction

The major purpose of both natural and artificial lights is to provide good and comfortable visibility for indoor and outdoor activities throughout the day regardless of weather conditions [1]. Daylighting is an introduction of natural light into an indoor environment to reduce the energy consumption by artificial light sources in the building [2, 3]. The amount and quality of illumination enable our indoor activities to be carried out effectively especially during nighttime, which is important to increase productivity and improve quality of life. From the various literature, it has been discovered that artificial lighting consumes as high as 40% of the annual building energy consumption, which is one of the major challenges for achieving the United Nations sustainable development goals [4]. The sun is a clean, abundant, and sustainable energy source, which is also the most fundamental source of renewable energies amongst others on the earth [2]. For residential and commercial buildings, solar energy can be harnessed without deteriorating our natural resources to provide heat, light, cooling (air-conditioning), and electricity. We can directly harvest solar energy as daylight to illuminate the indoor environment without energy conversion loss, which can indirectly minimize energy wastage [5]. Daylighting system is an already existing and fast-growing technology, which is designed to collect and distribute sunlight for effective internal illumination of a building, hence contributing to its sustainability [4, 6–8]. A sustainable building is designed in such a way that it conserves or advances the quality of life with positive influences on the climate and natural environment, where the natural resources can be preserved over a long period of time. Sustainability in a building design should never be disregarded, and it is crucial to bring a long-term impact to humans for the fast urbanization process recently in the world [9]. Irrespective of other constituents of a sustainable building, integration of daylighting system into the building architectural design cannot be overlooked as it is the most sustainable and healthy way of providing natural illumination inside the building. Also, most passive daylighting systems perform two functions of providing daylight and ventilation simultaneously for achieving the target of low-energy or green building.

The visible range of photonic energy from the sun can be extracted by using either a passive daylighting system that is associated with the building structure or an active daylighting system. Figure 1 illustrates a general idea of the two designs [10]. The differences between passive and active daylighting systems are well defined by how sunlight is captured and disseminated. In a passive daylighting system, static and nontracking designs are adopted for collecting, reflecting, and distributing the sunrays into the interior of a building, which includes the application of windows, sliding glass doors, static waveguide, and skylights. In an active daylighting system, sunlight is collected by a combination of optical and mechanical devices with a sun-tracking mechanism that actively tracks the sun and distributes daylight into the building's interior via waveguide [11, 12].

The advantage of an active daylighting system is its tracking devices, which makes it effective as daylighting commences from the very early morning to the late evening as compared to stationary passive daylighting systems. The disadvantage is that the active daylighting system incurs high initial installation cost associated with maintenance and operational costs in the future [13]. Three major merits of adopting passive daylighting in sustainable building design include affordability, stress-free installation, and stylishness in design [14]. The prominent benefits as indicated by Kubba are as follows [1]:

(1) At a very affordable cost, it can easily be reconstructed into completely built structures or even into an ongoing construction

(2) The air indoor is of better quality as forced air mechanisms are eliminated using a daylighting system

(3) In passive daylighting, minimum system maintenance is required as there is no mechanical device unlike in the active daylighting system

(4) Economized or eradicated cooling and heating costs since passive daylighting pays dividends over the lifespan of a structure

It has been observed by expert architects of passive solar designs that the design of buildings with passive daylighting systems costs a bit more than buildings made of only concrete blocks and bricks but saves money on a long-term basis. The challenges of integrating passive daylighting in sustainable building designs are the following:

(1) During the selection of building materials for houses with passive daylighting especially window glass, costly mistakes might be made as it is a difficult task to choose the accurate glass for the design. Selection of the accurate glass is dependent on the location (north, south, east, or west) of the glass in the building and the weather condition of the area of the building location

(2) Daylighting and heat are closely associated. The use of daylighting in the summer or countries with warm climate all year round can cause a rise in the amount of energy consumed by the air-conditioning system

(3) Inappropriate design of a passive daylighting system can cause glare on items and appliances at home such as furniture, television, fridge, and computers. Thus, the arrangement of things in the home requires cautious planning [15]

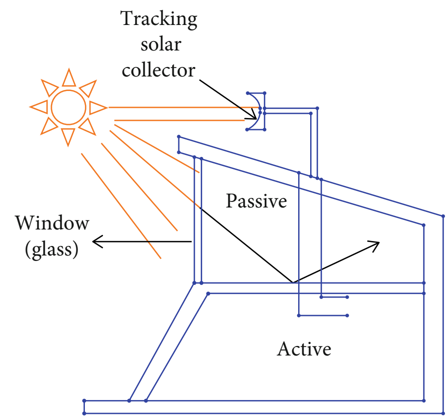


Figure 1: Active versus passive daylighting system.

In this paper, various kinds of daylighting systems will be reviewed under two major headings: "passive daylighting systems" which are the basic types of daylighting systems where sometimes waveguide is applied to increase the penetration of daylight and "active daylighting systems" which are advanced daylighting technologies consisted of a solar collector with sun-tracking system and waveguide is necessary for daylight distribution.

2. Technical Description of Passive Daylighting Systems

A passive daylighting system is mostly installed in buildings with inadequate openings from walls and is constructed such that natural light from the sun can pass through horizontal surfaces or rooftops of the building and into the interiors [16]. Nevertheless, the panic over the swift reduction of energy resources and the environmental effects of their uses has preceded designers to reimplement passive daylighting methods in buildings to lessen the energy consumption for lighting [17]. Passive daylighting systems include tubular daylight, louvers, skylights, roof windows, sloped glazing, soda pop bottle solar light, windows, light reflectors and shelves, and sawtooth roofs [18–38]. Table 1 shows a summary of various designs of passive daylighting systems encompassing the design configuration, critical problems,

Table 1: Summary of the various studies in passive daylighting system.

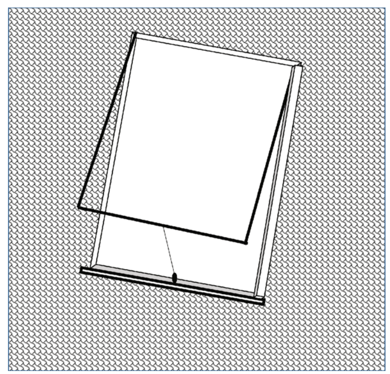
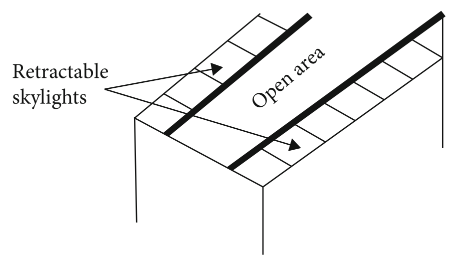
Reference	Category	Design configuration	Picture/drawing	Critical problem of the technique	Possible research work that can be done in the future
Wikipedia [21]		Fixed unit skylight			
Wikipedia [21]	Skylights	Operable skylight		(1) Skylights can only be fixed on the roof of the building or residential house (2) It has limited illumination area that only covers certain distance from the window, glazing, glass, etc. (3) It has other associated problems of daylighting including visual comfort, uncontrollable brightness, and heat (4) It can only be fixed at the top floor of the building	More research works are required for improving illumination, visual comfort, brightness, and control of the heat inside the building.
Wikipedia [21]		Retractable skylight			

Table 1: Continued.

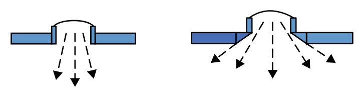
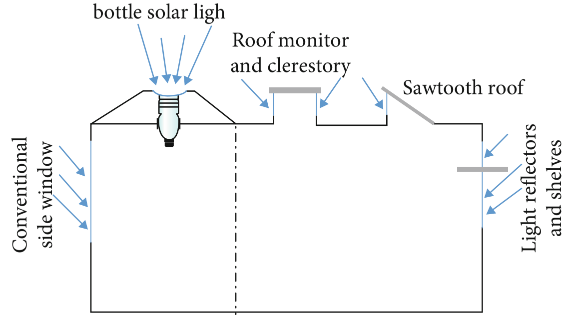
Reference	Category	Design configuration	Picture/drawing	Critical problem of the technique	Possible research work that can be done in the future
https://vedantfacade.com/sky-lights-3/ [25]; Cuce and Riffat [26]		Sloped glazing			
Livingstone [29]		Straight and splayed skylight			
https://www.pinterest.com/pin/548876891847323372/ [36]		Sawtooth roof			
https://www.aiche.org/chenected/2011/09/soda-bottle-solar-light-bulb [30]	Roof	Soda pop bottle solar light		This method is usually applied to the rural areas experiencing poverty. The associated problems include potential rain water leaking into the house especially when there is heavy rain with strong wind. Also, the durability and reliability of the soda pop bottle cannot be guaranteed. It cannot be implemented to the modern house or building where the distance between the roof and ceiling are larger than the length of the soda pop bottle.	More research works are required for improving illumination, visual comfort, brightness, and control of the heat inside the building.
Shi and Chew [31]	Windows	Conventional windows		(1) It can only be fixed to peripheral wall of the building	More research works are required for improving illumination, visual comfort, brightness, and control of the heat inside the building.
Omer [33], Shi and Chew [31]		Clerestory windows		(2) It has limited illumination area that only covers certain distance from the window, glazing, glass, etc.	
Boubekri [34]; Berardi and Anaraki [35]		Light reflectors and shelves		(3) The associated problem of daylighting via windows include visual discomfort, uncontrollable brightness, and heat	

Table 1: Continued.

