




Review

A Review of Daylighting System: For Prototype Systems Performance and Development

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Abstract: Daylighting systems make daylight illuminance possible, and the development of prototype daylighting systems can provide more efficient daylight illuminance. The purpose of this article is to review the development and performance of prototype daylighting systems in the last decade. The passive and active daylighting systems are listed separately and divided into the four categories by the presence and absence of hybrid. Each prototype daylighting system was evaluated in terms of cost and daylight performance and as well as their novel optical design. We evaluated the architecture and daylighting principles of each system by reviewing individual prototype daylighting systems. The cost of prototype systems still poses a challenge to development. How to use passive or active systems in different environments and whether or not electrical lighting assistance is needed is a controversial issue. However, active daylighting systems equipped with solar tracking systems are still mainstream. This research is a valuable resource for daylight researchers and newcomers. It is helpful to understand the advantages of various prototype daylighting systems and commercial daylighting systems that have been developed for many years; moreover, it is also possible to know the research directions suggested by the prototype daylighting systems. These will be of further use in developing innovative and better daylighting systems and designs.

Keywords: daylight; daylighting system; prototype; lighting; optical design; windowless; fiber daylighting system; Innovative daylighting system

1. Introduction

Research about the category of solar energy has been increasing and utilizing sunlight has become a trend of renewable energy. There are many applications that use sunlight. These studies show the main uses of solar energy and spectral characteristics, including solar power generation [1], daylighting systems [2–5], mental illness treatment [6], treatment or prevention of human diseases [7–9], non-imaging field [10], etc.

In this research, daylighting systems that utilize daylight illumination have been around since the inception of buildings. Indoor lighting was provided through windows and roof-skylights before the 16th and 17th centuries; electrical lighting became mainstream with many high-rise buildings and under-ground spaces in the 20th century.

However, in recent years, it has been found that lighting accounts for 40% of a building's energy consumption [2], and commercial buildings consume the most energy; about 19% of the electricity is consumed by the world, and almost 38% of US energy is consumed in buildings [11]. Therefore, if the proportion of electrical lighting can be reduced, then wasting energy and causing unnecessary environmental damage can be avoided [11–13].

The International Energy Agency (IEA) Task 21 project, executed from a large number of daylighting research activities, was carried out in Australia, North America and Europe in 1995 [14], during which innovative daylighting systems, lighting control and methods of daylight evaluation procedures in buildings and case studies were discussed. The main research of IEA Task 21 includes light shelves, louvers, diffusing reflecting louvers, roller blinds, shaded skylights, which function as passive daylighting devices or top glass windows. Those objects are dominated by a light guiding system, which is a beginning for new forms of daylighting systems, through the optical material and non-energy-consuming optical components for guiding daylight [2,14].

According to the geographical location, latitude, weather conditions and climate of the solar light guiding device, there may be different guiding efficiency or solar quality. Usually a static skylight can only provide a few hours of sunlight because daylight is a dynamic distribution with different elevations and azimuths angles as the seasons change [15]. In this case, different angles will cause changes in the angle and distribution of incidental light, lead to static skylight or other Light Guiding System (LGS) inefficiencies, and then therefore, daylight is not enough.

In order to attain more effective use of dynamic daylight, stable optical components and active devices of the daylighting system were studied. Common optical components are high-reflectivity light pipes [16–31], Fresnel lens [32–44], linear Fresnel lens [45–47], optical fiber with different materials [32], light guide [39], parabolic concentrator [48–50], Compound Parabolic Concentrator (CPC) [38,47,51,52], dish concentrator [1,53], cold mirror [48], IR filter [32,38], hot mirror [49] and prism structure [54]. Active devices with heliostat that are responsible for daylight reorientation, include tracking systems and a linear solar tracker [55–60]. As explained earlier, those optical components and active devices have been developed to improve the daylight efficiency of the entire daylighting system and includes the daylight factor.

The daylight index is used to determine the performance of a daylighting system. The daylight factor is the ratio of the indoor to outdoor irradiance flux on the same horizontal plane [2,61], and a good daylighting system requires 2% Daylight Factor (DF) under International Commission on Illumination (CIE) standard overcast conditions [62]. Because the higher the daylight index, the more electrical lighting sources can be replaced.

In addition to the daylight factor, Daylight Autonomy (DA) and Useful Daylight Illuminance (UDI) are also methods of daylight assessment. DA and UDI are dynamic daylight metrics that measure for window openings and public office space. The differences between static and dynamic daylight metrics is that the former is based on the fixed sky condition, while the other assessment is for real weather conditions, weather events, and time series based on the year [63]. The dynamic daylight metrics are specifically for the evaluation of the solar comfort of the occupant and the available daylight on the work plane [62,64].

In summary, DF is a traditional method of daylight forecasting, using average illumination on the horizontal plane, which cannot be applied to real daylight conditions. However, its measurement is convenient and rapid, and it is still the method for evaluating the performance of many daylighting systems. Therefore, this article evaluates the daylighting system according to DF.

This article contains a review of research literature, development of daylighting systems, and evaluation of prototype daylighting systems over the past decade. In addition to daylighting application and commercial daylighting systems, there is more research for the prototype daylighting systems. The included system is divided into detailed intervals, and only the integral daylighting system and application (Daylight comes from solar and is received by the system and illuminates through the diffuser). Focusing on the operation of the system energy requirements and hybrid applications,

we integrate and evaluate the cost level and daylight performance level of each system; analyze the environment and field of use and give the efficiency evaluation that compares daylighting systems.

In addition, this article also proposes the novel optical design of a prototype daylighting system, new concepts and design, thereby providing researchers with reference and sustainable innovation value.

This article focuses on investigating the prototype daylighting systems in the last decade. The daylighting system is defined as a complete daylight input, output component, and testing field.

Section 2 will introduce the progress from daylight to daylighting, and the benefits of daylight and application of daylighting.

Section 3 is the core of this article. The prototype daylighting system is discussed and we determine passive or active systems according to energy consumption; whether the passive and active systems are determining the hybrid based on artificial lighting use or not, and comment on these factors.

Section 4 additionally proposes the daylighting system's novel optical design; classification of systems for collation and transmission and we investigate these systems to give different design methods and optical principles.

Finally, the development and outlook of the current daylighting research field will be discussed.

2. Daylight

The progress of daylight research contributes to energy saving and enhances human welfare, improves physiological functions and prevents disease.

Many studies have shown that the body's melatonin is inhibited by daily sun exposure, which helps to improve daytime work efficiency and nighttime secretion, which can make people gain adequate rest.

The research of the human body's production of melatonin was revealed by Marc Hebert et al. in 2002 [65]; when human exposure to light exceeds or equals 2500 lux, it can effectively inhibit the secretion of melatonin by the pineal gland [65]. Melatonin is secreted when it is necessary for humans to rest. Therefore, in the case of UV-B in the morning, the human body will inhibit the secretion and increase work efficiency. After dusk, the illuminance will decrease. If the ultraviolet is less, melatonin will start to secrete, which can help sleep at night.

However, daylight can also promote health [66] and productivity improvement [67]. Meanwhile, UV-B also helps the body to naturally produce vitamin D-3. The production of vitamin D-3 is 7-dehydrocholesterol produced by ultraviolet irradiation of the human epidermis. Over 90% of the main forms of vitamin D-3 are dependent on sunlight, and only 10% come from abyssal fish glycerin or other food.

Vitamin D-3 is associated with human bone health, cardiovascular disease, cancer, central nervous system diseases, reproductive diseases, infections, autoimmune systems, and skin diseases [7,8,68]. Exposure to daylight and environmental solar radiation contributes to the prevention of colorectal cancer. There is also research that has shown that the test group with frequent sun exposure effectively reduces the risk of colorectal cancer in summer [69].

For the skin, the solar radiation UV-B causes red shift on the skin surface and structural damage to DNA, but conversely, UV-B also helps the body to induce vitamin D-3 production [70]. Moreover, the UVA-1 induces pigmentation of the IV-VI type in the skin (it also known as black light), but the result is integrated on both sides. The UVA-1 helps the nitric oxide derivative, which is unstable in human skin and releases nitric oxide. Released nitric oxide can protect the heart and controls blood pressure [71].

Ultraviolet has benefits and disadvantages, and it depends on how people use it. Limited use and without excessive exposure can effectively enhance human welfare.

Daylight is also associated with the prevention of skin cancer and increased incidence of diabetes in non-Caucasian races. Not only human physiological problems but also mental illnesses, such as seasonal mood disorders, depression and depression can be improved by illumination through

daylight [5,72]. As shown in Table 1, the benefits and disadvantages of daylight to the human body are compiled.

Table 1. The benefits and disadvantages of daylight to the human body.

The Benefits of Daylight	The Disadvantages of Daylight
Melatonin inhibits secretion [65]	Excessive UV-B can cause erythema or DNA damage [71]
Reduce the risk of cardiovascular disease [7,8,68,72]	UVA-1 induces pigmentation of IV-VI type
Improve psychological problems such as depression and seasonal mood [6,48,73,74]	Uncomfortable glare problem [2,75]
Reduce the risk of colorectal cancer [69]	Excessive heat will cause an increase indoor electrical energy consumption [16]
Reduce the incidence of diabetes [72]	

2.1. Application of Daylighting

Daylighting could be used for different applications, and it has much benefit in terms of energy saving and is salubrious for the body. In our lives in indoor buildings, part of the lighting source comes from daylight. And the normal daylight system is the top skylight and the window, and many architectural institutions, such as Leadership in Energy and Environmental Design (LEED), mention the important of daylight in the building.

However, daylighting is not always beneficial for buildings. Because of weather factors, geographical location and blocking of high-rise buildings etc., these reasons make the daylight hard to transmit to the depths of the buildings. The positives and negatives of daylighting in a building need to be determined in terms of daylight being evenly distributed in the indoor area, the quality of daylight and the endless supply [76].

Therefore, daylighting is not always beneficial in buildings, for the reasons mentioned above. For example, the average sunshine in the Mediterranean is more than twice that in Uppsala [41] because the more direct solar radiation that can be received in the area near the equator, and the daylighting is also tailored to local conditions. There are many studies devoted to daylighting activities; the concept is not entirely for illumination or energy conservation, but rather, for the welfare and benefits of daylight for human beings.

The following is an introduction of some of the articles on innovative research of historical building daylighting.

Magda Sibley et al. [77] studied the historic bathhouse ruins in Morocco. This study shows 13 still-operating baths (Figure 1a). The size of the top-roof opening is about 18–20 cm and the ratio of total opening area to internal building area rarely exceeds 2%. In this case, after repairing the roof, the maximum illumination and daylight factor both of less than 60 lux and 2%.

A museum in the UAE also considers the problem of roof-skylight daylighting; it is not the same as the remains of the baths, and there are many artifacts to be considered in the museum. The ultraviolet and infrared may cause photochemical and irreversible damage to the cultural relics. For most traditional relics, the main focus is on preservation and the avoidance of side effects, not for illumination [78].

In addition to the roof-skylight, there are also windows for illumination. A daylighting system called a solar screen has been installed for windows in Kuwait (Figure 1b). The function is to increase the indoor illumination and reduce the flow of heat. If the screen is not installed, the illuminance distribution in the room will float from 200 to 13810 lux, and the maximum indoor heat will reach 638.6 W/m². After using the screen, it can reduce the sunlight of 82~91.7% into the indoor space. And

the record shows that the illuminance of the screen can reach 175 to 200 lux and the heat can be reduced by 27.1% at the time of 12 pm to 4 pm, and after installation of two screens, it can reach 36.1~52.5% [79].

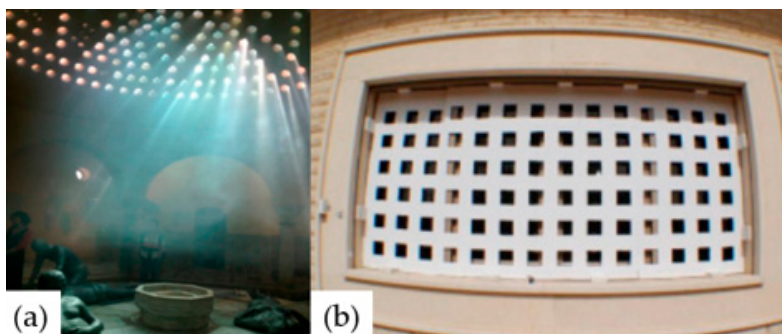


Figure 1. (a) Hammam al Bacha in Acre (18th Century Ottoman era); (b) Fisheye photography of the window with a single solar screen, a double solar screen.

Similarly, the reduction of heat problems plagued a hospital in the Mediterranean region. In order to achieve the H2020 building command, the first consideration is ventilation and lighting or shading, considering the high solar radiation in the Mediterranean. This was through the blinds to prevent solar radiation from causing glare or heat discomfort in the hospital interior [80].

The daylighting is not only for to provide much daylight, but also sufficient and necessary daylight, and there are corresponding daylighting strategies for different countries or regions and application methods. The roof-skylight and windows are the most common and cheap daylighting strategies. The advantage is the direct and diffuse solar radiation applied indoors, and the disadvantage is that the heat and electromagnetic waves generated by the sun need to be taken into consideration.

2.2. Progress of Daylighting Systems

Electrical lighting began to be supplied to most users on a large scale in 1950; that changed the appearance of indoor lighting [81]. When we discuss the relationship between buildings and daylight, we first consider the structure and equipment located outside and on the façade of the building; and the system that can transport daylight from the outside of the building into the indoor area is called the daylighting system.

The daylighting systems can be defined by the static daylighting system, which consists of external light guiding elements such as glass, roof-skylight, and solar shields. But it can also be defined by the dynamic daylighting system that uses dynamic components to compensate for the lack of static daylighting system.

Many researchers have reviewed the daylighting system: M.S. Mayhoub [82] published a hybrid lighting guide review in 2009. Commenting on Tubular Daylight Guidance System (TDGS), Hybrid Lighting System (HLS), and integrated systems. Given that HLS can provide better daylight quality than TDGS because the continuous innovation and lower cost of HLS are trusted by designers, and their systems can provide more effective daylight.

