A Review of the Evolution of Daylighting Applications and Systems Over Time for Green Buildings

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Abstract—The continuous increase in the world's population and the fact that humans spend most of their day in indoor environments has increased the demand for energy. The rational consumption of electricity, especially lighting and its provision in buildings using various strategies, has become an important topic on the minds of many researchers and developers. In recent years, with the increasing the awareness of sustainable development due to economic and social conditions, daylight is seen as an effective way to save the energy, reduce significant pressures on existing energy infrastructure and reduce the environmental impact. The use of daylight in buildings by different sunlight applications/systems, whether traditional or innovative, is more than just an alternative or supplement to electric lighting, as it has many benefits in terms of economic, environmental, and health. Traditional applications are divided into three strategies: general, improving, and developing. The interior spaces of multi-story buildings (i.e., taller and deeper) are often not illuminated by natural light during the daytime, due to the distance from these spaces to the nearest traditional general application through which daylight must enter. Innovative Daylighting Systems (IDS) or remote source systems have been developed to transmit daylight into the building core (i.e., inaccessible places or rooms) and windowless areas or parts so they can be called Structure Core Daylighting Systems (SCDS). Eighteen SCDS/IDS were reviewed and discussed in the form of a comparison between them in terms of their components, historical progress, installation locations, and a brief description. The study focused on the systems that had already been commercialized or at least produced a large-scale prototype that had been installed in a real structure over the past five decades. Although SCDS/IDS are technically powerful enough to provide illumination for remote spaces, there are some important shortcomings that have hampered or prevented their widespread use, such as the extremely high-cost, efficiency for some of them, utilization difficulties, and application limitations. In addition, the equilibrium between the cost of their components and their performance efficiency is one of the great fundamental decisions that an engineer designing for these systems must make. Finally, the paper presents the latest design approaches that have been developed to overcome their identified shortcomings.

Keywords—Structure Core Daylighting Systems, Sunlighting collection, Sunlighting guide, Sunlighting transport, Sunlighting distribution, Tubular Daylighting Guidance System.

Abbreviations

ADASY	Active Daylighting System
HSL	Hybrid Solar Lighting
HVAC	Heating, Ventilation, and Air Conditioning
IDS	Innovative Daylighting Systems
IEA	International Energy Agency
NIR	Near Infrared
OECD	Organization Economic Cooperation and Development
ORNL	Oak Ridge National Lab
SCDS	Structure Core Daylighting Systems
SLP	Solar Light Pipe
TDGS	Tubular Daylighting Guidance System
UFO	Universal Fiber Optic
UV	Ultraviolet

1. INTRODUCTION

Rapid growth of the world's population and related social and economic activities represent an issue pressing on the sector of energy worldwide, especially in the electricity production. During the period from 1974 until 2017, a great jump in the world production of electricity has achieved as it increased from 6,298 TWh to 25,721 TWh, with an average annual growth rate of 3.3% as shown in Fig. (1-A). Most of the world's electricity production (about 64.5%) is generated from burning fossil fuels (oil, natural gas, and coal) (Fig. 1-B) which has led to a significant increase in fossil fuel consumption [1]. The increasing consumption of fossil fuels is a serious issue of concern worldwide, due to the dire consequences for the global economy and environment. In addition to declining international reserves of fossil fuels and consequently increasing energy prices and the growing need for alternative energy resources, threats to the global ecosystem are growing as the world has faced severe environmental impacts of increasing global warming due to increased emissions of greenhouse gases, depletion of the ozone layer, air pollution, acid rain, and so on [2-4].

Most people spend about 90% of their time in indoor environments which has resulted in increased demand for electricity in residential and commercial sectors to meet building services such as HVAC and lighting systems [5]. Lighting is one of the major sources of electricity consumption in these sectors as it accounts for about 19% of the world's total electricity consumption; about 74% is consumed in residential and commercial sectors, 18% in industrial sector, and the remaining 8% is consumed in outdoor applications such as traffic lights, parking lots, street poles, and so on [6-7].