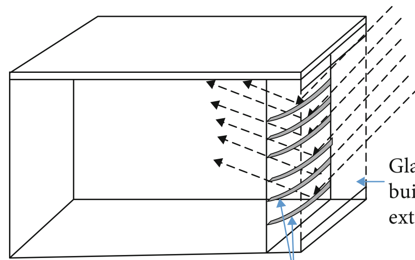
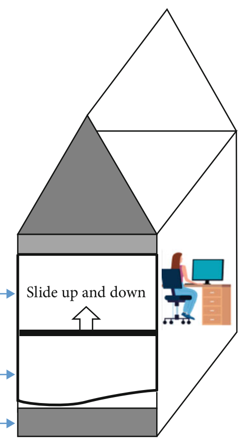
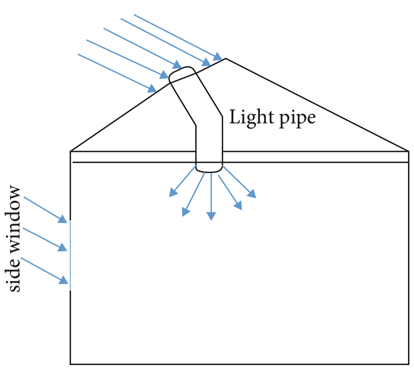
Reference	Category	Design configuration	Picture/drawing	Critical problem of the technique	Possible research work that can be done in the future
Shi and Chew [31]; Boubekri [34]		Louver system			
Kapsis et al. [38]; Shen and Tzempelikos [39]		Façade			
Ikuzwe and Sebitosi [37]		Passive zenithal light pipe		The optical loss increases with the number of light reflection in the light pipe.	
Paroncini et al. [22]	Skylights	Tubular daylighting device (TDD) or light pipe		Tube transmission efficiency is low at low sun altitude angle (during morning and afternoon period). Since there is no tracking system, the skylight element can only accept the sunlight with the incident angle less than acceptance angle of light pipe, where the sun reaches certain altitude angle.	More research works are required for increasing the acceptance angle and reducing the number of light reflection within the pipe.

Table 1: Continued.

Reference	Category	Design configuration	Picture/drawing	Critical problem of the technique	Possible research work that can be done in the future
Earp et al. (2004)[1] [40]; Wang et al. [41]; Earp et al. (2004)[2] [42]		Luminescent solar concentrators (LSC)		The LSC can only guide the light in the designated direction. It has high optical loss due to absorption and scattering inside the LSC material. The design uses total internal reflection to guide the sunlight and is highly dependent on the sun position that varies throughout the day.	More research works are required for increasing the acceptance angle and transmission efficiency.

and future research exploration. The critical problems are the views of the authors based on the compilation of multiple in-depth reviews of articles and their research experiences in the relevant subject.

2.1. Skylights. Skylights, including light conveying fenestration that makes a portion or the complete roof of the space of a building, are normally used to give a visual view of the outdoor surroundings for inhabitants inside as well as to allow illumination from the sunlight into the building via top lighting. Skylights are usually installed mainly on the highest floor of a multistory building or on the roof of a single-story building [20]. The type of material skylights are made of can have a significant impact on the quality of the daylight and also the energy efficiency of the building. Popular glazing materials used for skylights embrace several types of glass and plastics with a wide range of colors and thicknesses. Dome-shaped, pitched, and flat panel skylights are usually positioned on the same level as the roof of the building. One main part of skylight designs are light wells. Light wells guide the light through the building's roof and ceiling by controlling the daylight it receives before it gets into the building interiors. The light well is designed such that it concurrently distributes light and shields the viewer from very bright sunlight [13]. Below are various types of skylights but not limited to the following examples:

(1) Fixed unit skylight: this skylight has no ventilation and has a structural perimeter frame supporting the light-transmitting portion that is built from glass or plastic [21]

(2) Tubular daylighting device (TDD) or light pipe: this is a fixed unit skylight element mounted on the roof, which receives sunlight and distributes it through a light conveying optical conduit to a light diffusing element. This system collects and passes sunlight through a 0.254 m to 0.5588 m roof-mounted dome [21]. The dome captures the sunlight and redirects the light rays into an aluminum tubing system for dispersion into the building through multiple specular reflections [22, 23]. The size of the dome is dependent on the size of the building and is made from acrylic or polycarbonate for the aim of blocking ultraviolent rays

(3) Retractable skylight: this type of skylight consists of a retractable window frame or a set of retractable window frames installed on top of a roof. When the window frame is controlled, it rolls off the frame on a set of tracks so that the inner part of the building where it is fixed can completely open to the outdoors for direct daylight or ventilation. They operate on a motorized cable system and can be controlled to retract up and down or left and right [21]

(4) Operable skylight: this skylight design is also named a venting skylight or a roof window if it is accessible to the inhabitants of the house. Its appearance is like that of a single-window frame, which is hinged at the top and is opened a few inches towards the top direction to allow air circulation and more daylight. Manually operable skylight sometimes has a hand-operated latch, which can be used to open it to a certain level and completely close [24]

(5) Sloped glazing: in sloped glazing, a single assembly contains several infill panels in a framing system and is generally designed for a specific project and fixed in sections [25]. There are many types of glazing commonly used in residential windows, i.e., single clear glass, single glazing with gray tint, double clear glass, double glazing with gray tint, double glazing with selective tint, double glazing with low emissivity (Low-E), and triple glazing with Low-E [26, 27]. When daylighting and energy saving need to be considered simultaneously, selecting a window glazing becomes complicated [28]

(6) Straight and splayed skylight: these two designs allow daylight to enter a building from the roof. The dissimilarity between these two designs is that the splayed skylight design disperses the light more broadly in the building as compared to the straight skylight design. On the other hand, the spacing between the straight skylights is closer as compared to the splayed skylight to provide the same amount of illumination [29]

2.2. Soda Pop Bottle Solar Light. This is the most inexpensive and easiest way to obtain light in a dark room and is commonly found in rural homes where there is never any electricity [30]. A plastic coke bottle (preferably one and a half liters' size) made of polycarbonate is filled with water and some amount of liquid bleach to stop algae from growing in the bottle. It is then sealed with a cover and pushed halfway through a circular cut (with an exact diameter as the bottle) on a steel sheet, which holds the bottle in place to prevent it from slipping. It is then firmly fixed into a hole made in a corrugated iron roof and a sealant is applied around the hole to prevent rainwater from getting in. When the sun shines directly on the coke bottle, it illuminates the room.

2.3. Conventional Windows. Windows attached to the walls of a building is the most popular way to allow daylight into a building. Based on the weather condition and latitude of the building location, windows fixed at several orientations are usually combined to give a sufficient mix of light for the building. Increasing the number of windows and their size is the best approach to achieve more daylight in a building [31]. The amount of sunlight obtainable from a window can be enhanced in three diverse ways; (1) the first method is by inclining the sides of window openings such that the interior opening is bigger than the exterior opening so that more sunlight can be obtained in the room. (2) The second method is by installing the window nearby a light-colored wall so that the sunlight can reflect better. (3) The third method is by using an enormous light-colored windowsill to project sunlight into the room [32]. It is essential to choose the proper type and grade of glass for windows since it can have an impact on the light transmitted through the windows. The weakness of this daylighting system is that some buildings do not have sufficient area to fix window openings and the installed windows cannot spontaneously regulate the daylight when the sunlight is excessive to make the occupants comfortable [31].

2.4. Clerestory Windows. These are vertically placed high windows or a combination of windows above eye level. The clerestory roof windows, also known as high-level glazing because of their location are vertical or tilted openings projecting up from the roof plane [33]. They can be used to give access to diffuse daylight from the north in the northern hemisphere that uniformly illuminates a room. In addition, clerestory windows shine on interior wall surfaces painted with white or with a light color to enhance illumination in the room. It is a very brilliant way to admit natural light and fresh air to the inner spaces of a building coupled with its aesthetic characteristics.

2.5. Light Reflectors and Shelves. This is a mechanism used to redirect sunlight to the back of the room by reflecting it away from the ceiling [34]. Light reflectors and shelves can be regulated manually and are seldom used these days since a mixture of other methods, both artificial and natural, is now in existence. Nevertheless, it is still used in some areas where artificial light alone does not provide enough illumination. The incorporation of light shelves can advance the quality of daylighting close to the windows while the useful daylight illuminance (UDI) level at the back of the room reduces slightly [35]. They give an effect gotten by placing a white or reflective metal light shelf outside the window. During the summer season, a projecting eave shields the windows from direct sunlight. The light shelf projects farther than the shadow formed by the eave, and sunlight is reflected in the upward direction by the light shelves to illuminate the ceiling. The reflective illumination from the ceiling will reduce shadows and in so doing reduce the need for universal illumination. Light shelves also decrease the amount of heat entering the room via the window.

2.6. Louver System. This system receives the sunlight falling in front of the room and redirects it to the back of the room. With this system, the daylight level in the front room can be reduced while improving the illuminance level at the rear of the room [34]. There are two types of designs for the louver system which are static and dynamic. The dynamic type of louver system operates dynamically by following the sun position and has better performance as compared to the static type, but calibration and algorithms are needed to adjust the sun illumination required by the building as well as the heating and cooling requirements [31].

2.7. Sawtooth Roof. This type of roof can be seen in older factories where it uses a group of vertical roof glasses facing away from the equator corner of the building to collect diffused light. It is split apart by sloped roof elements. A portion of the glass support structure is angled, opaque, and well protected with a cool roof for insulation and a shiny barrier. This roof can be used to uniformly illuminate a large room while decreasing the impact on the building's overall height [36].

2.8. Passive Zenithal Light Pipe. Ikuzwe and Sebitosi proposed a novel solution called the passive zenithal light pipe for improving interior daylighting in existing schools located in the rural area of South Africa [37]. The passive zenithal light pipe is a system that can collect, transport, and distribute illuminance from the sun over extended distances in a building. It consists of a top plexiglass dome, which collects sunlight and reflects it down a pipe via numerous mirror-like reflections with the diffuser fixed at the bottommost part of the tube, typically to the ceiling, for distributing the daylight into the inner parts of the room. The light pipe's performance was tested by means of a plexiglass dome, mirrored pipe, and a polycarbonate prismatic diffuser, which has shown that a plexiglass dome has 90% sunlight capturing capacity on sunny days and 70% on cloudy days. From the experiments conducted on the diffuser, results showed that the polycarbonate prismatic diffuser can deliver better uniform spatial light distribution during cloudy days in comparison to the distribution during sunny days. They improved the efficiency of the passive light pipe from 178 lux to 350 lux as was needed inside the classroom based on the principle of edge ray by using a nonimaging optical collimator [37].