J.T. Kim et al. [55] studied optical daylighting systems such as light pipe systems and mirror systems, contains the parameters and appearance of the light pipe. They demonstrated the commercialization of light pipe systems, showing the limitations of traditional windows for daylight and the amount of daylight required. They assumed the architectural design and maintenance issues ignored optical lighting systems which can be used in more buildings and for more lighting applications.

M.S. Mayhoub [5] has discussed the problems encountered in the Innovative Daylighting System (IDS) in 2014, and IDS though better indoor illuminance by enhancing the quality of daylight and simultaneously gave comments on commercial IDS. However, the TDGS has a low initial cost and high daylight quality, but is limited to the roof style of buildings, and other IDS are difficult to build due to

high initial cost such as Heliobus, Parans and Himawari. The more complicated the system, the longer the pay-back period. For example, pay-back period is only 12 years for TDGS, but other IDS may be more than 20 years [5]. In addition to reducing the price of optical materials and the cost of technology, the initial design of the building considers IDS to reduce the difficulty of installation.

I.L. Wong et al. [3] proposed a daylighting system for the review of design for buildings, and discussed the advantages and disadvantages for Light Guiding System (LGS) and Light Transport System (LTS). LGS is cheaper but less efficient and mostly applied on tubular systems. Conversely, LTS are more expensive but can be used on more complex buildings and has greater flexibility and high daylighting efficiency, and is applied to current commercialized, demonstrated and prototyped systems.

As shown in Table 2, the commercial IDS is organized and given the installation year, composition and cost.

Table 2. Commercial Innovative Daylighting System (IDS) progress and composition.

IDS [5]	Installation [3]	Description [3]	Initial Cost [5]
Solatube	1987	Sun pipe with dome	Low
Monodraught	1974	Sun pipe, sun catcher	Low
Heliobus	1995	Heliostat and sun pipe systems	Very high
Himawari	1970	Fresnel lenses and Quartz Optical Fiber (QOF)	High
Parans	2004	Small Fresnel lenses and Fiber optics channels	High
Sundolier	2004	Skylight with mirrors and light duct	High
Sunportal	2012	Heliostat with an ultra-sunlight concentrator	Very high
SunCentral	2013	Skylight with curved mirrors	Middle
Velux	2005	Sun tunnel systems with dome and rectangular pipes	High

In addition to high cost, commercial IDS have another problem: cleaning. M.S. Mayhoub et al. [83] proposed a method of cleaning, since IDS is mostly composed of mirror or glass materials, the accumulation of dust and dirt can also lead to a decrease in optical efficiency and glass transmittance. The recommended cleaning methods are air blowing, high pressure water flow, dragging brush cleaning, soft brush to rotate on the surface of the collector, spraying water, and wiping. Dirty daylighting systems will reduce efficiency and daylight occupant's health. While cleaning increases the potential cost of IDS, it must be taken into consideration.

M.G. Nair et al. [4] introduced light guiding systems, light transmission systems, hybrid lighting systems, and integrated systems. These included light guide systems for light sun shields, suitable for use in tropical areas with direct solar radiation. However, it requires a large amount of façade space for daylight collection. The LTS with tracking mechanism can transmit daylight to the core of the building. Integrated systems such as solar louvers mainly use diffuser solar radiation. If used in the tropics, heat generation may cause uncomfortable glare.

Glare and daylighting strategies are also an important part of the daylighting systems that M.S. Alrubaih et al. [2] reviewed in the development of daylighting. Bringing daylight into the indoors to replace or supplement artificial lighting is called daylighting. The daylighting source needs to consider the solar elevation and azimuth angle. The strategies to be considered include top-roof daylighting and side daylighting. Daylight Factor (DF) is commonly used to determine the ratio of internal and outdoor horizontal illumination, which can be defined by dividing the indoor division by the outdoor illumination. Table 3 shows the recommended daylight factor provided by Stein 1992.

Table 3. Recommended daylight factor according to Stein 1992 [2].

DF	Task
1.5–2.5%	Ordinary seeing tasks, such as reading, filling, and easy office work.
2.5–4.0%	Moderately difficult tasks, such as prolonged reading, stenographic work, normal machine tool work.
4.0–8.0%	Difficult, prolonged tasks, such as drafting, proofreading poor copy, fine machine works, and fine inspection.

IDS are not only innovative in methods but also use optical and mechanical components such as light pipes, optical fibers, active concentrators, passive concentrators, and tracking system. In addition, these active devices enable innovative daylighting systems to have better daylight efficiency and usage in real-field applications.

In the future, IDS will not only be used to collect and transmit daylight, but will likely see the combination of daylighting systems and Photovoltaics (PV) generation, namely simultaneous use of daylight for photovoltaic power generation and daylighting purpose. And after sunset, the daytime storage energy will provide artificial lighting in the room, the solar concentrating power plant will be used such as in the case of using salt to store heat, to continue power generation in the evening [84].

C. Sapia et al. [48] proposed a research based on the Cassegrain concentrator with photovoltaic power generation in 2013. The focus is on the simultaneous use of daylight for power generation and illumination, and the use of electricity generated by photovoltaics to drive artificial lighting, resulting in higher solar utilization of the daylighting system.

The earliest commercial daylighting system was developed in the 1970s, which was the Himawari from Japan. However, there was high initial cost, high erection cost in comparison to electrical lighting, as well as the uncertainty of the daylighting systems and the bad continuity of sunlight making the visibility of the system in the illumination field not high.

In addition, it is also important to address the cleaning of the system, and this is the difficulty point encountered in the daylighting system currently. The same construction cost to buy the T5 fluorescent sources or LEDs can provide more stable illumination for thousands of hours indoors. Even though daylight is free and endless, dust and dirt could seriously affect daylighting efficiency.

In addition to commercial daylighting systems, M.S. and Wong et al. [3,5] have defined prototypes and demonstrated presented challenges and difficulties for many commercial daylighting systems in terms of installation, evaluation and simulation methods. However, there is still not a complete plan for the demonstration or prototypes studies; the performance of the prototype system is even better than some commercial IDS in certain regions and environments. As discussed above, certain regions represent development constraints that are faced by any daylighting systems. Generally, electrical lighting can be installed in any indoor and outdoor space, provided there is electricity, but daylighting systems need to take into consideration the latitude and whether the installation environment is suitable for the system. For example, a low latitude region is suitable for installing a light pipe system, while a high latitude light pipe requires a special design to capture low angle daylight [85].

Predominantly overcast skies or high-rise buildings are suitable for systems that have the ability to track the sun or redirect sunlight. These factors are the reasons for the difficulty in the development of the prototype daylighting system. However, there are still many ways worthy of study and follow-up improvements to be made in the prototype daylighting system. The following section will discuss the detail of the prototype daylighting systems developed after 2010. System classification is proposed by distinguishing whether the system itself consumes energy, with artificial lighting or not, checking the cost and efficiency of the system, analyzing which type of systems have advantages and suggesting design.

The next sections will categorize prototype daylighting systems from the past decades, namely by four types of systems, in order to evaluate applications while examining the system cost and efficiency.

Figure 2 shows the research volume and trends of the prototype daylighting system that are included in this article. This study has a strict definition of the daylighting system, only the complete system is included and only that which has undergone in-depth study. It can be seen that the number of active daylighting systems that require energy consumption continues to grow, and that the active device estimates are still the mainstream of research, presently and continuing on into the future.

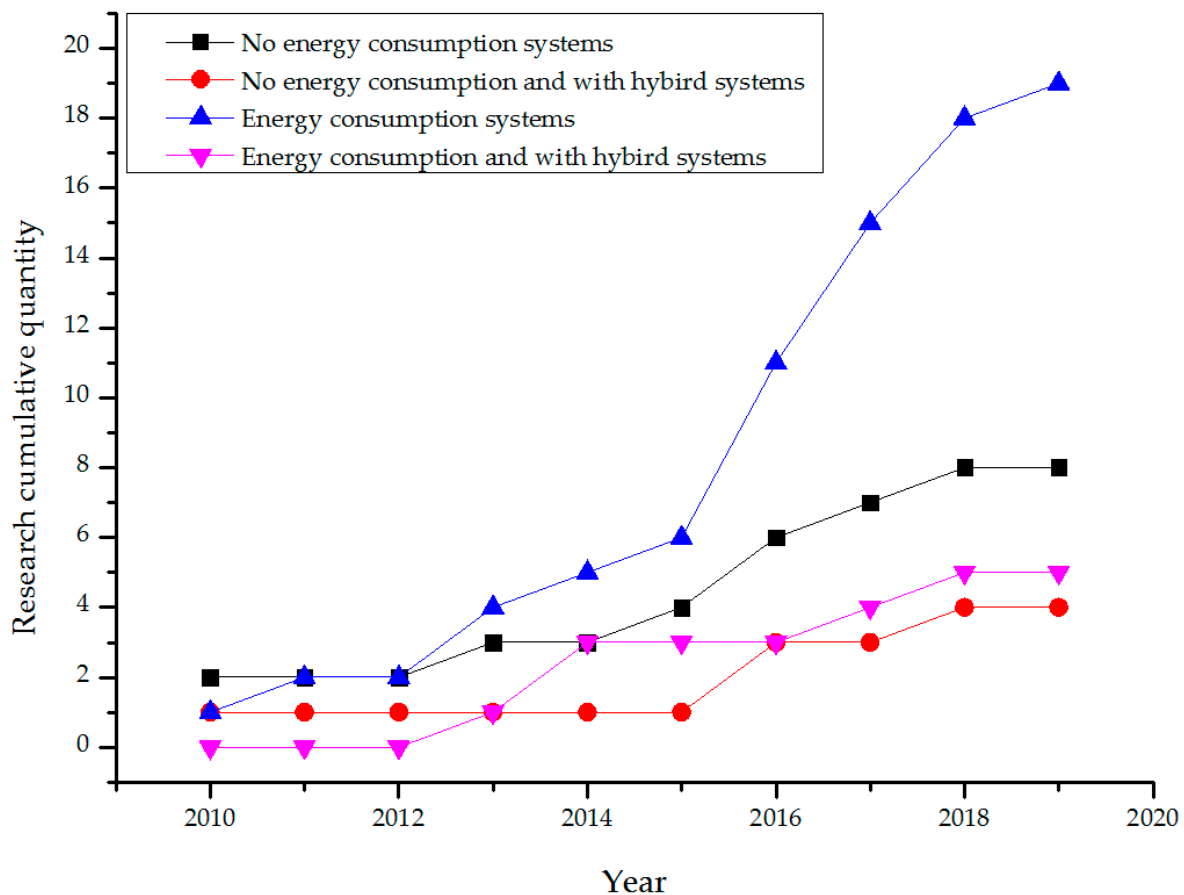


Figure 2. Prototype daylighting systems research literature quantity and trends.

3. Classification and Application of Prototype Daylighting Systems

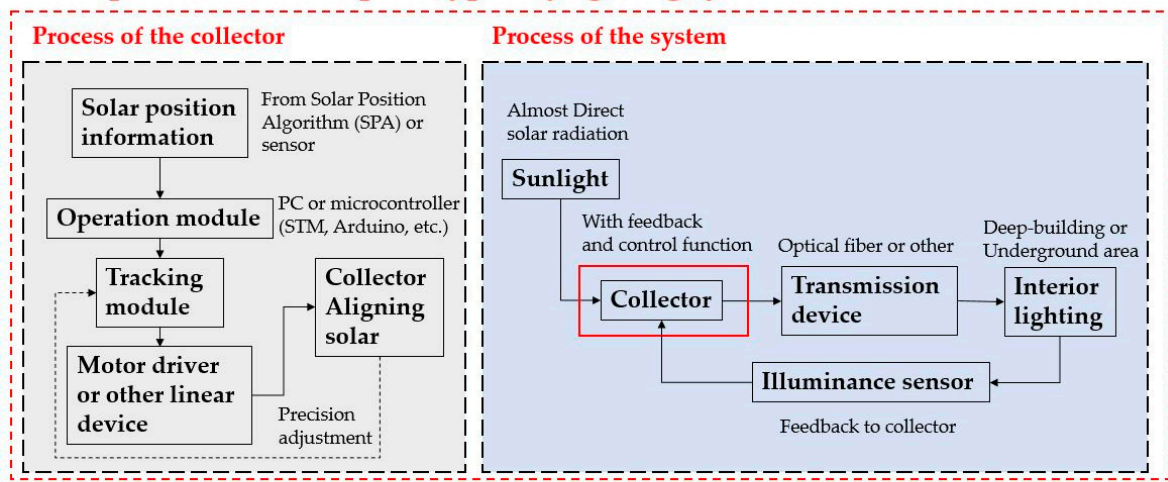
The number of prototype daylighting systems has increased over the past decade. From static daylight guides, tubular devices and active devices to HLS with electrical lighting. This development is in order to solve various needs of people's daytime illumination (such as comfort, daylight efficiency, long-term supply), and as a result, various daylighting systems appear at different stages.

This article divides the above systems into four categories. First, Type I describes a prototype daylighting system based on the Tubular Daylight Devices (TDDs), which is low initial cost and easy to use. Because of that, Type I focuses on the actual erection, experimentation and performance of the TDDs.

Second, Type II will discuss the hybrid lighting of Type I systems with electrical light source to explore the application and performance. Third, for Types III and IV, the active prototype daylighting systems application, cost and performance are collated. At the same time, active prototype daylighting systems with electrical lighting are also discussed (Type IV).

Finally, whether it is the passive or active system, its daylight performance and cost are also the point of this research. In addition to analysis of daylight performance and cost; this article also gives a visual diagram in Sections 3.1 and 3.2. The difference between the passive and active prototype daylighting systems in the work process is shown in Figure 3.

Work process of active prototype daylighting systems



Work process of passive prototype daylighting systems

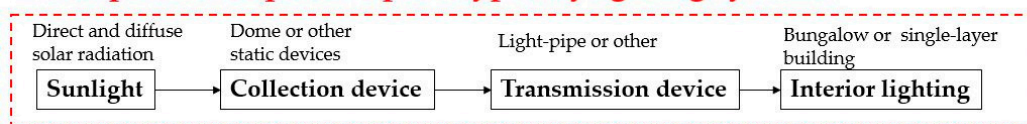


Figure 3. Compare the passive and active prototype daylighting system's work process.