Within the framework of sustainable development strategies, many countries are working to reduce the consumption of fossil fuels, which has led to the emergence of new technologies in the world of lighting to reduce the consumption of traditional electricity generated from fossil fuels. Some of these new lighting technologies rely on renewable energy especially solar energy [8-11].

2. RENEWABLE ENERGY BASED LIGHTING STRATEGY

Recently, different lighting strategies have emerged to replace the traditional ones for electric energy saving. These strategies can be applied either separately or combined together in different types of buildings to save the electricity. Some of these strategies are based on new energy-efficient artificial lighting technologies such as LEDs, rare earth fluorescent lamps, occupancy sensors, high-frequency electronic ballasts, etc. [12-13]. Others rely on natural daylight that is obtained from the largest source of light on Earth "the Sun". In such strategies the natural daylight is introduced to the space to be illuminated by different daylighting systems / applications, whether traditional or innovative.

Daylight is the visible portion of the solar spectrum and can be defined as a combination of direct sunlight and diffused light from the sky [14]. Manning [15] defined daylighting as any method by which natural light is brought into a space to replace or supplement artificial lighting. Its intensity and quality vary based on geographic latitude, year season, day in season, time of day, local weather, sky conditions, and building geometry [16].

3. IMPACTS OF DAYLIGHTING

Daylighting has many economic, environmental, and health benefits side that cannot be gained from artificial lighting [17-27]. As a result of introducing natural light into US buildings, energy demand could be reduced by 24 GW, as reported by McHugh et al. [28]. Moreover, another study by Muhs [29] indicated that the cooling requirements of the lit place can be reduced by up to 15%. This indicates that an energy saving of 10 to 40 % can be achieved, according to the used daylighting strategy, [30-32]. As a result of the energy saving achieved by the different daylighting strategy, 680.39 g carbon dioxide, 5.67 g of sulfur dioxide, and 2.27 g of nitrogen oxide per kWh of saved energy can be reduced. In 2010 a reduction of 223 million tons of CO_2 emissions could be achieved due to the use of different daylight applications [33-34].

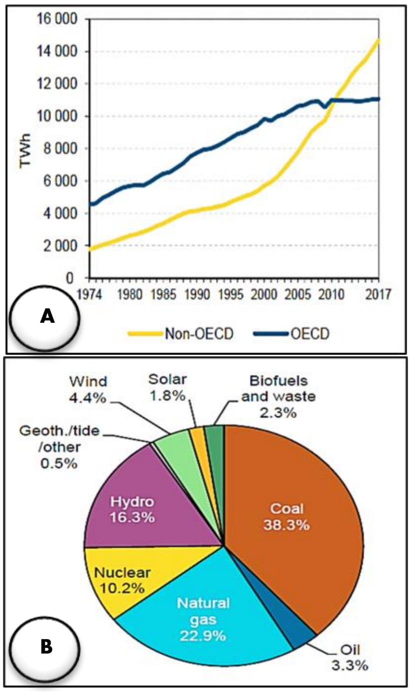

Fig. 1. *(**A**) Total electricity production for non-OECD and OECD countries until 2017 according to the International Energy Agency (IEA); (**B**) World gross electricity production by source in 2017 [1].*

The applications of daylighting strategies can also maintain the occupants of interiors in a good health [35]. The replacement of artificial light with natural light can improve the psychological well-being [36-39]. It can enhance the productivity by 15%, and reduce the absenteeism by 15% [40-41]. Also, it was reported that the students enrolled in day-lighted schools had better exam results (14% higher marks), as well as higher attendance rates than those in un-daylighted schools [42-44]. A technical report issued by the California Energy Authority in 2003 depicted that increasing the use of daylighting can improve the ability of workers to recall and mentally reflect a series of numbers by a significant figure of 13% [45]. In addition, it has been proven that there is a relationship between daytime lighting and an increase in the percentage of sales to retail stores, which can reach 40% [46]. On the physical side, natural light can improve vitamin D, visual system, and sleep quality, reduce the possibility of cancer and abnormal bone formation. in addition to being able to make the brain produce serotonin hormone (responsible for relieving pain, providing energy and making us feel happy) and melatonin hormone (responsible for regulating the body's internal clock or circadian rhythm) [47-48].