2.9. Façade. Kapsis et al. studied a bottom-to-top motorized roller shade having configurable automated control installed in office spaces as a means of implementing the idea of a basic three-section facade [38]. This concept is a potential method for integrating daylighting into facade design. Enhanced glass facade design may increase the use of daylight and yield major savings in electricity consumption of lighting [39]. In the three-section facade design, the lower level of the facade is opaque, the middle level is transparent for viewing, and the upper level directs the daylight into the building space. In other words, the bottom-up shade is actually a roller shade operating from top to bottom such that the bottom of the window is covered while daylight enters from the upper section of the window to the room as illustrated in Table 1. A remote control can be used to open or close the motorized shades whenever it is needed. From the study, in the parts of the room where electric lighting is needed as they are further away from the façade, the bottom-up shade gives 46% higher Daylight Autonomy (DA) as it allows natural light from the sun to go in via the upper level of the facade and further into the room for illumination thus decreasing the energy consumed for electric lighting by 21-41% annually [38].

Similarly, Shen and Tzempelikos examined the balance between daylighting and energy consumed in small secluded offices having one external facade with internal roller shades while considering the properties of glazing and shading and their control, size of the window, climate, and orientation in an incorporated daylighting method. Various analyses were carried out to show that north windows can permit enough daylight into the building for all locations with more than

30% window-to-wall ratios. East windows perform better for the other orientation because, during the morning hours, the shades would close for a short while in comparison to the south and west facades. They noted that DA rises based on window area and shading and glazing transmittance depending on climatic factors [39].

2.10. Luminescent Solar Concentrators (LSCs). Earp at al. proposed luminescent solar concentrators (LSCs) with three different colored fluorescent dyes (a pile of pink, green, and purple LSCs) to give a concentrated nearly white source of light that is coupled into polymer sheets to transport sunlight in the range of 10 m [40]. The concentrated light is transported by polymer light guide sheets that are flexible clear polymethylmethacrylate (PMMA) light guides rather than optical fibers as the light from LSCs is not a pointolite. Fluorescent dyes captivate and emit light isotopically in which the emitted light is greatly concentrated along the collector edges via total internal reflection. The narrow flexible polymer light guides are an extension of the collector, which guides the daylight into the building. It was noted that the main aim of the daylighting applications of LSC is the light-to-light efficiency, which is governed by the eye's spectral sensitivity. Light-to-light efficiency is the ratio of output to input luminous flux [41]. In their prototype, a collector area of $1.2\,\mathrm{m} \times 0.135\,\mathrm{m}$ has shown that indirect solar intensity of 100,000 lux can convey 1000 lm of nearly white light having a 6% light-to-light efficiency and luminous efficacy of 311 lm/W. They noticed that some light loss was triggered by surface defects including excessive adhesive and nonuniformity in flatness that can be avoided by the careful production of LSC. Besides, further concentrating the light eliminated by the LSC into a pointolite just to be able to convey it via optical fibers to a secluded place in a building is an energy-inefficient process. To overcome these problems, the fluorescent fiber solar concentrator (FSSC) system was proposed by Wang et al. [41]. However, Earp et al. defended that LSCs do not need a sun-tracking system, and their light output is easily coupled without any added optics and the LSC system appears to be the well-suited solar collector for use with bendable solid light guides [42]. Optimization of the design parameters can lead to adequate illumination of a room from the concentrated light. The advantage of LSCs compared to other daylighting systems is that they accept diffused and reflected sunlight and so require simple or no tracking devices.

3. Active Daylighting System

Numerous solar concentrators and highly efficient light couplers are essential for sufficient sunlight collection for indoor illumination. To save power consumption on electrical lighting, daylight can be provided for the interior of a building via sunlight focused by a solar concentrator and guided by a bundle of optical fibers. Active daylighting system with a solar concentrator requires a precise sun-tracking system to achieve high optical efficiency for daylight collection and distribution. Therefore, we can categorize the active daylighting systems under two major headings: single-axis tracking system and dual-axis tracking system [43]. Table 2 is a summary of several designs of active daylighting systems, including the optical design configuration, tracking system, and waveguide design, key findings, and the critical problems of the technologies from the perspective of the authors based on the compilation of multiple in-depth reviews of articles and their research experiences in the relevant subject.

3.1. Active Daylighting System with Single-Axis Tracking System. Active daylighting systems attached to single-axis trackers only have a single degree of rotational freedom to track the sun. It usually tracks the change of sun position due to the hour angle, but it is not designed to follow the seasonal change of the earth's equatorial plane with respect to the sun position [44]. This active daylighting system is an intermediate solution, which is simpler than the dual-axis tracking system but more complicated than passive daylighting system.

3.1.1. Linear Fresnel. Ullah and Shin proposed a new method for the linear Fresnel lens as shown in Figure 2 [45]. At the capturing stage, daylight was uniformly distributed to increase the efficiency of the system, and direct sunlight was focused via the linear Fresnel lens. The focused sunlight then went into and out of a collimating lens of which the collimated sunlight was guided by the optical fibers. Achieving a high concentration of light with the linear Fresnel lens was essential; hence, a popular nonimaging optical component called the trough compound parabolic concentrator (CPC) was introduced just before the optical fibers [45]. Also, silica optical fibers (SOFs) placed before plastic optical fibers (POFs) were used to distribute sunlight to each floor with small losses and less heat. Most existing linear Fresnel daylighting systems have some difficulties such as low accuracy in design, installation, and routing of hardware [46]. Tripanagnostopoulos et al. also discussed the application of a linear Fresnel lens to control the illumination of a building interior space due to its ability to segregate the beam and the diffuse solar radiation [47].

3.1.2. Parabolic Trough. Ullah and Shin proposed an approach of an active daylighting system by using a parabolic trough where sunlight was captured by the parabolic trough, focused towards a parabolic reflector, and directed into a multistory building through the optical fibers (POFs) [45]. Similar to the linear Fresnel system, to attain a very high concentration of light with the parabolic trough, a trough CPC was introduced before the optical fibers as shown in Figure 3 [45]. The advantage of their proposed system is just like that of the linear Fresnel system: it is expandable and simply requires a tracking module having one axis. POFs are ideal in daylighting systems as they are low-cost, bendable, durable, and suitable for complicated wiring in buildings. The disadvantage of their proposed system is that the uniformity of light inside the building is not yet achievable and SOFs are quite costly.

3.2. Active Daylighting System with Dual-Axis Sun-Tracking System. Active daylighting system attached to a dual-axis

Table 2: Summary of the various studies in active daylighting systems.

Reference	Optical design configuration	Tracking system	Waveguide design	Analysis type	Key findings	Critical problem of the technique	Possible future research
Ullah and Shin [45]	Linear Fresnel lens coupled to a plano-concave collimating lens and then to trough of compound parabolic concentrator before focusing sunlight onto linear array of optical fibers	Single-axis tracking	Silica optical fibers before plastic optical fibers to reduce the heat problem for distributing sunlight to each floor with small losses	Theoretical modelling using LightTools	(1) This hybrid system combines sunlight and LED light with electric lighting controls to achieve the required illumination levels at all times. Electric lighting power consumption is saved since an average illuminance of 500 lx is maintained (2) The simulated efficiency of the daylighting system is better than that of traditional lighting systems based on the average illuminance in the room interior and on the illumination quality of the system through combining daylight and LED light (3) Advantages: both design configurations are expandable and require only a single-axis tracking module (4) Disadvantages: for both designs, light uniformity is not achieved in the building interior and silica optical fiber is expensive	Due to single-axis tracking, linear reflectors encounter edge effect where some of the optical fibers are unable to receive the sunlight when the declination angle of the sun varies throughout the year. Tracking accuracy can affect the effectiveness of the daylighting system. Thermal issue for the optical fibers is a concern in this design. More practical data is needed for long-term observation on thermal stress and cycling effects to the optical fibers for durability and reliability test.	More study is required on the performance of the system when the sun is not at the normal direction of the concentrator. The impact of tracking accuracy on the performance. Detailed analysis for the durability and reliability of the system is required.
Ullah and Shin [45]	Parabolic trough coupled to a parabolic reflector and then to trough of compound parabolic concentrator before focusing onto linear array of optical fibers	Single-axis tracking					
Ullah and Shin [46] Ullah and Shin [49]	Point-focused Fresnel lens coupled to a plano-concave lens and to a bundle of optical fibers	Dual-axis tracking	Silica optical fibers coupled to plastic optical fibers for distributing sunlight to the building with small losses	Theoretical modelling using LightTools and experimental study	(1) Improved illumination levels can be attained via a combination of sunlight and LED light, as compared to the traditional lighting systems (2) The quantity of optical fibers in the bundle should be carefully chosen based on the surface area of the concentrator (3) More than 500 lx illuminance can be delivered uniformly to different parts of the building	Tracking accuracy can affect the effectiveness of the daylighting system. Thermal issue of optical fibers is a concern in this design. More practical data is needed for long-term observation on thermal stress and cycling effects to the optical fibers for durability and reliability test.	The impact of tracking accuracy on the performance Detailed analysis for the reliability and durability of the system is required.

Table 2: Continued.

Reference	Optical design configuration	Tracking system	Waveguide design	Analysis type	Key findings	Critical problem of the technique	Possible future research
Muhs [50]	Parabolic dish concentrator coupled to secondary faceted cold mirrors that divide the solar irradiance into visible and infrared spectrums while allowing only visible light to be reflected and focused into large core PMMA optical fibers. The solar irradiance in the infrared spectrum is used for electricity generation.	Dual-axis tracking	Large core plastic optical fibers	System-level design, preliminary performance, and cost evaluation	(1) Challenges such as cost, spatial and temporal variability, surplus illumination, glare, and energy efficiency encountered by most passive daylighting systems can be eased with the use of hybrid solar lighting (2) The estimated total system cost is ~$3000 for a 2 m2 collector, illuminating about 12 luminaires covering nearly 1000 ft2 of floor space. This means that installation cost is ~$3/ft2 with less than $2/Wp peak performance (3) The payback period of this daylighting system can be less than 5 years	There is a significant empty space on the receiver not filling up with the aperture of the optical fiber. This causes low packing factor with serious optical loss for the system. Thermal issue of optical fibers is a concern in this design. More practical data is required for long-term observation on thermal stress and cycling effects to the optical fibers for durability and reliability test.	More detailed study can be done to analyze the solar flux distribution produced by the parabolic dish concentrator and the entrance aperture of optical fibers must be optimized to increase the packing factor for receiving maximum concentrated sunlight.
Han et al. [51]	Fresnel lens fixed on a dual-axis tracker to focus sunlight which is transmitted via optical fiber	Dual-axis tracking	Plastic optical fibers	Experimental analysis and photometric analysis	(1) Continuous illumination was realized on the task plane during the day and at low solar altitudes (2) With the use of a light source having a correlated color temperature (CCT) of 5000 K in combination with sunlight, very bright daylight is delivered from a luminaire coupled to the optical fiber cable (3) Consumption of electric energy for indoor lighting in buildings could be drastically decreased by the hybrid system (4) This daylighting system can be used to achieve electric energy savings of 174 kWh when the luminous efficacy of the LED lamp is 17 lm/W and operation duration is 8 h/day for 110 days in a year	Tracking accuracy can affect the effectiveness of the daylighting system. Transmission efficiency of the fiber is 65%, and the total optical losses are not fully studied. The illumination distribution is not uniform.	The system can be made more cost effective by the use of electric lamps that has higher luminous efficacy together with an electric light placed closer to the diffuser [50].