3.1. Passive Prototype Daylighting Systems (Type I, II)

Most of the daylighting systems that do not require energy are passive tubular daylight devices, which can also be divided into Tubular Daylight Guidance System (TDGS) or Anidolic systems [86]. The difference between the two systems is that TDGS is usually a vertical light pipe and transfers sunlight from the outdoor to the core of the building [16,18,19,23,31,85], whereas Anidolic is a horizontal light pipe that transfers daylight from the façade to the indoor space [3,87–89].

The redirection and collection of the daylight that passes the transmission system to the indoors (deep underground space, tunnels, high-rise buildings, etc.) provides light a window cannot.

TDGS is a linear device composed of solar concentrator (dome or laser cut panels) [90], light pipe (light duct or light guide) and diffuser [91].

TDGS is also an IDS, the dome of high-transmittance material filters ultraviolet light and guides daylight into the system, due to the low solar angle at high latitudes area, which is a problem of an insufficient solar concentrator and the solution is to use a metal reflector placed in the dome [85]. This device can effectively capture low-angle daylight, although it sacrifices some high-angle sunlight efficiency, but is nonetheless useful for overall system efficiency improvement. Daylight enters the system and is transmitted through a light pipe. The light pipe is an efficient and simple optical transmission component that includes high color rendering, low glare, high service life and simple assembly [16–31].

However, the daylight efficiency of the transmission process is affected by the angle of incidence, the reflectance of the coating inside the tube and the ratio diameter/length. The lower the angle of the incident light, the higher the number of reflections and the lower the efficiency.

M Al Marwaei et al. [17] discuss the reasons why the tubular daylight guidance system can provide less daylight than windows:

- Pipeline condensation and dirt accumulation;
- Tubular daylight guidance system has no control;
- The daylight factor is less than 2%, and not enough to create a well-lit image and space;
- TDGS design lacks standards;

Mohelnikova [22] published a method for evaluating TDGS, explaining some of the parameters of the light pipe, useful for improving or setting standards and based on clear sky conditions and direct solar radiation. The following conditions affecting the light pipe were discussed: the elevation angle of daylight entering, and the relationship between the diameter and length of the light pipe, the transmittance of the dome, the reflectivity inside the pipes, etc. The following advice was given [22]:

- Use of a high transparency and low reflectivity roof cover (glass material), and a dome is better than a flat top.
- Recommended that the interior ceiling luminaire surface should be graphically designed to increase uniformity.
- The reflectance inside the light pipe is high and requires flatness. It is better to use it with a mirror material.
- Optical geometry of the straight tubular light guide: the ratio diameter/length is recommended 1/10, maximal permitted is 1/20.
- Light guides of small diameters (less than 0.2 m) are not efficient because of material waste and high light losses inside light guide.
- Tubular light guides are very efficient for direct solar radiation and they give low illuminance for conditions of an overcast sky.

The performance of the light pipe is not only affected by its own conditions [22] but also by factors such as sky conditions, solar position and external illumination [23,31]. Recently, studies of many tubular daylight guidance systems have shown that performance testing of light pipes is being carried out in many locations (e.g., Mediterranean [31], Romania [92], South Africa [85], India [16,93], Spain [88], China [24,26,94], Greece [31], United Kingdom [91] and South Korea [23,55]).

The performance of the light pipe in the daylighting systems must be demonstrated by experiments and real field tests on prototype systems. The following describes a tubular daylight guidance system with real field tests or experiments.

K. Vasilakopoulou et al. [31] spent 8 months to determine the performance of the light pipe in the Mediterranean region, and also mentioned that the performance of the light pipe is affected by the ratio diameter/length and reflectivity. The daylight penetration factor of the light pipe is affected by the clarity of the sky and the position of the sun, and it is initially found that the optical properties of the light pipe have a strong correlation with the sky conditions and the received solar radiation. Daylight Penetration Factor (DPF) is in clear sky or overcast conditions, the former has a higher value and the latter is non-significant, mainly because of the nature of diffuse solar radiations.

Ciugudeanu et al. [92] showed a case study that the use of planer daylight concentrator element did not help the daylight factor of tubular daylight guidance systems in Romania. The DF in clear sky conditions is only 0.36%, which is far from the 1.5% required [2] to create a bright enough field. The efficiency of the tubular system is not only the factors discussed above, but also more importantly with the optical design of light pipes.

A Ikuzwe et al. [85] installed a collimator (use of the aluminum foil lining) at the exit of the TDGS to improve the system output optical efficiency, using a mirrored lining and adding an anodized aluminum substrate to the dome to guide the low-angle light, helping the original the illuminance increased from 178 lux to 350 lux, and achieve the illuminance required in the experimental classroom.

Yun et al. [23] used the SIT corporation's light pipe to build a test cabin in South Korea. The amount of daylight that can be supplied by the TDGS is about 4 times worse on an overcast day than on a clear sky day, and therefore, local illuminance levels and climatic conditions should be considered when erecting the system. The shape of the light pipe is also the major cause that affects the system. Sharma et al. [16] put the light pipe parameters (provided by SOLATUBE from the United States) into a simulation program to achieve the best light pipe performance design by changing the width of the upper, middle and bottom of the pipe.

TDGS are still a popular device in the IDS, and there is still much research to be done through the adjustment of various components and sky conditions. Table 4 shows the actual experimental field of the Type I and II discussed in this article. At present, the TDGS does not include the cost of erection, and the initial cost of the commercially systems used light pipe is about \$400. The kit and domes are between \$190 and \$400. For example, the commercial system Solatube is priced between \$230 and \$550. Although the price is determined by the different kit, it is relatively inexpensive compared to other types daylighting systems.

In addition to providing illuminance, the prototype daylighting system is designed to save energy. MS Mayhoub et al. [82] proposed a daylighting system from passive to hybrid and integrated systems, which included artificial light sources such as LEDs. The hybrid lighting systems (HLS) consists of:

- The daylight collection device and daylight guiding device
- Artificial lighting systems
- Control system and lighting strategy

HLS provides daylight and electrical light sources to the indoor space and integrates the two into the luminaire. Among them, the TDGS is used earlier in the hybrid lighting systems, and then commercial lighting systems (e.g., Parans) are used. HLS are commonly used in deep building space or complex building structures, daylight is transmitted through the LTS into the center of the building or windowless room, and the HLS more suitable for the following situations:




- Window daylighting system or other types of daylighting systems
- With automatic control
- Artificial lighting system (with the intelligence function)
- Smart control with redirection device

The participation of electrical light source will increase the consumption of electric energy, but it can effectively increase the indoor illumination level. Xu Yu et al. [95] mentioned the importance of energy saving in daylighting systems. The energy saving of daylighting is determined by the amount of sunlight entering the indoor space from windows or roof-skylight. The way of energy saving control is roughly divided into the following types:

- Dimming control
- High frequency dimming control
- On/off control
- Continuous dimming
- Automatic dimming
- Combined occupancy

Bruno et al. [18] used a passive TDDs with electrical lighting. Experiments show that the daylight output of the light pipe can reach 6800 lm in a clear sky condition, and this far exceeds the 56-watt fluorescent. When the daylight output is higher than the electrical light source, the energy consumption can be effectively reduced, and it can save about 57% of the electrical lighting time and 336 W. Simei Ji et al. [94] used the TDDs for the daylighting systems of the underground parking space. The condition was that the target illumination is low (60 lux), and after the simulation, it can effectively save annual energy of 60.4%. KN Patil et al. [93] used the hybrid TDDs to evaluate the predictive model of the light pipe. They also mentioned that dimming control can save 50% energy each month. The research is based on different lighting controls, and can reduce CO₂ emissions by 15~50%.

Table 4. Experimental field of prototype tubular daylight guidance systems.

Ref/Year	Location	Method and System Type	Devices Details	Image
[16], 2018	IIT Delhi	Simulation, Real filed test; type I	<ul style="list-style-type: none"> • Dome (thickness of 3 mm) • Pipe (Length: 0.7 m; diameter: 230 mm) • The pipe has been supplied by Solatube • Diffuser (Thickness: 0.61 mm; diamond type) • Test room (L: 3 m; W: 3 m; H: 2.5 m, wooden) 	
[18], 2016	France	Mathematics, Simulation, Real filed test; type II	<ul style="list-style-type: none"> • MLP light pipe type is installed on the roof • SOLATUBE® Brighten Up® Series 160 DS Daylighting System • Diffuser (Dual Diffuseur Vusion® in PMMA) 	
[19], 2002	UK	Real field test; type I	<ul style="list-style-type: none"> • Pipe (Length: 610 mm; diameter: 330 mm) • Test room (2 m × 1.5 m garden shed, the light-pipe were installed at roof level 1600 mm) 	
[23], 2010	Korea	Real field test; type I	<ul style="list-style-type: none"> • Pipe (Manufactured by SIT Inc.) • The length of light-pipe is 1.32 m and diameter is 0.65 m (Aspect ratio of 2.03) • Test room (L: 6 m; W: 6 m; H: 4 m, windowless area), 	
[31], 2017	Greece	Real field test; type I	<ul style="list-style-type: none"> • The length of light-pipe is 2.6 m and diameter is 0.3 m • Test room (L: 5.76 m; W: 2.75 m; H: 2.35 m, windowless area), • Prismatic diffuser (Light transmittance of 0.8) 	
[96], 2016	Iran	Real field test; type I	<ul style="list-style-type: none"> • The collector that is installed in the façade of building • Horizontal duct • Distributing element for the internal space 	
[85], 2015	South Africa	Real field test; type I	<ul style="list-style-type: none"> • Plexiglas dome of 250 mm diameter • A 400 mm mirrored tube of 90% specular-reflectance • Polycarbonate-made prismatic diffuser 	

3.2. Active Prototype Daylighting Systems (Type III, IV)

Active prototype daylighting system is a device that needs energy to be used in the process of sunlight collecting, and the system uses mechanical structures to redirect or collimate light during light transmission. Generally, active daylighting system tracking is based on five categories: active, passive, semi-passive, manual and time tracking [97]. The design of the tracking is divided into single-axis and dual-axis tracking. The single-axis, through the middle pivot point, turns from one side to the other side to track the sun, the dual-axis is rotated through two pivot points to track the solar position in the horizontal and vertical axes. The most common tracking technology is spinning-elevation and azimuth-elevation tracking [98]. Table 5 shows the tracking methods, types, elements, and system objectives of the active prototype daylighting system.

Table 5. Element of the active prototype daylighting system.

Ref/Year	Tracking Method and Type	Element of Collection and Transmission	Purpose	Image
[48], 2013	Two-axis tracking; type III	Parabolic connector; optical fiber	Redirect and compress the light	
[55], 2010	Two-axis tracking; type III	Mirror reflector; free space	Redirect the light	
[99], 2018	Two-axis tracking; type III	Mirror reflector; free space	Redirect the light	
[52], 2016	Two-axis tracking; type III	Compound parabolic concentrator; optical fiber	Redirect and compress the light	
[39], 2016	Tracking simulation; type III	Linear Fresnel lens and waveguide; optical fiber	Redirect and compress the light	

Table 5. Cont.

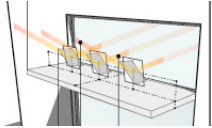
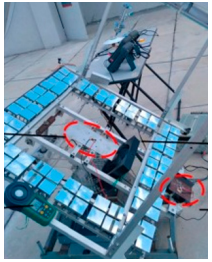

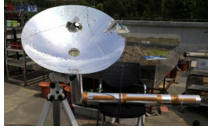



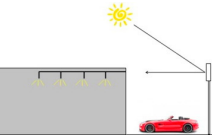

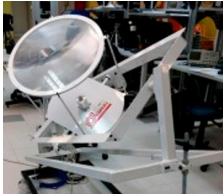

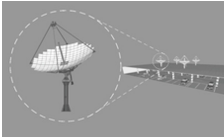
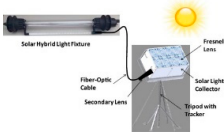
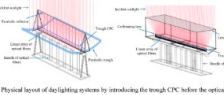
Ref/Year	Tracking Method and Type	Element of Collection and Transmission	Purpose	Image
[56], 2017	Two-axis tracking; type III	Mirror reflector; free space	Redirect the direct solar radiation	
[49], 2017	Two-axis tracking; type III	Flat mirror concentrator; optical fiber	Redirect and compress the light	
[41], 2013	Two-axis tracking; type III	Parans SP3; optical fiber	Redirect and compress the light	
[100], 2019	Two-axis tracking; type III	Parabolic concentrator; light pipe	Redirect and compress the light	
[44], 2018	Two-axis tracking; type III	Fresnel lens; optical fiber	Redirect and compress the light	
[50], 2017	One-axis tracking; type III	Parabolic concentrator; plastic optical fiber	Redirect and compress the light	
[101], 2014	Two-axis tracking; type III	Lens; plastic optical fiber	Redirect and compress the light	
[42], 2015	Two-axis tracking; type III	Fresnel lens array; plastic optical fiber	Redirect and compress the light	
[58], 2016	Two-axis tracking; type III	Mirror reflector; light-pipe	Redirect the light	

Table 5. Cont.

Ref/Year	Tracking Method and Type	Element of Collection and Transmission	Purpose	Image
[102], 2011	Tracking error angle analyze; type III	Co-focus compound parabolic concentrator; plastic optical fiber	Redirect and compress the light	
[32], 2018	Two-axis tracking; type III	Fresnel lens; plastic optical fiber	Redirect and compress the light	
[103], 2013	Two-axis tracking; type IV	Dish concentrator and secondary reflector; optical fiber	Redirect and compress the light	
[104], 2018	With tracking system; type IV	Dish reflector and secondary reflector; Optical fiber of bundles	Redirect and compress the light	
[38], 2017	Two-axis tracking; type IV	Fresnel lens and compound elliptical concentrator; Optical fiber of bundles	Redirect and compress the light	
[47], 2014	One tracking module; type IV	Parabolic trough or linear Fresnel lens; Plastic optical fiber	Redirect and compress the light	

Active daylighting system uses tracking technology to collect sunlight. After concentration or compression, the sunlight is transmitted through the optical fiber, light pipe or free space [105]. The technology transmitted through the optical fiber is also called Fiber Daylighting System [32,38–44,47–50,52,101–104,106–108]. However, the main materials of the optical fiber used in the fiber daylighting system are: SiO₂, PMMA and quartz. The specifications are shown in Table 6.