4. TRADITIONAL DAYLIGHTING APPLICATIONS

Several methods and applications have been utilized to bring daylight into the place to be illuminated. It is mainly can be divided into three categories; general, improving, and developing (Fig. 2) [49]. There are two types of general daylighting applications; side lighting and top lighting, as shown in Fig. 3 [50-53]. The first, which is the most common, is just an open window. The second is an opening in the ceiling or roof element of the building. The most common applications for overhead lighting are skylight, roof monitor, and saw-tooth. The general techniques have been modified and developed for the effective control of direct sunlight and its distribution so that more lighting can be sent to the back of the room. In addition, the problems caused by daylighting (such as heat gain, glare, etc.) were also reduced and the uniformity of light within the lit space was improved. The installation of "general applications" may be inapplicable in some cases such as interior rooms within taller and deeper buildings, as they distribute flux principally up to 6 m from the wall of a conventional application causing glare, high contrast, and excessive brightness, leaving the remainder of the perimeter zone and the core lacking sufficient light [54], and thus rely entirely on electrical energy for lighting.

Based on what was previously mentioned, there was a need to resort to "innovative daylighting systems" that could direct daylight into the interior spaces/core of the built environment (such as modern buildings, underground spaces, tunnels, deep staircases, etc. [55-59]) in a more controlled manner and increased uniformity, resulting in higher energy savings and more comfortable visual environment [60-65].

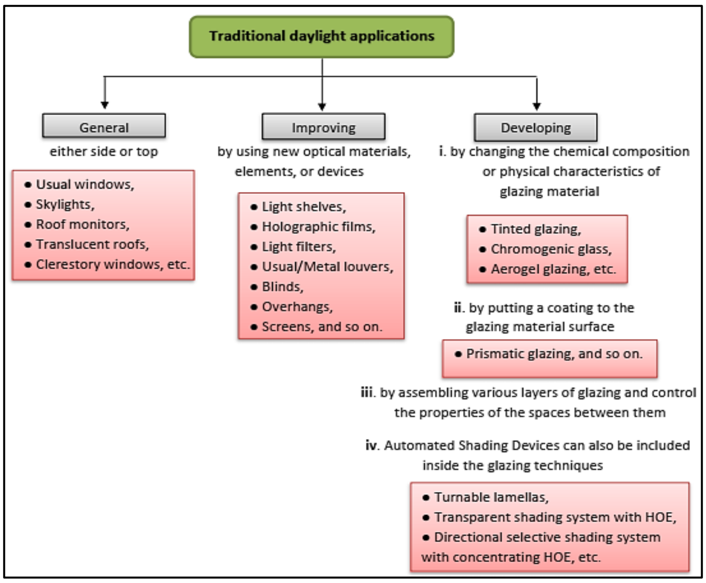

Fig. 2. *Flow chart clarifies the division of traditional applications.*

5. INNOVATIVE DAYLIGHTING SYSTEMS

Innovative Daylighting Systems (IDS) are used to carry daylight into the core of a building (i.e., inaccessible places or rooms) and windowless areas where daylight cannot be delivered via the traditional methods. Therefore, they can be called Structure Core Daylighting Systems (SCDS).