Table 2: Continued.

Reference	Optical design configuration	Tracking system	Waveguide design	Analysis type	Key findings	Critical problem of the technique	Possible future research
Pham et al. [52]	Convergent linear Fresnel lens collects sunlight, while the divergent linear Fresnel lens transmits the light.	Dual-axis tracking	Divergent linear Fresnel lens	Theoretical modelling using MATLAB and LightTools	(1) A high uniformity can be achieved via the daylighting systems' collector and transmitter. All the grooves of the Fresnel lens uniformly distribute the sunlight over the receiver such that the entire lens also uniformly distributes sunlight over the receiver (2) From simulation results, efficiency of ~80% with a tolerance of ~0.60 and a concentration ratio of 340 times can be achieved from the collector (3) High uniformity of more than 90% is attained from the divergent linear Fresnel lens	Overheating issue on the optic fiber is a concern due to high solar concentration ratio of 340 suns. The acceptance angle of the newly designed optical system is 0.60° at which the solar power received by the system drops to 90%.	More detailed analyses can be carried out related to the use of plate beam splitter (PBS) to convey more than 85% of the visible light to the optical fibers and reflect higher than 90% IR wavelength for other applications. A study on the optical losses of silica optical fibers (SOFs) combined to plastic optical fibers (POFs) can be performed.
Ullah and Shin [46]	Convex parabolic reflector coupled to concave parabolic reflector and then to a bundle of optical fibers	Dual-axis tracking	Silica optical fibers before plastic optical fibers to reduce the heat problem for distributing sunlight to the building with minimum losses	Experiments and theoretical modelling using LightTools	(1) With the use of a large sunlight collecting system, more sunlight can be directed into the optical fibers (2) More than 500 lx uniform illuminance can be sent into the building	Tracking accuracy can affect the effectiveness of the daylighting system. Thermal issue of optical fibers is a concern in this design. More practical data is needed for long-term observation on thermal stress and cycling effects to the optical fibers for durability and reliability test. Packing factor issue of optical fibers at the receiver should be optimized.	More research study can be carried out to reduce the poor packing factor of round optical fibers. The rectangular glass optical fibers proposed by Aslian et al. can be adopted in this design, but more analysis is required [66].

Table 2: Continued.

Reference	Optical design configuration	Tracking system	Waveguide design	Analysis type	Key findings	Critical problem of the technique	Possible future research
Schlegel et al. [53]	Parabolic dish concentrator coupled to faceted cold mirrors that is capable of dividing the solar irradiance into visible and infrared spectrum and allows visible light to be reflected and focused to large core PMMA optical fibers.	Dual-axis tracking	Plastic optical fibers	Theoretical modelling using TRNSYS transient simulation program	(1) The study considered an office building model attached with hybrid lighting. The yearly energy impact on lighting, cooling, and heating loads was considered in their simulation which was carried out in six localities in the United States (2) Based on a 10-year profit return period, the capital of the hybrid systems cost $2410 in Honolulu, HI, and $1995 in Tucson, AZ; and the hybrid lighting systems in these two cities performed best (3) The best economic place to mount a hybrid lighting system was found to be Honolulu, HI, with Tucson, AZ, being the best place in continental United States	There is a significant empty space on the receiver not filling up with the aperture of the optical fiber. This causes low packing factor with serious optical loss for the system.	Performance optimization can be carried out to improve the overall efficiency and hence decrease the system overall cost.
Sapia [54]	Primary parabolic collector (PPC) coupled to a secondary collector (SOE), both covered with a very reflective surface in the visible range but transparent in the near-infrared range (cold mirror) and then to a bundle of optical fibers	Dual-axis tracking	Plastic optical fibers	MATLAB simulation	(1) A substitute electrical lighting operation period of 12 h for 320 days in a year is expected of this daylighting system (2) The photovoltaic conversion of sunlight to electricity and then to light for daylighting can be avoided by use of this sunlight addressing system (3) The prorated overall cost of the entire system is USD 6538 for a collective area of 4.48 m2	There is a significant empty space on the receiver not filling up with the aperture of the optical fiber, which causes low packing factor with serious optical loss for the system. The overall efficiency of the system is only 21%.	

Table 2: Continued.

Reference	Optical design configuration	Tracking system	Waveguide design	Analysis type	Key findings	Critical problem of the technique	Possible future research
Ullah and Shin [5]	Heliostats direct sunlight towards the focusing mirror and from there to the mirror light pipe.	Dual-axis tracking	Mirror light pipe	Theoretical modelling and analysis	(1) To achieve high illumination in the interior of building, the mirror light pipe was coated with prismatic optical lighting film and multilayered optical film and was made in a cylindrical way to attain uniform illumination (2) Advantages of this daylighting system include affordability, manageability, the simplicity of design, the applicability of quick manufacturing, and expansion to produce large-scale system	The light intensity at different floors is different: occupants at the highest floor may suffer high light intensity while the occupants at the lowest floor may suffer due to low light intensity. Study carried out is only theoretical where the practical implementation of the whole system is not considered carefully. The design is complicated as it involves the control of heliostat fields to accurately focus the sunlight onto the central receiver. For the heliostats in the array, we need to take into consideration the shadowing and blocking effects between the heliostats.	More detailed research is required to integrate with light control system in each floor and to ensure that the light intensity in each floor is about the same. More studies can be done to optimize layout design of the heliostats to consider the land area usage and blocking and shadowing effects.
Tsangrassoulis et al. [54]; Kristensen [56]	Heliostat with concentrating Fresnel lens connected to a large core liquid fiber optic cable coupled to a luminaire in a windowless room	Dual-axis tracking	Liquid fiber and ordinary PMMA fibers	Theoretical and experimental analysis	(1) As a complementary source of lighting, a metal Halide projector with a 150 W BLV lamp and a Schott projector with a 150 W MH lamp are positioned together with the heliostat and two backup T5 fluorescent lamps embedded in the luminaire (2) The daylighting system integrated with efficient artificial lighting controls can reduce electrical energy consumption by 50–75% in commercial buildings [55]	The transmission efficiency of the proposed liquid optical fiber is low, which is only 3.4%. The brightness of MH lamps can be reduced using continuous or two-level dimming. However, the highest dimming range is roughly 30% of the rated lamp power. The problems associated with the dimming of the MH lamps include decrease in efficiency and reduced lifetime of the lamp by 90%.	More research should be carried out to increase the efficiency of the liquid optical fiber system. More studies are needed for the flux control dimming system and the light sources connected externally.
La Forêt Engineering Co. Ltd. [57]	Himawari lens focusing unit and optical fiber devices	Dual-axis tracking	Very pure quartz glass optic fiber cable conveys the visible rays with very little loss.	Theoretical and experimental analysis	(1) The major benefit of this system is that furniture carpets, rugs, and artwork would not fade and thus are safe (2) As Himawari products contain only a little amount of infrared radiation, there would be no interference with room temperature or air conditioning systems	The solar concentration ratio is 10,000 suns. Thus, they use highly pure quartz glass fiber to transmit the concentrated sunlight.	More research works on the thermal effect under ultrahigh solar concentration ratio on the highly pure quartz glass fiber cable are required.

Table 2: Continued.

Reference	Optical design configuration	Tracking system	Waveguide design	Analysis type	Key findings	Critical problem of the technique	Possible future research
Chen et al. [58]	Himawari system	Dual-axis tracking	Plastic optical fibers	Theoretical and experimental analysis	(1) The system can meet the lighting necessity at the horizontal work plane based on the visual performance in the office and also provide the circadian system entrainment which is the nonvisual effect of lighting at the same time (2) There is a great chance of achieving a suitable level of circadian light at a workspace with no window via the application of the fiber optics daylighting system (FODS) in northern China (3) In comparison with usual artificial lighting systems, circadian light can be delivered more efficiently via this daylighting system (4) This is the first study examining the FODS nonvisual performance	A normal window may still be preferable to occupants in a building compared to the FODS. Since the FODS have a narrow beam light intensity distributor, it must be used with a unique luminaire for indoor lighting dispersal. More so, balancing the illuminance levels and light uniformity of the illumination from the luminaire at horizontal and vertical planes might be difficult. Even though the FODS system has great merits for the wellbeing and health of the inhabitants, it has a higher cost of installation compared to the regular artificial lighting system. The FODS was only tested in the northern part of China. If used in a different location and climate, there is a high chance of occurrence of unidentified problems.	The photometric properties of the indoor luminaire can be improved upon. An improved luminaire reflector design having proper light intensity. Distribution might lead to an increase in the lighting performance of the FODS in terms of visual and nonvisual activities. To analyze the performance of the FODS via subjective assessment, experiment should be conducted in a real office with a human.
Song et al. [59]	Multiple concentrating lenses for focusing sunlight to the plastic optical fibers	Dual-axis tracking	Plastic optical fibers	Theoretical and experimental analysis	(1) 34% system transmission efficiency has been obtained via experiment, considering both the attenuation ratio of the optical fibers and the light transmittance of the lens (2) The tracking system is very good with a precision of 0.1° to accommodate the focusing at 2500 suns (3) The total internal reflection angle is $\pm 30^{\circ}$, and experimental results showed that larger incident angles result in greater attenuation (4) The benefit of this system is the provision of light to dim rooms or underpasses while preventing or reducing the transmission of energetic particles and infrared (IR) and ultraviolent (UV) rays, thereby reducing the amount of electrical power consumption for air-conditioning systems	Tracking accuracy can affect the effectiveness of the daylighting system as less than 0.1° sun-tracking error gives less than 20% output luminous flux loss. The illumination inside the room is not well distributed.	More research can be carried out to include an optical funnel as the secondary concentrator to reduce the impact of sun-tracking error. More studies are needed to improve the uniformity of illumination distribution.