Fresnel lenses are common light collection components for active daylighting systems. Many studies have actually used Fresnel lenses with fiber bundles to experiment in different test environment or sky conditions.

Table 6. Comparison of different characteristics between Plastic optical fiber (POF) and silica fiber [32].

Parameter	POF	Silica Fiber
Material	PMMA ^A	Silica ^B
Diameter	2 mm	0.20 mm
Attenuation	100 dB/km	8 dB/km
Numerical aperture	0.5	0.22
Price per meter	1 US\$/m	8 US\$/m
Maximum temperature	80 °C	Up to 900 °C
Specific mass	1 g/cm ³	2.5 g/cm ³
Bundle flexibility	High	Low

^A Poly (methyl Methacrylate), ^B SiO₂.

Ravi et al. [38] developed a Fresnel-based concentrating and fiber daylighting system for mobile devices, using a secondary optical design that allows for Fresnel lenses to collect sunlight without causing localized heat damage at the fiber entrance. This system can provide 2700 lm~3600 lm (based on different materials) with external illumination of 110 klx. The high concentration ratio of Fresnel lenses has been plagued by thermal damage to the optical fiber. However, due to system durability issues, most of the daylighting systems using Fresnel lenses and optical fiber are thermally protected.

Song et al. [109] focus on the infrared thermal effect that PMMA optical fiber and plastic fiber will have, whether it will produce irreversible thermal damage above 70 °C, because plastic fiber has a strong absorption capacity for the infrared band. The fiber can easily overheat and melt when the concentration ratio exceeds 2500 up. Therefore, the shortpass dichroic mirror has been developed to reduce the amount of infrared light entering the fiber to control the operating temperature and increase the service life, and this method is the same as many studies that use a hot mirror or a cold mirror. The purpose is to block or reduce infrared and ultraviolet light [109].

L. Sedki et al. [50] also discuss the protection of plastic fibers with high solar concentration ratio (over 2500 suns) for parabolic solar concentrators. In this case, through a three-stage mechanical system after using the UV and IR filters in the first stage. The filtered beam will pass through the vacuum to naturally dissipate the heat damage caused by the infrared rays. Finally, uniform illumination is produced by the Plano-convex lens and simultaneously reduces the thermal effect of collimated light. However, this design also includes a parabolic concentrator consisting of 340 mirrors. The experimental results show that a system with triple filtering has a light output of 5%, and without triple filtering, at 93 klx external illumination. The daylight efficiency with the filter unit in sunlight is 2.9%.

A parabolic concentrator is a high solar concentration ratio application. The advantage is that the Cassegrain mirror utilizes hyperbolic and parabolic reflections, and concave parabolic mirrors focus light parallel to the optical axis at focus point. The parabola reflects the received light onto the secondary optical element. Finally, secondary reflection is to the fiber and a coupler is connected to the part of transmission. Although an interface loss occurs with each reflection, this design method can protect the incident surface of the fiber, and can increase the sunlight collecting area to achieve a high solar concentration ratio. When the concentration ratio is higher, the system can transmit more sunlight into the indoor space.

Chong et al. [49] have used a number of small faceted reflectors to form a parabolic concentrator that can achieve an average solar concentration ratio of 66.6 suns. In this case, the collection area of 0.2 square meters can provide an average office space of 7.8 square meters above 500 lx. The higher the solar concentration ratio, the smaller the area required to represent the area of outdoor light collection, and this is a good solution for space-constrained places. Especially when the roof of a modern building is not enough large. Ullah et al. [47] use CPC slots in high-rise buildings for fiber daylighting systems using single-axis solar tracking to direct daylight into indoor areas; it also emphasizes that the use of a single large system is more efficient than multiple small systems.

Concerning cost, the structure of the concentrator is CPC, heliostat, parabolic reflector, optical collection components, etc. Irfan Ullah et al. [47] used the mechanical structure and a primary mirror,

and it cost approximately \$3200 on a CPC trough reflector. Ngoc-Hai Vu et al. [52] developed M-CPC for concentrating use. Due to mass production after mold opening, its 200-unit M-CPC cost only \$2050. The structure of heliostats is much simpler than other concentrators. However, Song et al. [99] have a research of large heliostat, due to the mechanical and the size of the mirror, the primary mirror and the secondary mirror requires about \$6500. But the transmission in the air does not require any cost, and the overall efficiency is high, so that a high amount of daylight is provided. Fresnel lenses, as concentrators with PMMA fibers cost \$4200, while the replacement of the material of fiber for SiO₂ that increased heat resistance came to \$7450 [39]. K. K. Chong et al. [49] used multiple faceted mirrors to replace a large system, while also being the cheapest, \$1231, and providing sufficient daylight. The cost prototype systems are mostly higher than current mainstream commercial systems. For example, Parans and Himawari can provide stable and sufficient daylight, and even can adapt to more real fields to application. The price of the product is about \$5800 to \$6000 (Entry vision) [41,52]. The commercial system is cheaper than many prototype systems. The potential reason is that the modularization of mass production reduces the cost. If the prototype daylighting system can consider the analysis of modular production, then the analysis of the initial cost will be of great help.

The concept of active prototype daylighting systems with hybrid systems are similar to passive systems. Both of these are aids in the unsustainable output of daylight and the system is aimed at energy saving.

Ullah et al. [47] suggested that HLS not only require solar tracking equipment, but also required sensors and lighting controllers to achieve the best daylighting quality (Figure 4). In addition to the mechanical and optical components of the daylighting systems, HLS require hybrid lighting fixtures to mix daylight and electrical lighting for illumination [38]. Effective use of daylight and electrical lighting is a good way to balance power consumption, because daylight is sufficient for reducing electrical power consumption and to add electrical lighting when there is insufficient daylight. This will not only save energy, but will also enhance human welfare [103].

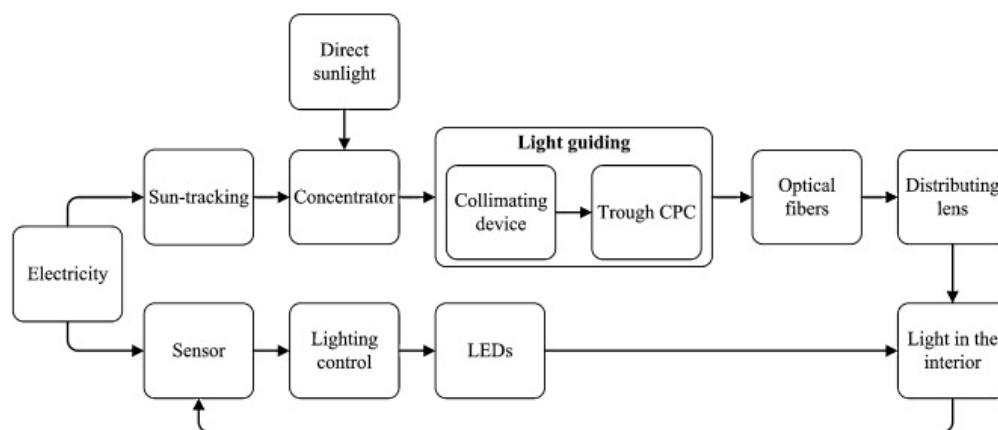


Figure 4. Flow chart of the proposed hybrid daylighting system [47].

3.3. Discussion

This study divides the daylighting systems into four categories. First, the research on passive prototype daylighting systems based on TDDs and that which revolves around the performance of the light pipe. Using straight tubes to conduct experiments in the test cabins, TDGS has the advantage of being cheap and easy to use, and the performance is improved due to the progress of the material of the dome or tube. In the tropics, with a large amount of direct sunlight, there is a good daylight performance/cost ratio, but TGDS is limited by architectural style. Although the daylight collecting area is small, the illuminating space has limitations. The TDGS using the hybrid is usually used in underground space or non-office space. Electrical lighting mixed with daylight achieves the effect of power saving.

The active prototyping system is suitable for any area with long hours of sunshine. With the technology of solar tracking becoming more advanced and having lower cost [47], the solar tracking systems have almost become the standard equipment for daylighting systems. Active prototype daylighting systems are ideal for installations that require long-distance transportation such as high-rise building and deep-planning architectural applications. Efficient delivery of daylight to the building core through flexible fiber or mirror systems with the functions of redirection. Most active prototype daylighting systems provide enough daylight to indoor space, but the system has more cost and energy consumption for long-distance transmission. These studies are not applicable to all type of buildings.

The optical fiber that transmits the longest distance also struggles to exceed 70 m due to the material limitation. If a material with lower loss ratio such as quartz fiber were to be used, it would be very expensive. However, the mirror system such as heliostat has no distance limitation, but requires a relatively large collection area and a transmission path without any obstacles.

Table 7 summarizes the passive/active prototype daylighting systems included in this article after 2010. According to the operation mode of each system, the four classifications of Type I to IV are added to the evaluation, and the reference level of cost is proposed. The cost is based on the system cost mentioned by these solar researchers in the article. Evaluations for the three designs of the system: concentrators, transmission components and diffusers [5,32,39–41,47–49,52,99,110]. The daylight performance standard is whether the daylight factor is above 2.5% or whether it can effectively supply more than 500 lx/m² of illumination. Finally, cost and daylight performance are used as reference factors for complex score. The complex score for each prototype daylighting systems is defined by giving three levels, and this is defined as the ratio daylight performance/cost.

At present, the difficulties encountered in active prototype daylighting systems are high cost, installation difficulty, low generality and subject to sky conditions. There is no uniform design standard for concentrators, which has too expensive research costs. The daylighting design recommendations and the usage scenarios of the hybrid are given below:

- Assess the geographical location of the target place and the level of sunshine to determine which type of daylighting system to use. For example, the level of sunshine in Uppsala is different from that in Egypt. Therefore, different daylighting systems should be used that follow the local conditions.
- Due to the sufficient direct solar radiation in the tropics, it is suitable for the development of TDGS. The effect of the light pipe receiving direct solar radiation is much better than diffuse solar radiation.
- At high latitudes, the daylight hours are short (especially in winter), and the angle of incidence light is much smaller than in the tropics. Recommended to use the high concentration of active daylighting system to harvest as much daylight as possible.
- Hybrid is suitable for any daylighting system. The purpose is not to fully utilize daylight illumination, but to use electrical lighting to save energy. The system is not completely dependent on the daylighting device, and the benefits include lower initial cost, ability to take care of human welfare and energy savings.
- Photovoltaic addition daylighting systems research has also increased recently. Using the flexible characteristics of thin-film batteries. The battery can be distributed on the surface of the concentrator, which not only can provide good optical performance but also generate electricity at the same time.
- Prototype daylighting systems may not have the stable cost and more applications fields as commercial daylighting systems. But the potential of the prototype system is large, whether it is focusing on cost savings or daylight performance. In fact, sometimes it is better than some of the commercial systems. If it can overcome the problem of localization, then many prototype daylighting systems could also be competitive.

Table 7. Type I to IV system performance, components, cost consolidation and evaluation.

Ref/Year	Type	Test Field (Length/Width/Height) *	Daylight Output (External; Indoor)	Component	Cost			Daylight Performance	Complex Score
					C *	T *	D *		
[31], 2017	Type I	Test room 5.76 × 2.75 × 2.36	60 klx; 0–1204 lx (avg. 100 lx)	Dome, Light pipe, Diffuser	L	L	L	M	0.67
[92], 2016	Type I	Low-rise tenement 4 × 4 × 2.5	41 klx; 151 lx (avg.)	Dome, Light pipe, Diffuser	L	L	L	M	0.67
[85], 2015	Type I	Classroom 18 × 10 × 2.5	Highest 519 lx	Dome, Light pipe, Diffuser	L	L	L	H	1
[96], 2016	Type I	Model room 0.9 × 0.5 × 0.27	Highest 400 lx, Max distance 20 m-300 lx	Duct, façade concentrator, rectangular illuminator	L	L	L	M	0.67
[16], 2018	Type I	Room area (L: 3 m; W: 3 m; H: 2.5 m)	850 W/m ² with 110 lx (improve type)	Dome, Tube, Diffuser	L	L	L	M	0.67
[55], 2010	Type I	Room area	34,779 lx; 492 lx, 79,247 lx; 1548 lx	Dome, Light pipe, Diffuser	L	L	L	M/H	1
[23], 2010	Type I	Test room area 6 × 6 × 4	Clear sky 83,060 lx; 647 lx, Overcast 49,018 lx; 170 lx	Dome, Light pipe, Diffuser	L	L	L	L/H	1
[88], 2013	Type I	Indoor area	Provide 40 m ² with 300–400 lx	Truncated compound parabolic concentrator, Light duct, Diffuser	M	L	L	M	0.5
[94], 2016	Type II	Underground car park 48 × 28 × 3.5 area 2088 m ²	Lane average 45 lx and parking space average 23 lx	Fresnel lens, Light pipe, baffle vane, thin sheet	M	L	L	L	0.25
[18], 2016	Type II	Standard room	140 klx; 6800 lm	Dome, Tube, Diffuser	L	L	L	H	1
[93], 2018	Type II	Room area 3 × 3 × 3	On overcast 40 klx; 60–120 lx On clear sky 55 klx; 5–180 lx	Dome, Tube, Diffuser	L	L	L	M(avg.)	0.67
[54], 2010	Type II	Traffic tunnels (Road width 3.5 m and the lamp altitude 4.9 m)	The average of illuminance is 167 lx without lens and 222 lx with lens for six lamps	Coupler with optical fiber, light pipe, an optical sensor and an LED array	L	L	L	M	0.67
[48], 2013	Type III	Area 100 m ²	145 fibers give out about 43.5 klm	Primary parabolic collector, Optical fiber bundles, Secondary flat optical reflector	H	L	n/a	H	0.75
[55], 2010	Type III	Fourth floors	Output 518 lx	Dome, Base, 2 Reflecting mirrors, Tracking control system, Activator	M	L	L	H	0.75
[99], 2018	Type III	Building core area 24 × 24, distance 70 m	110 klx; 20 klx–80 klx	Primary Heliostat, Secondary reflection mirror	H	n/a	n/a	H	0.75
[52], 2016	Type III		110 klx; 4400 lm (200*M-CPC)	Modified compound parabolic concentrator, POFs, Solar tracking component	H	L	L	H	0.6

Table 7. Cont.