A SCDS/IDS system often consists of three parts grouped together to collect, transmit and distribute daylight with the possibility of combining two parts of them into one. A passive (without sun tracking) or active (with sun tracking) collector is placed at the top of the system structure or linked to the structure facade. The collector is usually made of pure optical materials, mirrors, or lenses that are used to collect direct daylight and/or a diffuse skylight. The collected daylight is then transmitted through a light guide (pipe or duct), fiber optics (glass or plastic), or scatters through the air via vertical voids e.g., atrium using lenses and mirrors to adjust the direction and divergence of the ray. Then, inside the construction core or served space, the light is diffused by using the distribution devices which use extra optical elements [66-67].

Several SCDS/IDS systems have been developed using a variety of technologies and solutions along the past decades encompassing a wide range of applications. Some of the SCDS/IDS systems have already been commercialized or at least large-scale prototypes have been installed in a real structure.

The development of different types of SCDS/IDS systems are presented in chronological order in the following subsections. At the end of this section, the construction, historic advance, and current market situation of these systems are summarized in (Fig. 8) and (Table 1).

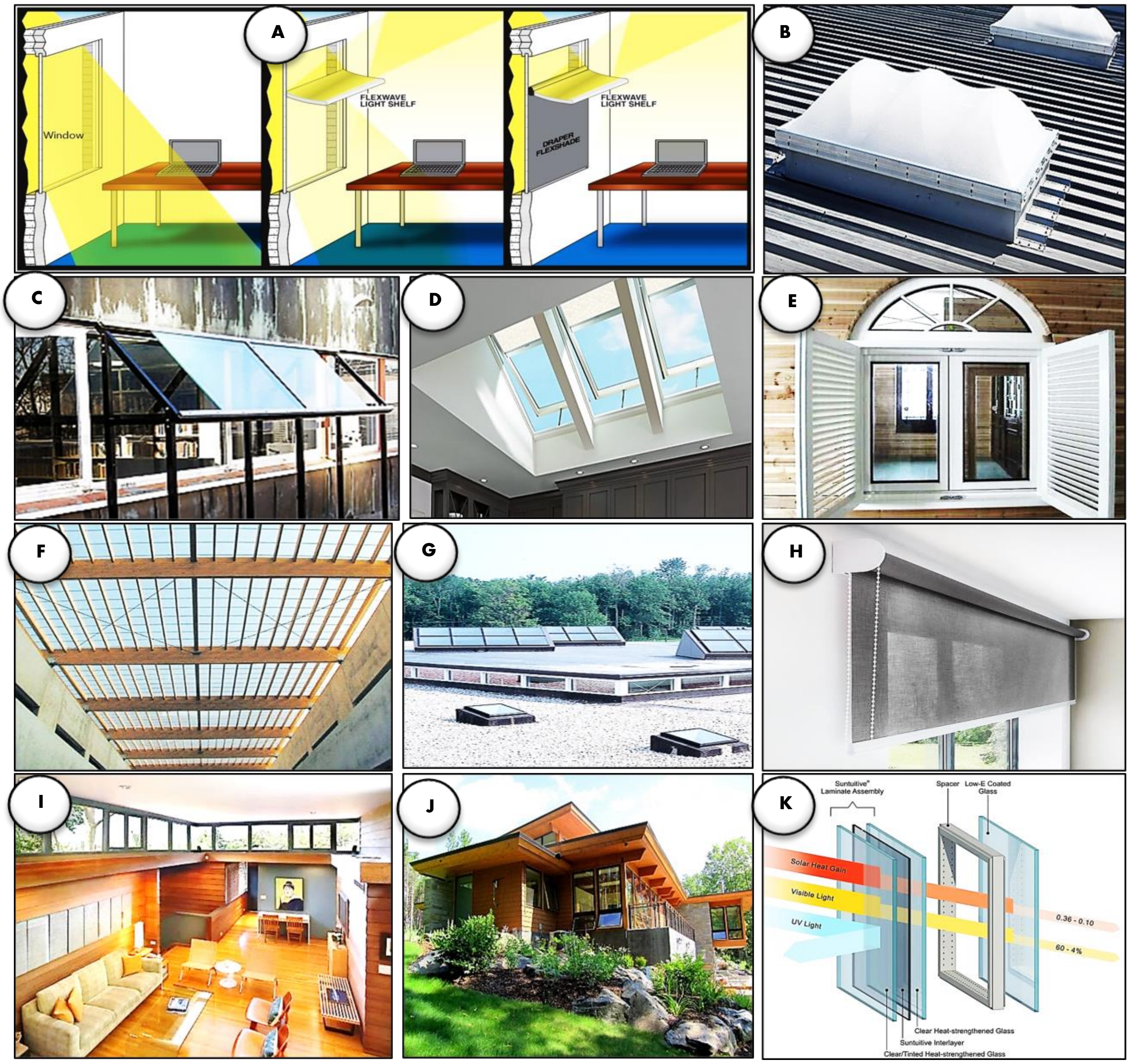

Fig. 3. *Some of traditional daylighting applications/methods; (**A**) Window and light shelf, (**B**) Prismatic glazing, (**C**) Holographic films, (**D**) Skylight, (**E**) Metal louver, (**F**) Translucent roof, (**G**) Roof monitor, (**H**) Roller blind, (**I**) Clerestory window, (**J**) overhangs, and (**K**) Assembling glazing [50-53].*

5.1. Heliostat System

The term "Heliostat" was mentioned for the first time in the textbook of the Dutch physicist William Jacob s'Gravesande in 1742 [68]. He coined the word from the Greek words for “sun” and “stationary”. Heliostat can be considered a specially designed system that contains very different components and shapes [69]. As shown in Fig. (4-A), the sunlight is passively or actively collected by using a collection of mirrors and/or lenses that transmit light through vertical and/or horizontal voids into the center of a building or the space to be lit. An additional set of optical components, such as a chandelier system or prism openings, can be used to scatter daylight and to provide special influences. Heliostat systems are used for various purposes and have recently been used for lighting buildings [70]. in 1974, the first commercial prototype of Heliostat system for lighting purpose was established at the Hyatt Regency Hotel in Chicago, where 3 large Heliostats were used to light the hotel lobby [71].