Table 2: Continued.

Reference	Optical design configuration	Tracking system	Waveguide design	Analysis type	Key findings	Critical problem of the technique	Possible future research
Khosravi et al. [60]	A combination of passive and active optical components: sunlight redirectors to redirect sunlight at a predetermined angle to the exterior facades of the building. The redirectors redirect sunlight such that the entire façade is bathed by sunlight and dispersed uniformly to multiple floors. A portion of the sunlight at each floor is captured, concentrated, and recollimated by the concentrator (lens and an enclosure containing a separate lens and mirror assembly) fixed on the facade of the building. The light coming from the concentrator is fed to the light guides.	Dual-axis tracking	Hollow rectangular pipe	Theoretical modelling	(1) With this daylighting system, uniform illumination can be provided in the building most of the time (2) The efficiency of the concentrator as it refers to the ratio of output light to the light that strikes the lens assembly is found to be 95% (3) Simulation result showed that about 77% of light can be gotten from the light pipe; 3% will return to the entrance of the pipe and exit the pipe, while materials in the pipe will absorb 20% (4) Overall system efficiency is calculated to be 30% (5) This daylighting system can only perform under direct sunlight as it cannot focus diffused light; hence, complementary electrical lighting is essential during overcast sky conditions	For high solar altitude angle, large portion of the sunlight can pass between the slats rather than interacting with them which causes the intensity of captured sunlight to be reduced.	More research works are needed to decrease the optical losses due to the change of sun position. Moving mechanism to track the sun position can be implemented.
Kim and Kim [61]	The first mirror is a circular-shaped aluminized glass that tracks the sun and reflects sunlight to a flat or concave secondary reflecting mirror.	Dual-axis tracking	Mirror sunlighting system with secondary reflecting concave or flat mirror	Experimental analysis	Experiments were conducted during clear and overcast sky conditions. The performance of the system was measured in terms of illuminance and sunlight illumination ratio. Results showed that with the mirror sunlighting system, the illuminance level in a semiunderground space can be improved by eleven times with the use of a flat secondary reflective mirror and fifteen times with the use of a concave secondary mirror. Thus, the concave secondary mirror was preferable.	Each optical daylighting system can only be applied to a single floor of a building. The mirror sunlighting may cause glaring and visual discomfort. The illumination inside the room is not uniform, and it is unable to illuminate a room without window.	More research works can be conducted to improve the visual comfort and uniformity of indoor illumination via diffuser.

Table 2: Continued.

Reference	Optical design configuration	Tracking system	Waveguide design	Analysis type	Key findings	Critical problem of the technique	Possible future research
Chong et al. [62]; Onubogu [63]; Obianuju and Chong [64]; Onubogu et al. (2019) [65]	80 primary facet mirrors coupled to 20 secondary facet mirrors and to densely packed plastic optical fibers for daylight distribution	Dual-axis tracking	Plastic optical fibers	Theoretical modelling using LightTools and experimental study	(1) The equivalent power conversion efficiency of the prototype 2S-NISC was found to be 22% based on 170 W input solar power (2) The proposed 2S-NISC daylighting system having an optimized 4 m2 collective area was projected to cost USD 1231.20, which is cheaper than most active daylighting systems (3) Taking a 4% interest rate and a 2% fuel inflation into consideration, a total profit period of 6.1 years was estimated. This is practical as the active daylighting system has a lifetime of at least 15 years	The sun-tracking error may cause a significant drop in efficiency. The current design is not suitable for mass production because each facet mirror is aligned for its own predefined tilted angle.	More research works can be conducted to design the solar concentrator via 3D printing method or mould casting the geometry of the concentrator.

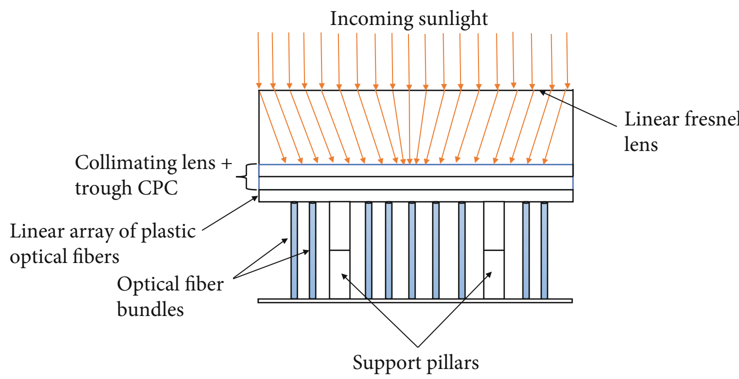


Figure 2: Front view of the physical layout of linear Fresnel lens daylighting system by introducing the trough compound parabolic concentrator (CPC) before the optical fibers (source: adapted from [45]).

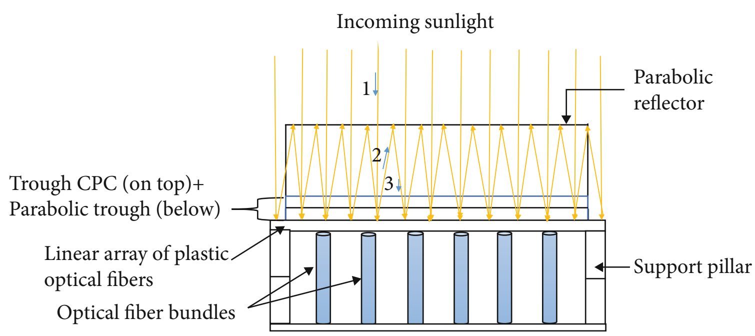


Figure 3: Front view of the physical layout of parabolic trough daylighting system by introducing the trough compound parabolic concentrator (CPC) before the optical fibers (source: adapted from [45]).

tracker has two degrees of rotational freedom, which is capable of perfect alignment to the sun at all times to achieve maximum optical performance throughout the year [48]. Conveyance of uniform sunlight to areas such as the basement, storerooms, windowless rooms, and various floor areas was mentioned to be possible via an active daylighting system [46].

3.2.1. Fresnel Lens. Ullah and Shin proposed a uniformly illuminated daylighting system for the interior of a building by using a point-focused Fresnel lens coupled to a light pipe or a bundle of fibers [46, 49]. A Fresnel lens having a constant pitch of 0.5 mm was employed for the Fresnel lens daylighting system as illustrated in Figure 4 [49]. For the Fresnel lens daylighting system, a plano-concave lens is employed to yield collimated light which illuminates the entrance aperture of the optical fibers uniformly [46, 49]. POF with a large core diameter was selected for distributing the daylight as it has favorable features as listed in Section 3.1.2. Since POFs cannot withstand the high intensity of sunlight, SOFs were introduced before the POFs to absorb some heat first. Also, index matching gel was employed to lessen losses caused by the air gap in between the SOF and the POF [49].

Muhs described a similar type of Fresnel lens daylighting system incorporated with a dual-axis tracking solar concentrator scheme which utilizes Fresnel lenses to directly focus sunlight to the entrance of a series of optical fiber [50].

Han et al. have developed an active daylighting system that uses a Fresnel lens placed on a two-axis tracker to track and receive sunlight and then transmit it via optical fiber cables where continuous illumination is achieved by supporting the light from the sunlight with artificial light as required [51].

Pham et al. presented a daylighting system with a new design of a linear Fresnel lens that can achieve high uniformity. Each groove of the lens uniformly disseminates sunlight over the receiver in such a way that the entire lens also disseminates sunlight over the receiver uniformly [52]. In their design, the collector or receiver is built with a convergent linear Fresnel lens, whereas the divergent linear Fresnel lens is used in fabricating the distributor. They also mentioned that the two linear Fresnel lenses are built at right angles to each other and orthogonal to the incoming bundle of sun rays.

3.2.2. Parabolic Dish/Mirror. Ullah and Shin proposed an efficient approach with a parabolic mirror for the fiber-based daylighting system as shown in Figure 5 [46]. Here, a parabolic mirror captured and focused sunlight on a secondary mirror that subsequently illuminated the optical fiber bundles uniformly. Features of the parabolic mirror include a small f/D ratio, a high concentration ratio, and a big aperture area to get the most of the sunlight captured. Concave and convex parabolic reflectors were employed to yield collimated light. For the purpose of rotating the light-

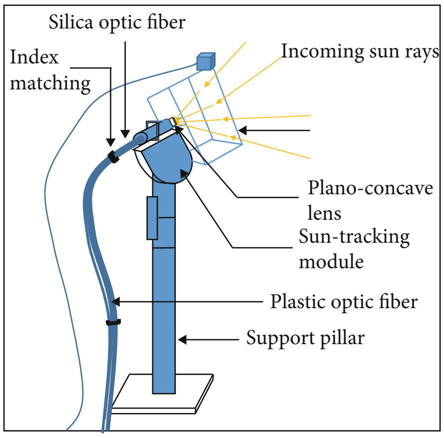


FIGURE 4: Physical layout of Fresnel lens daylighting system showing ray-tracing and sun-tracking module (source: adapted from [46]).

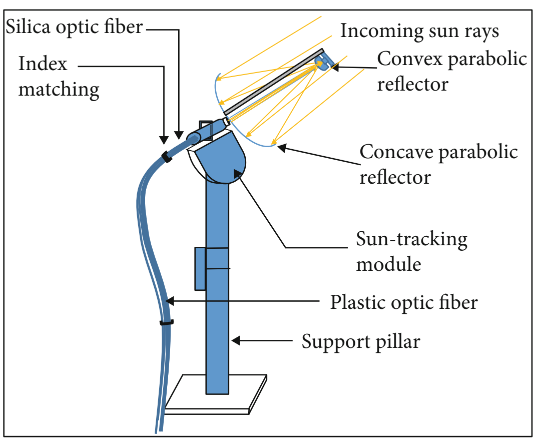


FIGURE 5: Physical layout of the parabolic mirror daylighting system showing ray-tracing and sun-tracking module (source: adapted from [46]).

collecting components to the sun, a two-axis sun-tracking device was included in the daylighting system. The circular shape organization of the bundle of optical fibers enabled maximum sunlight to be received.