Ref/Year	Type	Test Field (Length/Width/Height) *	Daylight Output (External; Indoor)	Component	Cost			Daylight Performance	Complex Score
					C *	T *	D *		
[39], 2016	Type III	Deep-plan building case1	74° solar angle at 12:00; 105 klx 2 mm diameter (22157 lm) 10 mm diameter (9847 lm)	Linear Fresnel lens, POFs (2 mm)	H	H	n/a	H	0.5
[39], 2016	Type III	Deep-plan building case2		Linear Fresnel lens, POFs (10 mm)	H	L	n/a	H	0.75
[56], 2017	Type III	Indoor 7 × 4 × 3	Summer 300 lx	Mirror, Tracking device	L	n/a	n/a	N/A	N/A
[49], 2017	Type III		Total output 3921.9 lm	80°Primary facet mirrors, 20°Secondary facet mirrors, Sun tracking, POFs	H	L	n/a	H	0.75
[40], 2016	Type III		100 klx; 4625.7 lm	Primary concentrator Point focus Fresnel lens, Truncated cone tapered plastic optical fiber, Parabolic mirror, Convex lens, Direction flat mirrors, 2 * linear Fresnel lens	H	L	L	H	0.6
[41], 2013	Type III	Test room 11.2 × 9 × 2.5	130 klx; 4600 lm	Parans SP3	H	L	L	H	0.6
[100], 2019	Type III	Model room (DIALux) 5 × 3 × 2.5	Solar radiation, 1100 lm with no tracking, 5300 lm with solar tracking	Solar concentration, Novel four-mirror active tracking, Collimation, Beam alignment, Light pipe	H	L	L	H/H	0.6
[44], 2018	Type III	Underground tunnel	100 klx; 360 lx (Background < 1 lx)	Large Fresnel lens, POFs, Hot mirror, Dual-Axis solar tracking	H	L	n/a	M	0.5
[50], 2017	Type III	Test room 2 × 2 × 3	103 klx; 2000 lx (without TFM) 103 klx; 1900 lx (with TFM)	Parabolic Solar concentrator (345°mirror), POFs, Solar tracking, triple filtering machine	H	L	n/a	H	0.75
[107], 2017	Type III		Clear sky solar radiation 1000 W/m ² , each fiber 13 lm, 314 fibers output 4082 lm	Two-stage reflective Non-Imaging Dish Concentrator (NIDC), Primary reflective, Secondary mirror, POFs, Linear actuator, Dual axis tracking	H	L	n/a	H	0.75
[101], 2014	Type III	Underground tunnel 4.6 × 4.2	2 mm fiber provide 26.7 lx after 10 m	POFs, Solar tracking model	H	L	L	L	0.2
[42], 2015	Type III	Underground tunnel 8.6 × 4.2 × 2.3	32 Concentrator in experiment, 70 klx; 122 lx (avg.)	49 Concentration unit, Dual axis tracking system	H	L	L	M	0.4

Table 7. Cont.

Ref/Year	Type	Test Field (Length/Width/Height) *	Daylight Output (External; Indoor)	Component	Cost			Daylight Performance	Complex Score
					C *	T *	D *		
[58], 2016	Type III	Model road tunnel 1.85 × 0.8 × 0.36	Simulation input illuminance 106325 lx 97858 lx; 1691 lx (Road surface)	Heliostat, Mirror, Light pipe	H	L	L	H	0.6
[102], 2018	Type III		100 klx; 2371.5 lm (from optical fiber)	Primary concentrator, Cylindrical reflector, Deflector, Secondary CPC, Optical fiber	H	L		H	0.75
[32], 2011	Type III	Model dark room 1 × 1 × 1.4	Diameter 12 mm; L: 3 mm 120 klx; 400 lx	Dual axis solar tracking, Fresnel lens, POFs, IR filter	H	L	n/a	M	0.5
[103], 2013	Type IV		99634 lx; 1060 lx 25288 lx; 380 lx	Dish concentrator, secondary mirror, homogenizer tube, fiber optic cable or liquid light guide, terminal device	H	M	n/a	H/M	0.6
[104], 2018	Type IV		Output 284 lx on the floor on FEB 25, 2016. Output 353 lx on the floor on AUG 17, 2016.	Dish-type concentrator (POE), Secondary reflector (SOE), FOB	H	L	n/a	M	0.5
[38], 2017	Type IV		110 klx; 3600 lm (acrylic, highest)	Fresnel lens, IR filter, Tripod with tracker, Secondary TIR lens, POFs	M	L	L	H	0.75
[47], 2014	Type IV		Simulation input 62.7 klx; and output 892 lx and 900 lx	3-stage reflective type of linear focusing, Parabolic reflector, Trough CPC, POF+QOF	H	H	n/a	H	0.5
[47], 2014	Type IV		Simulation input 62.7 klx; and output 840 lx and 847 lx	3-stage reflective type of linear focusing, Linear Fresnel, Plano-concave lens	H	L	n/a	H	0.75

C *: Parts of collection, T *: Parts of transmission, D *: Diffuser or luminaries, (Length/Width/Height) *: Unit is meter.

Finally, Figure 5 shows the complex score distribution of Type I–IV, where the number of studies is the most in Type III, followed by Type I and then Type III and IV. The average of the complex scores of the four types is calculated as Equation (1), and the standard deviation of the complex score is calculated as Equation (2).

$$\mu = \frac{1}{N} \sum_{i=1}^N x_i \tag{1}$$

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - \mu)^2} \tag{2}$$

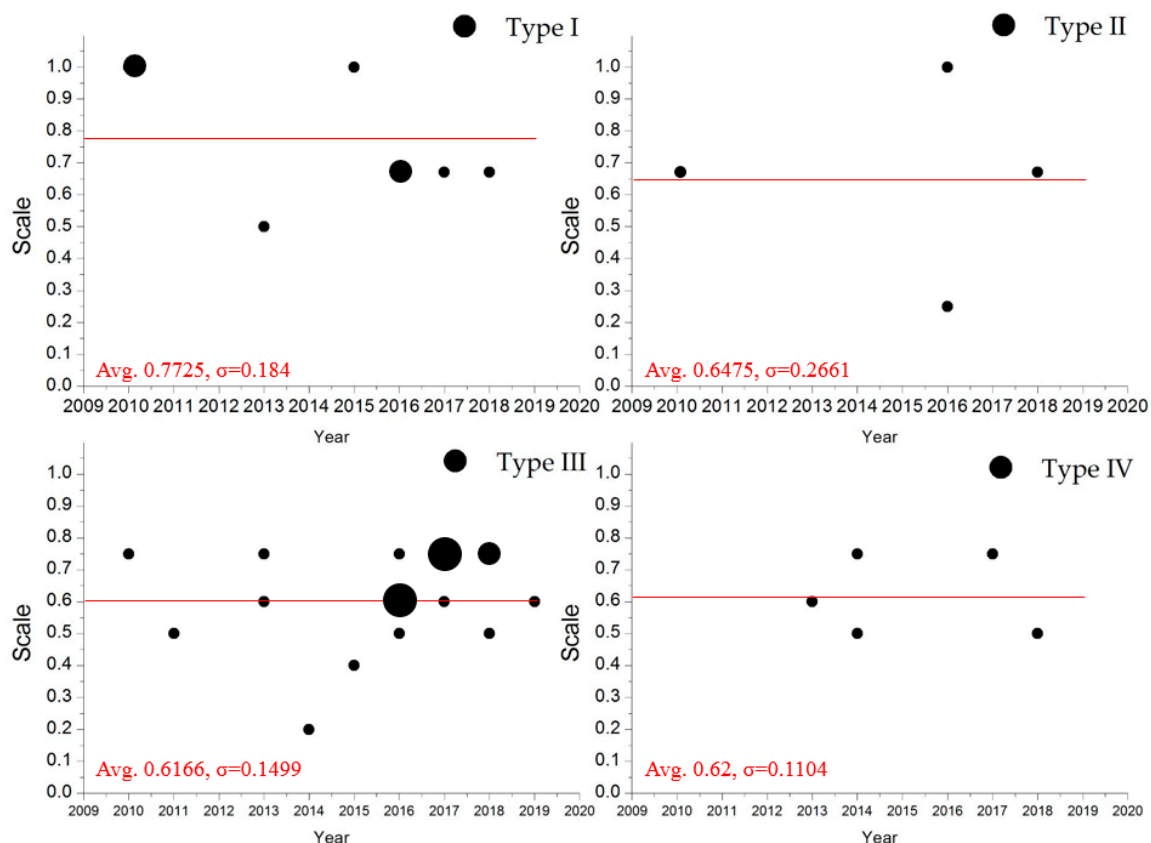


Figure 5. Daylight performance/cost distribution of the four types system.

On average, Type I which is dominated by TDDs has the best overall average score: 0.7725, far exceeding Type III with active device. The reason is that the cost of the TDGS is much lower than high-concentration devices, and the TDGS can also effectively provide the indoor daylighting required. Conversely, there is Type II and IV, with the electrical light uneven distribution due to the small number of studies. Every system with a hybrid has its own special application and cannot be depicted by the same standard.

In Type II, the highest and lowest ratio daylight performance/cost are distributed. The significance of these independent distributions is also worth exploring. In the light pipe experiment proposed by Bruno et al. [18], the mirror lining pipe is used to effectively collect enough daylight. However, the purpose of the research from Simei Ji et al. [94] is to illuminate underground parking area, and the illumination standards for parking area is different for office space. Even so, Simei Ji et al. still reduced the annual electricity consumption by 60.4%. Therefore, the two studies of Type II caused different distributions because of different purposes.

Three well-performing studies of Type I are due to the use of a dome with high transmittance materials and high reflectivity pipe [23,55], even using diffuser designed to increase daylight performance by more than two times [85].

Finally, in Type II, there is the second-order solar tracking module proposed by Jifeng Song et al. [101], where the field of daylight is an underground tunnel, with the concentration ratio of 2500 suns. It can, though, provide illumination of more than 100 lx but there have 40% energy thrown into the wall and therefore causes waste.

4. Novel Optical Design of Daylighting Systems

Optical design is an important part of daylighting systems, and many studies are dedicated to improving the efficiency of various daylighting systems.

The following is a classification of optical systems:

- Progress in optical materials
- Parts of light collection and transmission

This section separates the optical design from the prototype daylighting systems without any automatic control and various daylighting strategies.

We explore the optical efficiency, feasibility and performance of each component.

4.1. Material Progress of Daylighting Systems

In the composition of the daylighting systems, material is an important basis for system efficiency. Through high refractive index, high reflectivity and high transmittance materials, the systems can have better optical properties in application. For example, when using an acrylic dome with a transmittance of more than 0.95 or using a cold/heat mirror, the reflectance or transmittance exceeds 0.95.

With the advancement of optical materials technology, many optical systems have improved due to the improvement of basic materials. The four basic optical materials commonly used are glass, crystalline, polymers and plastic [111].

Glass, polymers and plastics are most often compared in daylighting systems. The design principle is biased toward geometric optics and does not consider dispersion or quantum problems. The design focuses on the optical characteristics: refraction, reflection, transition and absorption of incidental light.

For example; Polymethyl Methacrylate (PMMA) is a thermoplastic plastic substitutes with high transparency (0.92) and is used for many optical components at a low price, but it is not without disadvantages. Its melting point is low and can be easily damaged by high temperatures and there is no way to completely remove the 300 nm–400 nm band on the ultraviolet [111].

Ravi Gorthela et al. [38] used the compound elliptical concentrator (CEC) for the daylighting system, and using four different materials to the product: Acrylic, Dow1002, Dow184 and Nusil 6003. Differences in materials led to a drop in performance.

N.H. Vu et al. [39] and Regina et al. [32] conducted studies based on materials analysis of transmission components in daylighting systems. Fibers used in daylighting systems typically have three materials: plastic, cerium oxide and glass. However, the glass fiber is too expensive and not good in buildings because of a lack of flexibility [50]. Therefore, most of the discussion is about SiO₂ bundles (SOFs) and plastic bundles (POFs). The results show that although the heat resistance of SOFs is higher than POFs, considering the balance of cost and optical efficiency, most daylighting systems still choose the POFs. Special daylighting system such as Himawari use Quartz Optical Fibers (QOFs), but the unit cost of the system is sacrificed.

Usually, the efficiency of the daylighting systems is determined by the design or performance of the optical material. A. Ikuzwe et al. [85] roughened the surface of the component in order to adjust the illuminance for the requirements.

4.2. Parts of Collection and Transmission of Daylighting Systems

The solar concentrating system is important for the entire daylighting system.

Acting as a function of receiving direct solar radiation and diffuse solar radiation, the daylight quality of the daylighting system is controlled by a part of the light collection system.

The entire daylighting system is a multi-stage system. The process of serial connection and coupling of each stage may be the result of reduced efficiency.

Therefore, it is important to emphasize the optical efficiency of each component. The maximum use of daylight entering the system is very important for the daylighting systems.

At present, the common daylighting system collection includes parabolic reflector, trough CPC, CPC, Fresnel concentrator, linear Fresnel concentrator, multi-stage mirror and optical guidance systems. These concentrating systems have several identical features: compressing the light or changing the direction which the light travels path. We therefore recommend using a high-concentration system if there is not enough concentrating area.