Similarly, Muhs and Schlegel et al. studied a combined hybrid lighting system using a parabolic dish concentrator with dual-axis tracking as shown in Figure 6 [50, 53]. Schlegel et al. mentioned that their hybrid lighting systems had an outstanding performance in Honolulu, HI, and Tucson, AZ, mitigating their systems' capital costs of \$2410 and \$1995 per module, with a 10-year profit period [53]. Muhs listed the five major elements of the integrated hybrid lighting system which are sunlight and electric lamps as the light sources, sunlight collection and tracking systems, light dissemination systems, hybrid lighting control systems, and the hybrid luminaires [50]. The direct normal irradiance gathered by the two-axis tracking concentrator was reflected to a secondary element that is capable of dividing the solar irradiance into two spectrums: visible and infrared. The secondary element consists of eight faceted cold mirrors that

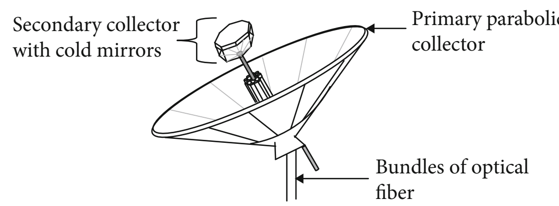


FIGURE 6: Hybrid lighting prototype showing the secondary collector with eight faceted cold mirrors (source: adapted from [53]).

only permit the reflection of visible light which is focused into large core PMMA optical fibers that transport the sunlight into parts of the building where it is needed [53].

Sapia presented a daylighting system comprising a primary parabolic collector (PPC) covered with a very reflective film and a secondary collector (SOE) with a very reflective surface in the visible range but transparent in the near-infrared range (cold mirror). This daylighting system design resembles that of Figure 6. The secondary collector reflects the solar irradiance towards the top of the bundles of optical fibers with only the visible part. After the light travels for approximately 10 m through the fibers, it arrives at the tubular diffusing components in the luminaries [54].

3.2.3. Heliostat Field. Ullah and Shin proposed an inexpensive idea of a solar tower daylighting system to distribute sunlight to each floor of a multiple-story building by means of collecting, directing and disseminating sunlight through the heliostats, mirror light pipe, and light guide as shown in Figure 7 [5]. The heliostats with circular plane mirror having a diameter of 0.7 m each were organized in circular arcs of radii at 1.5 m, 2.5 m, 3.5 m, and 4.5 m at one corner of the mirror light pipe. Each heliostat is operated with a two-axis sun-tracking system to track the sun at all times during the day. The focusing mirror of 1 m diameter was mounted at 0.5 m above the mirror light pipe. Each heliostat directed sunlight to the focusing mirror. The focusing mirror made an angle of 10.12° relative to the ground axis and was structured to insert the light into the mirror light pipe that was then conveyed and distributed to each floor of the building via a directing mirror. Five floors of 50 m^2 area each were illuminated with thirteen heliostats. To attain very good illumination in the buildings' interior, the mirror light pipe was coated with prismatic optical lighting film and multilayered optical film and was built in a cylindrical form to attain uniform illumination. They claimed that the system had numerous advantages such as affordability, manageability, simplicity of design, the applicability of quick manufacturing, and expansion to produce a large-scale system. However, the study is still in the stage of theoretical modelling and analysis.

Tsangrassoulis et al. presented a prototype of a hybrid lighting system (the heliostat-liquid fiber optic lighting system) that conveys daylight from a heliostat with a concentrating Fresnel lens to a luminaire in a room without window, via a large core liquid optic fiber [55]. The system was called the Universal Fiber Optic (UFO) system, which

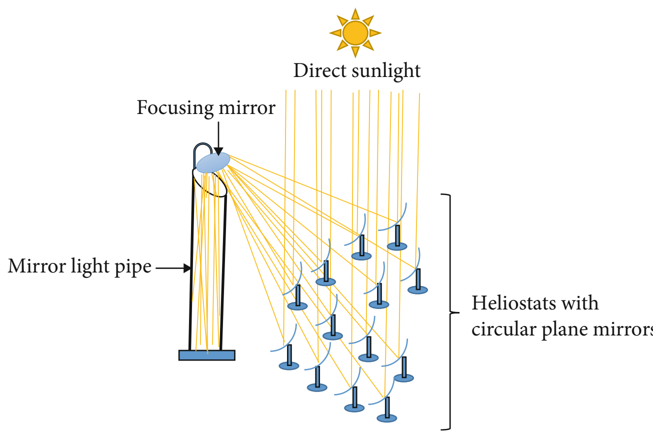


Figure 7: Conceptual design of solar tower heliostat array daylighting system for the illumination of multifloor buildings via mirror light pipe (source: adapted from [5]).

was mounted on the highest roof of the University of Athens, Physics Department building, during the 2002 summer. The modules of the UFO system embrace a heliostat to capture the sun with the Fresnel lens of 1 m diameter of which the light goes through the fiber optic cables consisting of liquid fiber and ordinary PMMA fibers. As a complementary source of lighting, a metal Halide projector with a 150 W BLV lamp and a Schott projector with a 150 W MH lamp is positioned together with the heliostat and two backup T5 fluorescent lamps embedded in the luminaire. The daylighting system integrated with efficient artificial lighting controls can reduce electrical energy consumption by 50–75% in commercial buildings [56].

3.2.4. Himawari. La Forêt Engineering Co. Ltd. introduced a commercial Himawari system consisting of a lens focusing unit and optical fiber devices with a sun-tracking system [57]. They have two types of products, which are 36 Lens Himawari XD-100S/36AS capable of supplying daylight to 6 terminals and 12 Lens Himawari XD-50S/12AS capable of supplying daylight to 2 terminals. To compute the sun's position and alter its angle, the Himawari system has a built-in sun sensor, an interior clock device, and a microprocessor. After the sun sets, it shuts down and resets its position to get prepared for the subsequent sunrise. At the focal point of the lens, an inlet end of an optical fiber cable is fixed in which light is focused via a Fresnel lens and only visible light goes into the optical fibers. A very pure quartz glass fiber cable conveys the visible rays with negligible loss. The major benefit of this system is that furniture carpets, rugs, and fade artwork would not fade and thus are safe. As Himawari products contain only a little magnitude of infrared radiation, they would not interfere with room temperature or air conditioning systems. Figure 8 shows the schematic diagram of the front view of the Himawari solar lighting system.

Chen et al. studied the potential of the Himawari system to give occupants appropriate lighting to aid visual functions and attain the circadian system entrainment in a particular office in Beijing, China [58]. They mentioned that the system can meet the lighting necessity at the horizontal work plane based on the visual performance of the occupants' in the office and also provide the circadian system entrainment which is the nonvisual effect of lighting at the same time.

3.2.5. Multiple Concentrating Lens System. Another active daylighting system called "double-axis sun-tracking and concentrating system" consisting of multiple concentrating lenses was suggested and developed by Song et al. [59]. This daylighting system consists of plastic optical fibers, two-axis sun-tracking technology, and lenses for focusing and transmitting sunlight as shown in Figure 9. The entrance of the fiber is 2 mm in diameter, and light is focused on a 2 mm diameter spot which is directly on top of the entrance face of the fiber. Considering both the attenuation ratio of the optical fibers and the light transmission power of the lens, the transmission efficiency of the system was calculated as 34% via experiment. They made a very good tracking system of 0.1° precision to accommodate the system focusing level at 2500 suns. The system is comprised of two feedback circles, namely, coarse and fine adjustments, via an angle encoder and a special photodiode array accordingly. The advantage of this system is that it can provide light to dark rooms or underpasses by preventing or reducing the dissemination of infrared rays (IR), ultraviolet (UV) rays, and energetic particles thus reducing the amount of electrical power consumption for air-conditioning systems [59]. The total internal reflection angle was ±30°, and their experimental results showed that the outcome of greater incident angles is greater attenuation.

3.2.6. Core Sunlighting System. Khosravi et al. presented and described a novel approach to daylighting called core sunlighting system (CSLS), which is consisted of active and passive optical modules to collect sunlight outside multifloor buildings and then transfer the sunlight to the dark parts of the building [60]. In the new approach, sunlight redirectors that redirect sunlight at a predetermined angle to the exterior facades of the building were mounted at the roof level all around the building. The redirectors redirect sunlight such that the entire façade was bathed by sunlight and dispersed uniformly amongst multiple floors. A portion

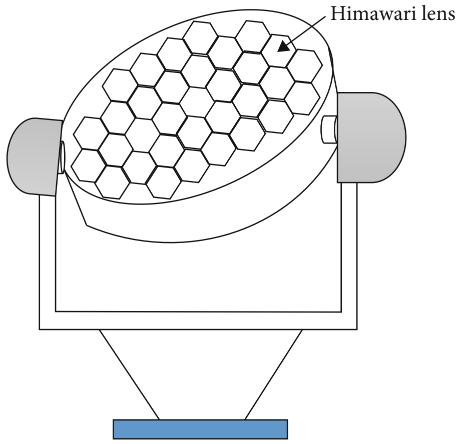


Figure 8: Himawari solar lighting system (source: adapted from [57]).