The prototype daylighting system is divided into two parts: light collection and light transmission. The novel optical design principles are divided into three categories: collection [33,100,111–115], transmission [99] and collection with transmission [32,38–40,44,47,49,52,56,96,103,106,116] (Table 8).

Li Zhu et al. [112] proposed a new dynamic concentrating module that can be integrated with buildings and provide power generation. The module's optical efficiency is up to 78.68% and the maximum deviation is allowed to be 1 degree, and it relies on a two-stage concentrating module and dynamic tracking system to complete. MG Nair et al. [33] designed a profiled solar concentrator based on Fresnel lens. The difference is that not having a tracking mechanism, but rather, directly calculating the influence of the solar position on the Fresnel lens. It produces profiled faces to the south and north, and we propose that the focus will change from the solar movement.

In addition to relying on active solar tracking, special optical design can also have good results.

Zijun Zhao et al. [113] attempted to collect daylight using the micro-optical plate concentrator for the coupling direct solar radiation to planer waveguide and connecting the fiber. This design is similar to the stepped waveguide with fiber [39]. The purpose is to change the direction of the light, and to reduce the loss as possible. Therefore, the prism structure [54] and the compact spherical surface concentrator [116] are the same concept. The reason for the optical efficiency decrease comes from the transmission material and the multi-level coupling surface. Moreover, the transmission of free space is the goal pursued by many daylighting systems.

Jifeng Song et al. [99] use the heliostat with solar tracking and secondary reflector to guide the daylight. Since the light travels in the air does not change direction and composition. Vu N.H. et al. [40] proposed the Modified Optical Fiber Daylighting System (M-OFDS), collimated by Fresnel lens and spreads through free space for more than 30 m. The optical collimator is responsible for the beaming of light. Compared with the plastic optical fiber, collimator provided effectively improve the transmission efficiency of the daylighting system. Of course, there are also research about liquid fiber [117], but very expensive and ineffective.

The design of the optical concentrator considers the vertical incident light and the maximum deviation allowable angle, if the static concentrator is instead of the active solar tracking device to complete the concentrating. Designing a concentrator without an active device, then the effect is unpredictable. Although it can decrease cost, the deviation angles and application may be a challenge.

The challenge of transmission comes from the divergence of light and distance limit. The light pipe has good transmission efficiency but is limited by its own optical geometry limitation. Optical fiber has flexibility and low cost, but is limited by the loss of material. Optical waveguide combines the benefits of the light pipe and the optical fiber to transmit farther and has more optical efficiency.

Finally, free space transmission is the ultimate pursuit of daylighting systems, but the problem is that it cannot change the direction and spectral characteristics of light during transmission. These are common and thriving transmission methods for daylighting systems and will continue to be improved and updated in the future.

Table 8. Innovative optical design components, optical materials and performance.

Ref/Year	Type *	Optical Component	Optical Materials	Test Method	Performance
[100], 2019	C+T	Active Daylight Harvesting System (ADHS) with solar mirror concentration, collimation and beam alignment, light pipe	M1 peak reflectivity (3M film) over 95% M2 is a high-pass mirror (transmit 80% of the infrared and reflect 95% of the visible light), light pipe (Alanod 4200AG, total light reflection reaching 98%)	Real/ Simulation	2.6% light extraction 65% transmission efficiency at M5
[104], 2018	C+T	Dish-type concentrator: (Cassegrain optical structure), confocal secondary hyperbolic reflector disk (SOE), Fiber Optics Bundle (FOB), diffuser	Beam splitting film (ZnS and MgF ₂), FOB (with PMMA)	Simulation	40% utilization ratio of solar energy, conversion efficiency of solar cells is about 19%
[99], 2018	C+T	Heliostat (Mirror area is 22.95 m ²), Secondary reflection mirror	Heliostat (ultra-clear silver mirrors with reflectivity is 92%)	Real	Total efficiency 82.8%
[44], 2018	C+T	Protective glass, Fresnel lens, primary reflector, secondary reflector, hot mirror, homogenizer, FOB	Transmittance of the protective glass is 92% Transmittance of the Fresnel lens is 92% Reflectivity of the primary reflector is 93% Reflectivity of the secondary reflector is 93% Transmittance of the hot mirror is 95% Loss rate of homogenizer is 16%, fiber attenuation rate with length (10 m) is 46%	Real/ Mathematical	Daylighting efficiency is about 11–13%, theoretical efficiency is 29%
[32], 2018	C+T	Fresnel lens and a plastic optical fiber bundle, in which tip the lens concentrates the solar radiation	POF (with PMMA and attenuation at visible spectrum is 100 dB/km), Filter used is a 12.5 mm diameter IR cutoff filter, luminaires (with two POF bundles with 120 fiber)	Real	The POF attenuation rate about 15%
[112], 2018	C	Square Fresnel lens, concentrating module	Fresnel lens consists of glass panel of ultra-white float glass with 91% light transmissivity, concentrating module (K9 glass and the reflective index is 1.5163)	Simulation	The optical efficiency of the module can reach 76.87%
[113], 2018	C	Planar micro-optic solar concentrators that comprises lenslet arrays, coupler	The optimized spherical lens is made of PMMA, material of doublet first element is PMMA, second element is Polycarbonate and waveguide is BK-7	Simulation	92.14% collection efficiency within ± 30-deg
[38], 2017	C+T	Comprised faceted conical, compound elliptical concentrator, Fresnel lens, fiber optic cable, IR Filter, Secondary lens (TIR)	Prototype secondary lenses fabricated from acrylic and optical silicones, fiber-optic cable (Acrylic)	Real	Measured efficiency for the acrylic secondary lens is about 66%, while the Photopia is about 69%

Table 8. Cont.

Ref/Year	Type *	Optical Component	Optical Materials	Test Method	Performance
[56], 2017	C+T	Active Sunlight Redirection System (ASRS) consists of the mirror	For each mirror, a specular reflectance of 98%	Simulation	The ASRS enhances illuminance uniformity and during the summer solstice
[49], 2017	C+T	Two-stage Non-Imaging Solar Concentrator(2S-NISC) consists of 80 primary facet mirrors, 20 secondary facet mirrors and plastic optical fibers, hot mirror	Model of plastic optical fiber is CK-120 Hot mirror has a high transmissibility of 98% for visible light	Real	2S-NISC prototype is obtained as 22% when input solar power of 170 W
[50], 2017	C+T	Parabolic solar concentrator (with 345 pieces of mirror), POF, UV and IR filter	Parabolic concentrator inner surface was covered with 345 pieces of mirror tiles with 94% reflectivity, POF	Real	Light factor of 2.9% (Exterior global illuminance of 103 klx corresponds indoor 3 klx)
[107], 2017	C+T	Non-imaging dish concentrator, primary and secondary reflectors, plastic optical fibers	POF (with PMMA and model CK-120), total loss 45.7% (including coupling loss)	Real	Equivalent power conversion efficiency is 19.6%
[96], 2016	C+T	Anidolic Daylighting System (ADS) consists of horizontal tube system, façade concentrator, rectangle duct	Coating materials for Anidolic is 85%	Real	Daylight factor with 3.5 m distance from collector was 6.1%
[52], 2016	C+T	M-CPC (Modified-compound parabolic concentrations), plastic optical fibers, collimated CPC	POF refractive index: core/cladding (1.492/1.402)	Real/ Simulation	The simulation results indicate that 84% of optical efficiency (achieved at $C_{geo} = 100$)
[39], 2016	C+T	Fresnel lens array, stepped thickness waveguide, plastic optical fibers	Fresnel lens (with PMMA), POF (attenuation 0.45 dB/m, refractive index:1.492/1.402 (Core/Cladding)), stepped thickness waveguide with a commonly used optical pure plastic material	Simulation	Using proposed daylighting system can save 28.68% of electric power consumption for illumination
[40], 2016	C+T	Modified optical fiber daylighting system, linear Fresnel lens, large-core plastic optical fiber, collimator (parabolic mirror and a convex lens)	Linear Fresnel made by DiYPRO Co., Ltd. Fresnel lens material is PMMA, POF (attenuation 0.45 dB/m, refractive index:1.492/1.402 (Core/Cladding))	Simulation	Simulation results demonstrated a maximum optical efficiency of 71%
[114], 2016	C	Compound Truncated Pyramid and a Cone (CTPC), fiber optics cables, multifunction photovoltaic cells, coupler	The material of both the CTPC and the plate was BK7 optical glass	Simulation	The efficiency of the designed coupler was 92%

Table 8. Cont.

Ref/Year	Type *	Optical Component	Optical Materials	Test Method	Performance
[47], 2014	C+T	Three-stage reflective type of linear focusing, parabolic trough, trough CPC, linear Fresnel, collimating lens (Plano-concave lens), plastic optical fiber	Parabolic trough manufactured by using aluminum foil, which can reflect 95% of sunlight, linear Fresnel lens mad by PMMA, which had a refractive index of 1.494	Simulation	Using biconcave lens and a concave convex lens with parabolic trough had 1.43% of solar utilization ratio at 12PM
[33], 2014	C	Proposed profiled Fresnel collectors (Performance of the north- and south-facing collector at different times), light pipe module	The light pipe was measured at the base of the pipe with a diffuser of transmissivity 89%, the light pipe top was covered by a flat acrylic, the pipe made of PVC with aluminum sheet (reflectivity 52%), linear Fresnel lens made of PVC, which refractive index is 1.545	Real	The profiled Fresnel collector provided a relatively uniform illuminance ratio between 0.5 and 0.6 (South-facing with light pipe)
[115], 2014	C	Dielectric Compound Parabolic Concentrator (dCPC)	The dCPC made of normal acrylic material with refraction index of 1.5 and has the transmissivity is 90% (measured for 8 mm thickness)	Real/ Simulation	The non-coated dCPC rod had the highest transmittance of about 80%
[116], 2013	C	Optical brick collecting module (Two-layer static collecting structure), RI-to-IR light guide, coupler and central unit	For optical simulation software, used BK7 (refractive index is 1.51872 at 546.1 nm) to define the two types of materials in the static collecting modules, and coating of the 45° mirror at 95% reflectance	Simulation	The efficiency of the nine-stack circular collecting module reached 33%, and the square module reached 48%
[118], 2010	C	New Luminescent Solar Concentrators (LSC) consists of totally 150 pieces of luminescent fibers	The material for these luminescent fibers is acrylic with quantum dots, and the fibers have a refractive index of 1.49 and a light transmission rate of 93%	Real	Radiation flux ratios with a mean value of 5.7%, the luminous flux up to 114.1 lumens, and the light efficiency of 0.56% have been achieved during the trial run

Type*: Classify light collection element (C) and light transmission element (T).

5. Conclusions and Outlook

The daylighting system brings people daylight illumination, and is a commercial daylighting system that has been developed for more than 40 years. The welfare of daylight for humans well-established. Therefore, how we can use daylight more effectively is of great importance.

Current daylighting systems are divided into four parts: commercialized, demonstrated, prototyped and theoretical [5]. Many daylighting activities were developed in 2000 and began with a prototype static light guide system. By guiding the daylight into the indoor space, people can use the daylight spectrum. However, with the advancement of components such as computer, motor and sensors, many static daylighting systems have gradually turned to dynamic systems, and this change brings about a significant increase in daylight efficiency and continuity. The research activities of the prototype daylighting system are also gradually increasing. These daylighting activities lead the whole research field of daylighting.

Through the review of various prototype daylighting systems, it can be seen that the prototype is still struggling with the balance between cost and efficiency. While pursuing the daylight factor and quality in each daylighting system, it sacrifices the basic value of lighting of human society. The problem of huge cost or low versatility makes daylighting expensive and inconvenient than electrical lighting.

As described in this article, the daylighting system has different daylight performances and applications according to geographical locations, times and building forms. However, after the evaluations in Section 3, it is undeniable that TDGS's ratio daylighting performance/cost is higher than others, even higher than the active daylighting system and hybrid system. Therefore, we conducted an investigation, according to the form of building and geographical location; the results are as follows:

- TDGS has the advantages of being low-cost, having high color rendering, and high daylight quality in general residential buildings (Bungalow type). The TDGS is installed on the roof and the daylight supply is less than 10 m, which works best with TDGS's own advantages.
- The low-cost and flexible property of optical fiber in the deep-building type is regarded. If applied to complex buildings and transmission distances within tens of meters, then these conditions are suitable for active prototype daylighting systems with optical fiber that reduce the barriers to building daylighting.
- Different times and geographical environments lead to different levels of daylight and energy requirements. Therefore, the hybrid with daylighting and artificial lighting has been developed.
- The solar is a periodically celestial body that we can predict effective the solar radiation. Therefore, we can plan an effective daylighting strategy.
- Although climatic conditions are difficult to predict, we still have the basis of weather predict methods such as Typical Meteorological Year (TMY) [119].

The above conditions determine the application range and rule of prototype daylighting systems. However, Type I and other tubular devices are suitable for tropical areas than more direct solar radiation. Type III, which is based on active concentrator, is suitable for various geographical locations and environments, but cost is a consideration. Finally, hybrid prototype daylighting systems such Type II and IV are suitable for utilizing in public areas in a variety of geographical and climatic conditions.

In the future, more prototype daylighting work should begin and systems should be developed that consume less energy and have a short pay-back period.

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Nomenclature

μ	The average of the complex scores
N	Score quantity of each type
x_i	Order of the sort in each type
σ	The standard deviation of the complex score

References

- Coventry, J.; Andraka, C. Dish systems for CSP. *Sol. Energy* **2017**, *152*, 140–170. [[CrossRef](#)]
- Alrubaih, M.S.; Zain, M.F.M.; Alghoul, M.A.; Ibrahim, N.L.N.; Shameri, M.A.; Elayeb, O. Research and development on aspects of daylighting fundamentals. *Renew. Sustain. Energy Rev.* **2013**, *21*, 494–505. [[CrossRef](#)]
- Wong, I.L. A review of daylighting design and implementation in buildings. *Renew. Sustain. Energy Rev.* **2017**, *74*, 959–968. [[CrossRef](#)]
- Nair, M.G.; Ramamurthy, K.; Ganesan, A.R. Classification of indoor daylight enhancement systems. *Light. Res. Technol.* **2014**, *46*, 245–267. [[CrossRef](#)]
- Mayhoub, M.S. Innovative daylighting systems' challenges: A critical study. *Energy Build.* **2014**, *80*, 394–405. [[CrossRef](#)]
- Zeng, Q.; Dellenbaugh, T.; Maldonado, M.; Moon, J.; Hornstra, R. Vitamin D status of psychiatric inpatients at a community teaching hospital in the Midwest. *Nord. J. Psychiatr.* **2016**, *70*, 208–214. [[CrossRef](#)] [[PubMed](#)]
- Holick, M.F. Vitamin D: Importance in the prevention of cancers, type 1 diabetes, heart disease, and osteoporosis. *Am. J. Clin. Nutr.* **2004**, *79*, 362–371. [[CrossRef](#)]
- Holick, M.F. Sunlight and vitamin D for bone health and prevention of autoimmune diseases, cancers, and cardiovascular disease. *Am. J. Clin. Nutr.* **2004**, *80*, 1678S–1688S. [[CrossRef](#)]
- Reichrath, J. Skin cancer prevention and UV-protection: How to avoid vitamin D-deficiency? *Br. J. Dermatol.* **2009**, *161*, 54–60. [[CrossRef](#)]
- Courret, G.; Scartezzini, J.-L.; Francioli, D.; Meyer, J.-J. Design and assessment of an anidolic light-duct. *Energy Build.* **1998**, *28*, 79–99. [[CrossRef](#)]
- Baldwin, S.; Bindewald, G.; Brown, A.; Chen, C.; Cheung, K.; Clark, C.; Cresko, J.; Crozat, M.; Daniels, J.; Edmonds, J. *Quadrennial Technology Review: An Assessment of Energy Technologies and Research Opportunities*; Technical Report; US Department of Energy: Washington DC, USA, 2015.
- Yun, G.; Yoon, K.C.; Kim, K.S. The influence of shading control strategies on the visual comfort and energy demand of office buildings. *Energy Build.* **2014**, *84*, 70–85. [[CrossRef](#)]
- Mardaljevic, J.; Heschong, L.; Lee, E. Daylight metrics and energy savings. *Light. Res. Technol.* **2009**, *41*, 261–283. [[CrossRef](#)]
- Atif, M.R.; Love, J.A.; Littlefair, P. *Daylighting Monitoring Protocols & Procedures for Buildings*; National Research Council Canada: Ottawa, ON, Canada, 1997.
- Mayhoub, M. Guidelines for daylight guidance systems application. In Proceedings of the 28th International PLEA Conference on Sustainable Architecture + Urban Design: Opportunities, Limits and Needs—Towards an Environmentally Responsible Architecture, PLEA, Lima, Peru, 7–9 November 2012.
- Sharma, L.; Ali, S.F.; Rakshit, D. Performance evaluation of a top lighting light-pipe in buildings and estimating energy saving potential. *Energy Build.* **2018**, *179*, 57–72. [[CrossRef](#)]
- Al Marwae, M.; Carter, D.J. A field study of tubular daylight guidance installations. *Light. Res. Technol.* **2006**, *38*, 241–258. [[CrossRef](#)]
- Malet-Damour, B.; Guichard, S.; Bigot, D.; Boyer, H. Study of tubular daylight guide systems in buildings: Experimentation, modelling and validation. *Energy Build.* **2016**, *129*, 308–321. [[CrossRef](#)]
- Carter, D.J. The measured and predicted performance of passive solar light pipe systems. *Light. Res. Technol.* **2002**, *34*, 39–51. [[CrossRef](#)]
- Jenkins, D.; Muneer, T. Modelling light-pipe performances—A natural daylighting solution. *Build. Environ.* **2003**, *38*, 965–972. [[CrossRef](#)]
- Canziani, R.; Peron, R.; Rossi, G. Daylight and energy performances of a new type of light pipe. *Energy Build.* **2004**, *36*, 1163–1176. [[CrossRef](#)]
- Mohelnikova, J. Tubular light guide evaluation. *Build. Environ.* **2009**, *44*, 2193–2200. [[CrossRef](#)]

23. Yun, G.Y.; Shin, H.Y.; Kim, J.T. Monitoring and Evaluation of a Light-pipe System used in Korea. *Indoor Built Environ.* **2010**, *19*, 129–136. [[CrossRef](#)]
24. Li, D.H.W.; Tsang, E.K.W.; Cheung, K.L.; Tam, C.O. An analysis of light-pipe system via full-scale measurements. *Appl. Energy* **2010**, *87*, 799–805. [[CrossRef](#)]
25. Ekren, N.; Gorgulu, S. An investigation into the usability of straight light-pipes in Istanbul. *Energy Educ. Sci. Technol. Part A* **2012**, *30*, 637–644.
26. Wang, S.X.; Zhao, J.P.; Wang, L.X. Research on energy saving analysis of tubular daylight devices. *Energy Procedia* **2015**, *78*, 1781–1786.
27. Kennedy, D.M.; O'Rourke, F. Experimental analysis of a scaled, multi-aperture, light-pipe, daylighting system. *Sol. Energy* **2015**, *122*, 181–190. [[CrossRef](#)]
28. Garcia-Hansen, V.; Edmonds, I. Methods for the illumination of multilevel buildings with vertical light pipes. *Sol. Energy* **2015**, *117*, 74–88. [[CrossRef](#)]
29. Vasilakopoulou, K.; Synnefa, A.; Kolokotsa, D.; Karlessi, T.; Santamouris, M. Performance prediction and design optimisation of an integrated light pipe and artificial lighting system. *Int. J. Sustain. Energy* **2016**, *35*, 675–685. [[CrossRef](#)]
30. Mushtaha, E.; Kana'an, B.A.; Al-Jawazneh, R.A.; Hammad, R.S. Effect of using different light pipe parameters on the daylight quality in buildings: The case of Jordan. *Int. J. Green Energy* **2016**, *13*, 1590–1598. [[CrossRef](#)]
31. Vasilakopoulou, K.; Kolokotsa, D.; Santamouris, M.; Kousis, I.; Asproulias, H.; Giannarakis, I. Analysis of the experimental performance of light pipes. *Energy Build.* **2017**, *151*, 242–249. [[CrossRef](#)]
32. Allil, R.C.; Manchego, A.; Allil, A.; Rodrigues, I.; Werneck, A.; Diaz, G.C.; Dino, F.T.; Reyes, Y.; Werneck, M. Solar tracker development based on a POF bundle and Fresnel lens applied to environment illumination and microalgae cultivation. *Sol. Energy* **2018**, *174*, 648–659. [[CrossRef](#)]
33. Nair, M.G.; Ganesan, A.R.; Ramamurthy, K. Conceptual design and assessment of a profiled Fresnel lens daylight collector. *Light. Res. Technol.* **2015**, *47*, 533–547. [[CrossRef](#)]
34. Ullah, I.; Lv, H.; Whang, A.J.W.; Su, Y.H. Analysis of a novel design of uniformly illumination for Fresnel lens-based optical fiber daylighting system. *Energy Build.* **2017**, *154*, 19–29. [[CrossRef](#)]
35. Kim, Y.; Jeong, H.J.; Kim, W.; Chun, W.; Han, H.J.; Lim, S.H. A comparative performance analysis on daylighting for two different types of solar concentrators: Dish vs. Fresnel lens. *Energy* **2017**, *137*, 449–456. [[CrossRef](#)]
36. Barbon, A.; Sanchez-Rodriguez, J.A.; Bayon, L.; Barbon, N. Development of a fiber daylighting system based on a small scale linear Fresnel reflector: Theoretical elements. *Appl. Energy* **2018**, *212*, 733–745. [[CrossRef](#)]
37. Ullah, I.; Whang, A.J.W. Development of Optical Fiber-Based Daylighting System and Its Comparison. *Energies* **2015**, *8*, 7185–7201. [[CrossRef](#)]
38. Gorthala, R.; Tidd, M.; Lawless, S. Design and development of a faceted secondary concentrator for a fiber-optic hybrid solar lighting system. *Sol. Energy* **2017**, *157*, 629–640. [[CrossRef](#)]
39. Vu, N.H.; Shin, S. A Large Scale Daylighting System Based on a Stepped Thickness Waveguide. *Energies* **2016**, *9*, 71. [[CrossRef](#)]
40. Vu, N.H.; Pham, T.T.; Shin, S. Modified optical fiber daylighting system with sunlight transportation in free space. *Opt. Express* **2016**, *24*, A1528–A1545. [[CrossRef](#)]
41. Lingfors, D.; Volotinen, T. Illumination performance and energy saving of a solar fiber optic lighting system. *Opt. Express* **2013**, *21*, A642–A655. [[CrossRef](#)]
42. Song, J.; Jin, Z.; Zhu, Y.; Zhou, Z.; Yang, Y. Development of a fiber daylighting system based on the parallel mechanism and direct focus detection. *Sol. Energy* **2015**, *115*, 484–493. [[CrossRef](#)]
43. Tsangrassoulis, A.; Doulos, L.; Santamouris, M.; Fontoynt, M.; Maamari, F.; Wilson, M.; Jacobs, A.; Solomon, J.; Zimmerman, A.; Pohl, W.; et al. On the energy efficiency of a prototype hybrid daylighting system. *Sol. Energy* **2005**, *79*, 56–64. [[CrossRef](#)]
44. Li, L.; Wang, J.; Yang, Z.; Luo, G.; Tong, K.; Zhao, J.; Song, J. An optical fiber daylighting system with large Fresnel lens. *Energy Procedia* **2018**, *152*, 342–347. [[CrossRef](#)]
45. Barbon, A.; Sanchez-Rodriguez, J.A.; Bayon, L.; Bayon-Cueli, C. Cost estimation relationships of a small scale linear Fresnel reflector. *Renew. Energy* **2019**, *134*, 1273–1284. [[CrossRef](#)]
46. Pham, T.T.; Vu, N.H.; Shin, S. Daylighting system based on novel design of linear Fresnel lens. *Buildings* **2017**, *7*, 92. [[CrossRef](#)]

47. Ullah, I.; Shin, S. Highly concentrated optical fiber-based daylighting systems for multi-floor office buildings. *Energy Build.* **2014**, *72*, 246–261. [[CrossRef](#)]
48. Sapia, C. Daylighting in buildings: Developments of sunlight addressing by optical fiber. *Sol. Energy* **2013**, *89*, 113–121. [[CrossRef](#)]
49. Chong, K.K.; Onubogu, N.O.; Yew, T.K.; Wong, C.W.; Tan, W.C. Design and construction of active daylighting system using two-stage non-imaging solar concentrator. *Appl. Energy* **2017**, *207*, 45–60. [[CrossRef](#)]
50. Sedki, L.; Maaroufi, M. Design of parabolic solar daylighting systems based on fiber optic wires: A new heat filtering device. *Energy Build.* **2017**, *152*, 434–441. [[CrossRef](#)]
51. Tian, M.; Su, Y.H.; Zheng, H.F.; Pei, G.; Li, G.Q.; Riffat, S. A review on the recent research progress in the compound parabolic concentrator (CPC) for solar energy applications. *Renew. Sustain. Energy Rev.* **2018**, *82*, 1272–1296. [[CrossRef](#)]
52. Vu, N.H.; Shin, S. Cost-effective optical fiber daylighting system using modified compound parabolic concentrators. *Sol. Energy* **2016**, *136*, 145–152. [[CrossRef](#)]
53. Islam, M.T.; Huda, N.; Abdullah, A.B.; Saidur, R. A comprehensive review of state-of-the-art concentrating solar power (CSP) technologies: Current status and research trends. *Renew. Sustain. Energy Rev.* **2018**, *91*, 987–1018. [[CrossRef](#)]
54. Whang, A.J.W.; Chen, Y.Y.; Yang, S.H.; Pan, P.H.; Chou, K.H.; Lee, Y.C.; Lee, Z.Y.; Chen, C.A.; Chen, C.N. Natural light illumination system. *Appl. Optics* **2010**, *49*, 6789–6801. [[CrossRef](#)]
55. Kim, J.T.; Kim, G. Overview and new developments in optical daylighting systems for building a healthy indoor environment. *Build. Environ.* **2010**, *45*, 256–269. [[CrossRef](#)]
56. Kontadakis, A.; Tsangrassoulis, A.; Doulos, L.; Topalis, F. An active sunlight redirection system for daylight enhancement beyond the perimeter zone. *Build. Environ.* **2017**, *113*, 267–279. [[CrossRef](#)]
57. Dogan, T.; Stec, P. Prototyping a facade-mounted, dynamic, dual-axis daylight redirection system. *Light. Res. Technol.* **2018**, *50*, 583–595. [[CrossRef](#)]
58. Peña-García, A.; Gil-Martín, L.M.; Hernández-Montes, E. Use of sunlight in road tunnels: An approach to the improvement of light-pipes' efficacy through heliostats. *Tunn. Undergr. Space Technol.* **2016**, *60*, 135–140. [[CrossRef](#)]
59. Oh, S.J.; Dutton, S.; Selkowitz, S.; Han, H.J. Application of a coelostat daylighting system for energy savings and enhancement of indoor illumination: A case study under clear-sky conditions. *Energy Build.* **2017**, *156*, 173–186. [[CrossRef](#)]
60. Koo, K.W.; Kim, T.J.; Kim, Y.; Ryu, B.J. Solar tracking performance using a heliostat and uniform irradiation of LED light for a plant factory. *Trans. Korean Inst. Electric. Eng.* **2015**, *64*, 1761–1767. [[CrossRef](#)]
61. Smith, B.J.; Phillips, G.M.; Sweeney, M. Chapter 9—Daylighting. In *Environmental Science*; Routledge: London, UK, 2014.
62. Reinhart, C.F.; Mardaljevic, J.; Rogers, Z. Dynamic daylight performance metrics for sustainable building design. *Leukos* **2006**, *3*, 7–31. [[CrossRef](#)]
63. Nabil, A.; Mardaljevic, J. Useful daylight illuminances: A replacement for daylight factors. *Energy Build.* **2006**, *38*, 905–913. [[CrossRef](#)]
64. Nabil, A.; Mardaljevic, J. Useful daylight illuminance: A new paradigm for assessing daylight in buildings. *Light. Res. Technol.* **2005**, *37*, 41–57. [[CrossRef](#)]
65. Hebert, M.; Martin, S.K.; Lee, C.; Eastman, C.I. The effects of prior light history on the suppression of melatonin by light in humans. *J. Pineal Res.* **2002**, *33*, 198–203. [[CrossRef](#)] [[PubMed](#)]
66. Van der Rhee, H.J.; de Vries, E.; Coebergh, J.W. Regular sun exposure benefits health. *Med. Hypotheses* **2016**, *97*, 34–37. [[CrossRef](#)] [[PubMed](#)]
67. Leslie, R.P. Capturing the daylight dividend in buildings: Why and how? *Build. Environ.* **2003**, *38*, 381–385. [[CrossRef](#)]
68. Kechichian, E.; Ezzedine, K. Vitamin D and the Skin: An Update for Dermatologists. *Am. J. Clin. Dermatol.* **2018**, *19*, 223–235. [[CrossRef](#)] [[PubMed](#)]
69. Valles, X.; Alonso, M.H.; Lopez-Caleya, J.F.; Diez-Obrero, V.; Dierssen-Sotos, T.; Lope, V.; Molina-Barcelo, A.; Chirlaque, M.D.; Jimenez-Moleon, J.J.; Tardon, G.F.; et al. Colorectal cancer, sun exposure and dietary vitamin D and calcium intake in the MCC-Spain study. *Environ. Int.* **2018**, *121*, 428–434. [[CrossRef](#)]
70. Boubekri, M. Chapter 4—Natural light and health. In *Daylighting, Architecture and Health*; Boubekri, M., Ed.; Architectural Press: Oxford, UK, 2008; pp. 63–85. [[CrossRef](#)]