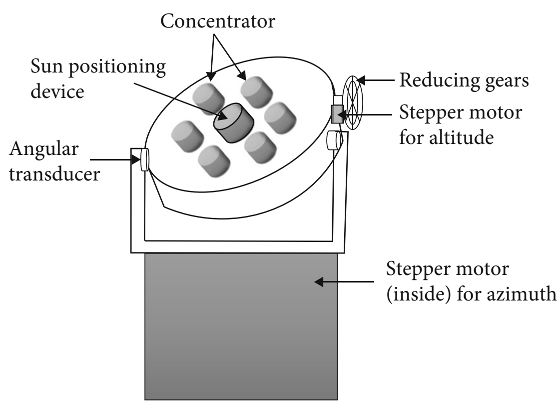


Figure 9: Active daylighting system consisted of dual-axis sun-tracking and concentrating system (source: adapted from [59]).

of the sunlight at each floor was captured, concentrated, and recollimated by the concentrator components mounted on the facade of the building. The concentrator consisted of the lens and an enclosure containing a separate lens and mirror assembly. The light coming from the concentrator was fed into the light guides and was then dispersed to the core of the building efficiently. In the new design, sunlight was captured from all sides, and therefore, it was stress-free to transport uniform light to every part of the building either small or large. To achieve high efficiency at high solar altitudes, the vertical array of mirrors was replaced by a new rotating redirector unit that can operate in two modes based on the solar elevation [60].

3.2.7. Mirror Sunlighting System. Kim and Kim proposed a mirror sunlighting system consisting of two optical systems in which the first mirror is fixed on top the roof of the building in the northern hemisphere to guide the sunlight through the building's core and to distribute the sunlight via a secondary mirror reflector network to the areas inside the building [61]. Their system had an 80 cm diameter clear dome, double reflecting mirrors, a base, a tracking mechanism, and an activator. The roof dome made of a see-through acrylic covered with an ultraviolet shield material was used to protect the initial reflecting mirror as shown in Figure 10 and also ensure the transmittance of the sun remains high. The primary mirror was designed with aluminized glass having a circular shape of 75 cm diameter and 2.5 mm thickness since it was meant to track the sun, receive the sunlight, and maintain high reflectance and durability. The secondary reflecting mirror was made either flat or concave for improving the adaptability to receive reflected sunlight from the primary mirror reflector. For performance evaluation, the mirror sunlighting system was positioned on the rooftop of a four-story building in South Korea, and on the first floor of the same building, a secondary mirror was fixed ahead of the opening in a room to direct sunlight to the inner part of the room. Experiments were conducted during clear and overcast sky conditions, and the performance of the system was measured in terms of illuminance and sunlight illumination ratio. Results showed that with the mirror sunlighting system, the illuminance level in a semiunderground space can be improved by eleven times with the use of a flat secondary reflective mirror and fifteen times with the use of a concave secondary mirror. Consequently, the concave secondary mirror was preferable for the mirror sunlighting system [61].

3.2.8. Two-Stage Nonimaging Solar Concentrator. Majority of the optical fiber daylighting systems are costly and easily affected by pointing error and have a complex optical design in which many stages of focusing devices are required to reduce the nonuniformity of concentrated sunlight. To solve the above-mentioned issues, Chong et al. proposed an alternative active daylighting system with a two-stage nonimaging solar concentrator (2S-NISC) incited by their earlier research work in nonimaging optics as shown in Figure 11 [62–65]. The prototype 2S-NISC is made up of 80 pieces of 5 cm by 5 cm primary facet mirrors, 20 pieces of 8 cm by 8 cm secondary facet mirrors, and compactly packed POFs as a daylight delivery system. The equivalent power conversion efficiency of the prototype 2S-NISC was found to be 22% based on 170 W input solar power. For economic analysis, the proposed 2S-NISC daylighting system having an optimized 4 m^2 collective area was projected to cost USD 1231.20. Taking a 4% interest rate and a 2% fuel inflation into consideration, the total profit period of 6.1 years was estimated. This is practical as the active daylighting system has a lifetime of at least 15 years.

4. Waveguide of Daylight as Light Transporting System

The waveguide of daylight, embracing optical fiber, light pipe, light tubes, etc., plays an important role to transport and distribute the collected daylight deep inside the building. For an active daylighting system, a waveguide is purposely designed to guide the daylight for a long distance in the building especially to reach the room without a window. For a passive daylighting system, a waveguide is only designed for a certain application with a short distance

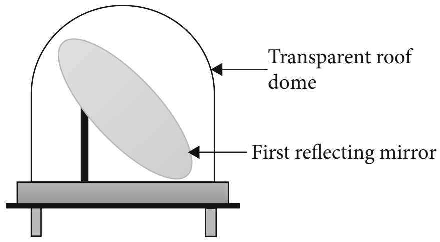


Figure 10: Mirror sunlighting system showing the first reflecting mirror (source: adapted from [61]).

transmission inside a room in which the transmission efficiency is not as good as an active daylighting system.

4.1. Solar Pipe or Sunpipe. Solar pipe or sunpipe, as it is normally called and trademarked by Solatube, has several other names trademarked by various manufacturers which include light pipes, solar tunnels, sun tubes, light tubes, sunlight tubes, daylight pipes, and light tunnels. This type of waveguide has been in existence for approximately 4000 years, which was first used by the Egyptians to send light to the center of the pyramid via mirrors and light shafts. For instance, a passive daylighting system consists of a top collector as a skylight dome, reflective pipe tube, and an emitter mounted inside the room to be lit. The passive daylighting system reflects sunlight and normal daylight via an aluminum pipe with a pure silver base mirror finish. The light pipe is sealed using a clear ultraviolent stabilized polycarbonate top dome to avoid dust. The light uniformly spreads into the room under the sun pipe through a smooth opaque finish or plain opal diffuser located at the ceiling of the room. Kocifaj et al. highlighted that for the light tube to be highly efficient, it must be targeted directly to the sun [23].

4.2. Fluorescent Fiber Solar Concentrator (FFSC). Wang et al. proposed a fluorescent fiber solar concentrator (FFSC) consisting of an optical fiber-based solar concentrator with a PMMA plate and 150 pieces of 1 m long and 2 mm diameter three-colored (green, red, and yellow) fluorescent fibers [41]. The material of these fluorescent fibers is acrylic with embedded quantum dots and there are 150 pieces of fluorescent fibers evenly inserted into 1200 × 1200 mm PMMA plate with 2 mm space in between two fibers. An aluminum brushing connects each fluorescent fiber at the edges of the FFSC plate with a 10 m long and 2 mm diameter PMMA clear optical fiber and fixed by a kind of ultraviolent glue. The concentrated light was transported through the clear optical fiber to a remote dark room. The FFSC has great prospective in remote interior daylighting for application in building integration and can also be applied in underground areas of buildings such as car parks during the daytime. This device produces light that has the same color as direct sunlight. Wang et al. emphasized that irrespective of the advantages, a limitation was faced during their research which was the deficiency in the fluorescent fiber market because only fluorescent fiber of 2 mm diameter was available and supplied [67].

4.3. Air-Clad Optical Rod Daylighting System. Shao and Callow presented a novel static tubular daylighting device composed of a set of light rods used in conveying light from outside a building to areas with low illumination or dark rooms within a building in Singapore [66, 68]. This device called an air-clad optical rod daylighting system can receive light passively similar to a light pipe and conveys light via total internal reflection with high productivity like a fiber optic cable having a small diameter. The light rod is a very polished rod-shaped piece of optical clarity PMMA and can be built into most existing buildings without the need for structural adjustment as they are suitably small with a diameter of 50 mm. It is manufactured from optical quality polymer and clad by air. In this design, the total internal reflection uses the refraction of light at the boundary between two surfaces having dissimilar refractive indexes by covering a core material with a higher refractive index with that of a lower refractive index. The air surrounding the rod served as an ultralow refractive index cladding, which led to a 180-degree total acceptance angle obtained theoretically that is needed for a full, static collection of skylight all day. Test results showed that these rods have a light transmittance equivalent to light pipe with an aspect ratio six times smaller. To investigate the performance, Shao and Callow compared the rod with a well-established daylighting technology: 300 mm diameter Monodraught Sunpipe called a light pipe, in which both work using the same principles and perform about the same function. It was realized that the same transmittance efficiency and diffuser-surface illuminance of the light pipe is now available in a more compact system, which is an advantage. On the other hand, the ends of the rods are quite eye-catching and would deliver a very good lighting effect with reduced glare. Light pipes would be selected over the rods if the building envelope permits the installation of light pipes. In contrast, if the building fabric has limitations on the size of the device or where a rare visual effect is needed, the rods are advantageous [68, 69].

4.4. Rectangular Glass Optical Fiber. Aslian et al. proposed the application of glass optical fibers having a rectangular cross-section in a combined concentrator photovoltaic and daylight system [70]. The use of rectangular glass optical fiber (RGOF) can give better efficiency in coupling and light power transmission compared to that of round fibers, as a bundle of RGOFs is more tightly packed with very minimum gaps between the fibers. Results of their simulation showed a good match between the distribution of output flux and the solar cell dimensions for the case of RGOF, which is the same as the higher coupling efficiency of RGOF.

5. Economic Feasibility of Active and Passive Daylighting Systems

When approaching the issue regarding the economic feasibility of daylighting technologies, the first predicament faced is the initial investment cost between the daylighting system and the conventional lighting system. Conventionally, the major considerations of an economic feasibility study for

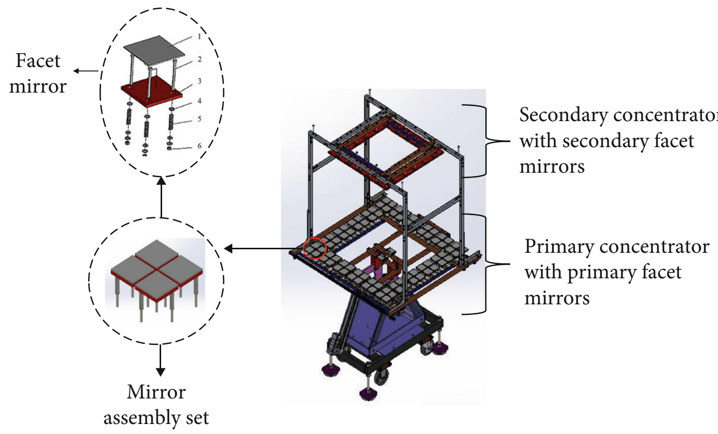


FIGURE 11: Active daylighting system consisted of two-stage nonimaging solar concentrator (2S-NISC) (source: adapted from [63]).

daylighting systems embrace capital investment cost and operation, and maintenance costs, which can be quantified easily [71]. The real value of daylighting cannot be only rated on electricity saving as there are other long-term benefits such as natural lighting, low-energy building, sustainable lifestyle, and reducing greenhouse gas emission.