71. Stengel, F. Homeostasis in Topical Photoprotection: Getting the Spectral Balance Right. *Am. J. Clin. Dermatol.* **2018**, *19*, 40–44. [CrossRef] [PubMed]
72. Lindqvist, P.G.; Landin-Olsson, M. The relationship between sun exposure and all-cause mortality. *Photochem. Photobiol. Sci.* **2017**, *16*, 354–361. [CrossRef]
73. Veleva, B.I.; van Bezooijen, R.L.; Chel, V.G.M.; Numans, M.E.; Caljouw, M.A.A. Effect of ultraviolet light on mood, depressive disorders and well-being. *Photodermatol. Photoimmunol. Photomed.* **2018**, *34*, 288–297. [CrossRef]
74. Küller, R.; Ballal, S.; Laike, T.; Mikellides, B.; Tonello, G.J.E. The impact of light and colour on psychological mood: A cross-cultural study of indoor work environments. *Ergonomics* **2006**, *49*, 1496–1507. [CrossRef]
75. Pierson, C.; Wienold, J.; Bodart, M. Review of Factors Influencing Discomfort Glare Perception from Daylight. *Leukos* **2018**, *14*, 111–148. [CrossRef]
76. Azhar, S.; Carlton, W.A.; Olsen, D.; Ahmad, I. Building information modeling for sustainable design and LEED® rating analysis. *Autom. Construct.* **2011**, *20*, 217–224. [CrossRef]
77. Sibley, M. Let There Be Light! Investigating Vernacular Daylighting in Moroccan Heritage Hammams for Rehabilitation, Benchmarking and Energy Saving. *Sustainability* **2018**, *10*, 3984. [CrossRef]
78. Al-Sallal, K.A.; AbouElhamd, A.R.; Bin Dalmouk, M. UAE heritage buildings converted into museums: Evaluation of daylighting effectiveness and potential risks on artifacts and visual comfort. *Energy Build.* **2018**, *176*, 333–359. [CrossRef]
79. Alawadhi, E.M. Double solar screens for window to control sunlight in Kuwait. *Build. Environ.* **2018**, *144*, 392–401. [CrossRef]
80. Calama-Gonzalez, C.M.; Leon-Rodriguez, A.L.; Suarez, R. Daylighting and Energy Performance Evaluation of an Egg-Crate Device for Hospital Building Retrofitting in a Mediterranean Climate. *Sustainability* **2018**, *10*, 2714. [CrossRef]
81. Al-Obaidi, K.M.; Rahman, A.M.A. Toplighting systems for improving indoor environment: A review. In *Renewable Energy and Sustainable Technologies for Building and Environmental Applications*; Springer: Berlin, Germany, 2016; pp. 117–136.
82. Mayhoub, M.S.; Carter, D.J.; Chung, T.M. Towards hybrid lighting systems: A review. *Light. Res. Technol.* **2010**, *42*, 51–71. [CrossRef]
83. Mayhoub, M. Cleaning innovative daylighting systems: Review and suggested methods. *Light. Res. Technol.* **2017**, *49*, 1015–1033. [CrossRef]
84. TORRESOL ENERGY INVESTMENTS, S.A. Available online: <http://torresolenergy.com/en/gemasolar/> (accessed on 24 April 2019).
85. Ikuzwe, A.; Sebitosi, A.B. A novel design of a daylighting system for a classroom in rural South Africa. *Sol. Energy* **2015**, *114*, 349–355. [CrossRef]
86. Scartezzini, J.L.; Courret, G. Anidolic daylighting systems. *Sol. Energy* **2002**, *73*, 123–135. [CrossRef]
87. Vázquez-Moliní, D.; González-Montes, M.; Fernández-Balbuena, A.Á.; Bernabéu, E.; García-Botella, Á.; García-Rodríguez, L.; Pohl, W. ADASY (Active Daylighting System). In *Proceedings of the Optical Modeling and Measurements for Solar Energy Systems III*, San Diego, CA, USA, 20 August 2009; p. 74100H.
88. Vázquez-Moliní, D.; González-Montes, M.; Álvarez Fernández-Balbuena, A.; García-Botella, Á.; Pohl, W.; Galan, T.; Bernabéu, E. Horizontal daylighting system for office buildings. *Energy Build.* **2013**, *67*, 525–530. [CrossRef]
89. Whitehead, L.; Upward, A.; Friedel, P.; Cox, G.; Mossman, M. Using core sunlighting to improve illumination quality and increase energy efficiency of commercial buildings. In *Proceedings of the ASME 2010 4th International Conference on Energy Sustainability*, Phoenix, AR, USA, 17–22 May 2010; pp. 309–316.
90. Carter, D. LRT Digest 2 Tubular daylight guidance systems. *Light. Res. Technol.* **2014**, *46*, 369–387. [CrossRef]
91. Al-Marwae, M.; Carter, D. Tubular guidance systems for daylight: Achieved and predicted installation performances. *Appl. Energy* **2006**, *83*, 774–788. [CrossRef]
92. Ciugudeanu, C.; Beu, D. Passive Tubular Daylight Guidance System Survey. *Procedia Technol.* **2016**, *22*, 690–696. [CrossRef]
93. Patil, K.N.; Kaushik, S.C.; Garg, S.N. Performance Prediction and Assessment of Energy Conservation Potential for a Light Pipe System in Indian Composite Climate of New Delhi. *J. Sol. Energy Eng. Transact.* **2018**, *140*, 9. [CrossRef]

94. Ji, S.M.; Cao, G.Y.; Zhang, J.H.; Yu, F.N.; Li, D.S.; Yu, J.J. Lighting design of underground parking with tubular daylighting devices and LEDs. *Optik* **2016**, *127*, 1213–1216. [[CrossRef](#)]
95. Yu, X.; Su, Y. Daylight availability assessment and its potential energy saving estimation—A literature review. *Renew. Sustain. Energy Rev.* **2015**, *52*, 494–503. [[CrossRef](#)]
96. Roshan, M.; Barau, A.S. Assessing Anidolic Daylighting System for efficient daylight in open plan office in the tropics. *J. Build. Eng.* **2016**, *8*, 58–69. [[CrossRef](#)]
97. Hafez, A.Z.; Yousef, A.M.; Harag, N.M. Solar tracking systems: Technologies and trackers drive types—A review. *Renew. Sustain. Energy Rev.* **2018**, *91*, 754–782. [[CrossRef](#)]
98. Chen, Y.; Kribus, A.; Lim, B.; Lim, C.; Chong, K.; Karni, J.; Buck, R.; Pfahl, A.; Bligh, T.J. Comparison of two sun tracking methods in the application of a heliostat field. *J. Sol. Energy Eng.* **2004**, *126*, 638–644. [[CrossRef](#)]
99. Song, J.F.; Luo, G.; Li, L.; Tong, K.; Yang, Y.P.; Zhao, J. Application of heliostat in interior sunlight illumination for large buildings. *Renew. Energy* **2018**, *121*, 19–27. [[CrossRef](#)]
100. Li, X.; Wei, Y.; Zhang, J.; Jin, P. Design and analysis of an active daylight harvesting system for building. *Renew. Energy* **2019**. [[CrossRef](#)]
101. Song, J.; Zhu, Y.; Jin, Z.; Yang, Y. Daylighting system via fibers based on two-stage sun-tracking model. *Sol. Energy* **2014**, *108*, 331–339. [[CrossRef](#)]
102. Xue, X.; Zheng, H.; Su, Y.; Kang, H. Study of a novel sunlight concentrating and optical fibre guiding system. *Sol. Energy* **2011**, *85*, 1364–1370. [[CrossRef](#)]
103. Han, H.J.; Riffat, S.B.; Lim, S.H.; Oh, S.J. Fiber optic solar lighting: Functional competitiveness and potential. *Sol. Energy* **2013**, *94*, 86–101. [[CrossRef](#)]
104. Song, D.F.; Lv, H.; Liao, J.; Huang, W.J.; Huang, S.H.; Cheng, C.F.; Zhou, H.L.; Su, Y.H.; Riffat, S. Evaluation of a large dish-type concentrator solar lighting system for underground car park. *Int. J. Energy Res.* **2018**, *42*, 2234–2245. [[CrossRef](#)]
105. Chen, B.J.; Chen, Y.T.; Ullah, I.; Chou, C.H.; Chan, K.C.; Lai, Y.L.; Lin, C.M.; Chang, C.M.; Whang, A.J.W. Innovative light collimator with afocal lens and total internal reflection lens for daylighting system. *Appl. Optics* **2015**, *54*, E165–E170. [[CrossRef](#)] [[PubMed](#)]
106. Al-Obaidi, K.M.; Munaaim, M.A.C.; Ismail, M.A.; Rahman, A.M.A. Designing an integrated daylighting system for deep-plan spaces in Malaysian low-rise buildings. *Sol. Energy* **2017**, *149*, 85–101. [[CrossRef](#)]
107. Obianuju, O.N.; Chong, K.-K. High Acceptance Angle Optical Fiber Based Daylighting System Using Two-stage Reflective Non-imaging Dish Concentrator. *Energy Procedia* **2017**, *105*, 498–504. [[CrossRef](#)]
108. Lv, Y.; Xia, L.; Yan, J.; Bi, J. Design of a Hybrid Fiber Optic Daylighting and PV Solar Lighting System. *Energy Procedia* **2018**, *145*, 586–591. [[CrossRef](#)]
109. Song, J.; Zhu, Y.; Tong, K.; Yang, Y.; Reyes-Belmonte, M.A. A note on the optic characteristics of daylighting system via PMMA fibers. *Sol. Energy* **2016**, *136*, 32–34. [[CrossRef](#)]
110. Schlegel, G.O.; Burkholder, F.W.; Klein, S.A.; Beckman, W.A.; Wood, B.D.; Muhs, J.D. Analysis of a full spectrum hybrid lighting system. *Sol. Energy* **2004**, *76*, 359–368. [[CrossRef](#)]
111. Sudarsan, V. 8—Optical Materials: Fundamentals and Applications. In *Functional Materials*; Banerjee, S., Tyagi, A.K., Eds.; Elsevier: London, UK, 2012; pp. 285–322. [[CrossRef](#)]
112. Zhu, L.; Shao, Z.B.; Sun, Y.; Soebarto, V.; Gao, F.; Zillante, G.; Zuo, J. Indoor daylight distribution in a room with integrated dynamic solar concentrating facade. *Energy Build.* **2018**, *158*, 1–13. [[CrossRef](#)]
113. Zhao, Z.J.; Ong, J.R.; Chu, H.S. Optimization of wide-angle planar micro-optic solar concentrator systems for deployment in tropics. *J. Photon. Energy* **2018**, *8*, 12. [[CrossRef](#)]
114. Aslian, A.; Asli, B.H.S.; Tan, C.J.; Adikan, F.R.; Toloei, A. Design and Analysis of an Optical Coupler for Concentrated Solar Light Using Optical Fibers in Residential Buildings. *Int. J. Photoenergy* **2016**. [[CrossRef](#)]
115. Yu, X.; Su, Y.; Zheng, H.; Riffat, S. A study on use of miniature dielectric compound parabolic concentrator (dCPC) for daylighting control application. *Build. Environ.* **2014**, *74*, 75–85. [[CrossRef](#)]
116. Tsai, M.C.; Whang, A.J.W.; Lee, T.X. Design of a high-efficiency collection structure for daylight illumination applications. *Appl. Opt.* **2013**, *52*, 8789–8794. [[CrossRef](#)] [[PubMed](#)]
117. Werring, C.G. *Design and Application of Fiber Optic Daylighting Systems*; Kansas State University: Manhattan, KS, USA, 2009.

118. Wang, C.; Abdul-Rahman, H.; Rao, S.P. A new design of luminescent solar concentrator and its trial run. *Int. J. Energy Res.* **2010**, *34*, 1372–1385. [[CrossRef](#)]
119. Wang, J.; Wei, M.; Chen, L. Does typical weather data allow accurate predictions of daylight quality and daylight-responsive control system performance. *Energy Build.* **2019**, *184*, 72–87. [[CrossRef](#)]



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