For active daylighting systems, Chong et al. conducted a reasonable analysis based on various designs of active daylighting systems with single-axis and double-axis trackers [62]. The study only considered the costs of the solar concentrator and sun-tracking system without waveguide and building fitting for illuminating daylight. The costs are USD 600-800 per m^2 for linear focusing concentrator such as parabolic trough and linear Fresnel lens with single-axis tracking, while the costs are as high as USD 1500-1882 per m^2 for point focus parabolic reflector and Fresnel lens with two-axis tracking.

For passive daylighting system, the initial capital investment will be lower than that of active daylighting system because it does not require a solar concentrator with a sun-tracking system. Instead, the illumination control system is essential for both active and passive daylighting systems, which is important to sense the available daylight and then control the illuminance level of the artificial lights by dimming or turning off the electric lights to achieve energy saving. Li et al. analyzed the cost of integrating hybrid semitransparent photovoltaic and daylighting system to the office building in which the simple monetary payback of just around 15 years was estimated considering electricity tariff, chiller plant cost, and CO_2 trading in the calculation [72].

For maintenance cost, both active and passive daylighting systems require a regular basis of cleaning to ensure the optimal performance of the system. Hence, the cleaning cost can be considered the most dominant factor in the maintenance of both daylighting systems [73]. Additionally, active daylighting system requires extra maintenance costs for the tracking mechanism such as equipment service and repair cost. For the operation cost, the active daylighting system requires electricity to operate the motor and control devices of the sun-tracking system. Since passive daylighting does not require any electricity to function, the operating cost can be negligible.

Besides the aforementioned cost analyses, some researchers also included factors that are more difficult to identify and quantify in the feasibility study such as building heating and cooling saving, green building index, carbon tax savings, CO_2 trading, and the effect of daylight on human wellbeing in their cost-benefit analysis [71, 72, 74].

In 2009, Li et al. have performed the cost analysis of lighting and daylighting schemes in Hong Kong by installing energy-efficient lighting together with dimming control in a Chinese restaurant [75]. By taking into account all the cost factors, the simple payback period and internal rate of return are 2.8 years and 26%, respectively. Kirankumar et al. studied the cost-saving of a triple-glazing system with different configurations of reflective glasses to achieve payback period ranging between 2.1 years and 4.5 years [76]. In 2016, Fontoynont et al. conducted the economic analysis of different daylighting strategies for a standard French office building to include moving service spaces to the periphery, increasing ceiling height, and adding lightwells of various shapes. The minimum payback period of the investment is 41 years based only on savings on lighting electricity, but the benefits should be beyond the electricity-saving that include occupants' well-being, safety increase of an electrical blackout, high rental and resell value [77]. In the same year, Mayhoub and Papamichael conducted a cost-benefit analysis for building core sunlighting system (BCSS) by varying electricity cost, electricity-saving, initial cost, and cleaning cost [73]. Their study concluded that the increment of electricity has a significant impact on the reduction of the payback period of the BCSS. They also stated that the BCSS is unlikely to achieve a positive economic performance if the energy saving of the system is less than 50%. From the above literature, it can be concluded that the payback period of daylighting system is location-dependent due to different local weather conditions (external illumination level), local electricity tariff, and, labor cost.

The vision of daylighting must not be restricted within the worthiness of investment in a short-term monetary benefit but towards the aim of decarbonization for a long-term impact. It is also necessary to consider the quality of the visual environment contributed to the occupant satisfaction and psychophysiological wellbeing through a connection to the outdoors and support for circadian rhythms [78]. From the environmental point of view, greenhouse gases such as CO_2, SO_2, and NO_x emission from power generation are one of the main causes of air pollution which are threatening the health of human beings. The energy saved from daylighting can reduce the usage of fossil fuel and greenhouse gas emission to the environment to provide a greener and cleaner planet earth for us and our future generation [75].

6. General Challenges and Prospects of Daylighting Systems

Even though daylighting systems are known for their benefits, some challenges still need to be overcome before they can be widely deployed to reduce electricity consumption for building lighting. By gathering various technological and economic issues of daylighting systems, the challenges are listed and discussed as the following [41, 45]:

(1) Most active daylighting systems are still expensive to install because the whole system design is complicated including solar collectors/concentrators, light transmission systems, and electronic control systems. Hence, it needs a large initial capital investment for the hardware and software based on the width of the roof space, which is the reason why many people are still discouraged from installing active daylighting systems, especially for residential houses

(2) Solar energy is intermittent and not available at night. A hybrid system must be built to complement a situation when solar irradiance is low or not available during nighttime in which the daylighting system is required to couple with a conventional lighting system. The direct component of solar irradiance can illuminate a space more effectively and efficiently in both active and passive daylighting systems. Moreover, a cloudy day with a high diffuse component of solar irradiance can greatly reduce the performance of daylighting. As a result, the consumer should consider the cost of daylighting on top of the existing artificial lighting in the architectural design of the house, and a control system with sensors is also necessary for managing the hybrid lighting systems

(3) Passive daylighting systems have various limitations including the extra brightness gotten from the daily and annual movement of the sun, heat, the limited penetration depth inside the house, and blocking by nearby buildings. Furthermore, the architectural design of the house also affects the harnessing of passive daylighting in which solar irradiance usually does not reach some areas of the house such as an intermediate room without a window, dining area, and basement. To overcome this issue, the passive daylighting systems require additional investment in light pipes for guiding the daylight deep into the house but it still encounters difficulty in network distribution of light pipes or waveguides by considering the bending angle of the waveguide. A large bending angle can cause significant optical loss of daylight transported via waveguide based on the total internal reflection principle and subsequently suffers lighting energy losses. Therefore, an appropriate study is required on a case-by-case basis due to the location and orientation of the house, proximity to tall buildings, etc.

(4) The solar radiation varies with latitude, longitude, local weather conditions, and geographical landscape, which makes the availability of sunlight with the regional locations change significantly according to seasons. During winter in some countries, the sunrays collected by solar collectors are not sufficient to meet the day-to-day daylighting needs. Hence, a supplementary source of power must be used, leading to extra costs

(5) Solar concentrators in an active daylighting system must be equipped with a sun-tracking system at a reasonably high accuracy during daily operation. The sun-tracking system is crucial to align the sunlight parallel with the central axis of the solar concentrator for the purpose of focusing and transmitting the sunlight through the waveguide. It is essential that the acceptance angle of the solar concentrator be larger than that of the pointing error of the sun-tracking system to achieve high optical efficiency of the solar concentrator. Consequently, the performance of the sun-tracking system determines the performance of the daylighting system

(6) Active and passive daylighting systems can be a source of glare and radiate heat to the inhabitants while providing illumination to the building, which can make them uncomfortable and affect their eyes. A house inhabitant who exposes his eyes to a bright patch of daylight, either direct or reflected, will need time to readjust his eyesight to see at lower light levels. Regular eye adaptation caused by these issues can negatively affect the eye leading to an eye defect. Thus, daylighting control is very important to make available enough illumination while keeping unnecessary heat gain to a minimum

(7) If the location of a daylighting system is within or around a shaded area, its performance will be poor because shade has a negative effect on solar collectors. Shades and solar daylighting systems cannot coexist together even though some manufacturers claim that their daylighting systems are shade tolerant

The purpose of our review article is to review the various existing configurations of passive and active daylighting systems, which can lead to a more sustainable configuration in the future. Some critical findings and future scopes of studies based on the articles reviewed are listed as follows:

(i) Smart home technology will be getting more popular in the future; hence, the integration of daylighting systems into a smart controller for artificial lighting systems can save unnecessary electricity bills during the daytime. More research works can be carried out to analyze the economic feasibility and environmental impact on future smart homes with the integration of daylighting systems

(ii) Artificial intelligence software can be developed for designing active and passive daylighting systems into the architectural design of buildings and residential houses. The artificial intelligence software must be able to simulate the daily and annual illumination pattern inside the house by considering various factors including local weather data, geographical location of the subject, and nearby objects such as trees, buildings, and hills

(iii) Comprehensive research works on the various impacts of integrating daylighting systems into the building including heat effect, the initial capital cost of investment and return of investment, daylight illumination pattern from a window, and comfortability of daylight during different times must be put into consideration

(iv) Material research is another aspect to accelerate the deployment of a passive daylighting system into the building. Referring to an article in Nature, Korgel commented that the advancement in electrochromic window materials, which change color and/or transparency when subjected to an electric field, can revolutionize the design of new window glass by regulating the heating and lighting requirements of buildings by responding to environmental changes [79]. Not long ago, in 2017, Davy et al. fabricated a new organic solar cell made of hexabenzocoronene (cHBC) derivatives in a laboratory at Princeton University harvesting near-ultraviolet photons to fulfill the unmet requirement of powering smart windows to allow daylight by significantly reducing heat and hence saving about 40% in an average building's energy costs [80]. Definitely, this is just one part of material science to show the advancement of new material to influence the deployment of daylight in the building

Through the review of the technologies and designs of the existing daylighting systems, we can know what has been done so far and the niche areas required for further research and development. For sustainable development and energy efficiency of buildings, there is still room for exploration to increase the utilization of daylight. As part of a sustainable building design, daylight deployment should be considered in the early stages of a building project development [81].

7. Conclusion

As lighting consumes as high as 40% of the annual building energy consumption, we have presented a comprehensive review on both the active and passive daylighting systems for achieving sustainable buildings. The economic feasibility has been analyzed in detail where the initial investment cost is considered high by taking into account electricity saving alone, while the integrating of daylighting system into the architecture of the building can bring long-term impact for a sustainable building including occupants' well-being, natural lighting, low-energy building, sustainable lifestyle, and reducing greenhouse gas emission. In general, the challenges of daylighting systems are also discussed to understand the existing problems hindering the extensive implementation of daylighting system in the building. More research works should be encouraged in developing better and more creative designs of daylighting systems for sustainable buildings that are affordable, easy to install, environment-friendly, less energy-intensive, comfortable, and capable of providing uniform illumination. In a view of long-term impact, United Nations Sustainable Development Goals and the government policy are important factors to increase awareness and to encourage the adoption of daylighting systems for achieving sustainable buildings.

Data Availability

The numerical data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors have no conflicts of interest to declare.

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