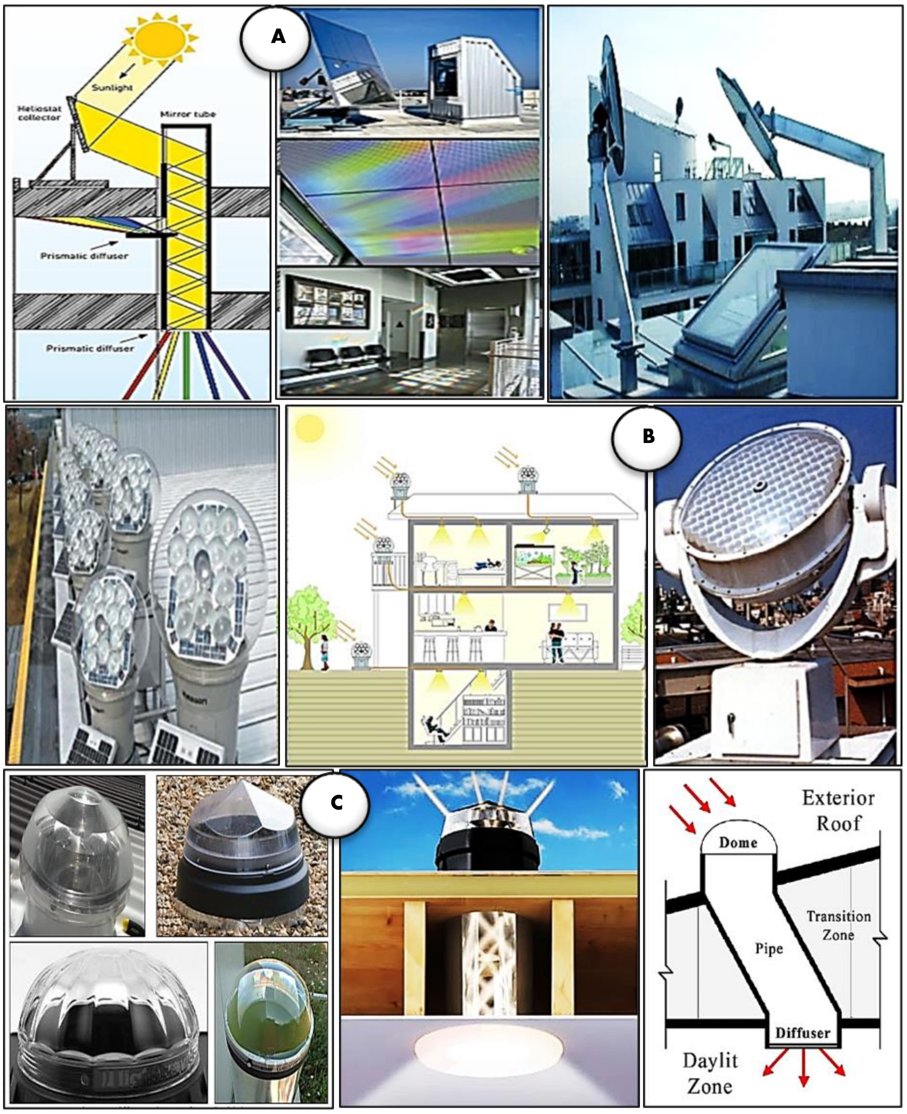

Fig. 4. *Schematic and picture representation of; (**A**) Heliostat, (**B**) Himawari, and (**C**) TDGS system [69-76].*

5.2. Himawari System

Himawari daylighting system; Fig. (4-B) was developed in Japan in the late 1970s by Professor Kei Mori. It was named after the Japanese word for sunflower. The first commercial prototype was issued in 1978 by the Japanese 'Himawari' daylighting system company. It is believed to be the first commercial fiber optic daylighting system. Over the following twenty years, a lot of models have been developed [72]. A picture and schematic representation of Himawari daylighting system is shown in Fig. (4-B). Using multiple tracking Fresnel lenses, the sunlight is collected and concentrated on the inlet end of the quartz glass optical fiber that transports the light. Then, using a range of custom-designed luminaire-like elements, light is distributed [72-74]. The acrylic dome covering the lenses is used to screen out 'ultraviolet' rays and hence, it does not damage fibers.

5.3. TDGS System

The TDGS (Tubular Daylighting Guidance System); Fig. (4-C) was invented in Australia in 1986 and installed in 1987. The first product was put on the market in 1991 [75]. 4 years later, this technology spread in the United Kingdom (U.K.) under the name “Sunpipe” [76]. As shown in Fig. (4-C), the daylight is passively collected by a clear dome installed at the upper end of a light guide lined with a highly reflective material. The daylight transmitted by the light guide is spread throughout the space to be lit by a diffuser fixed at the lower end of the guide [77]. Several attempts have been made to improve the efficiency of the system, such as the use of Fresnel lenses, the use of light tracking devices, the consolidation of additional electric lighting devices, or the integration with ventilation components [75-76]. Some products have a Bohemia crystal glass dome rather than the commonly used plastic domes to improve the system performance [78]. Reflective mesh devices or sun-tracking mirrors are included in other products [79-80].

5.4. Anidolic Ceiling System

In 1996 and via the "Solar Energy and Building Physics Laboratory (LESO-PB)" at the EPFL campus, Switzerland, the first prototype of the “Anidolic Ceiling” was designed, installed, and tested experimentally. The device has been demonstrated in several locations and has been taken into account in two projects in the architectural design phase, but it does not appear to be really implemented [81-83]. This system depends on a non-imaging optics device fixed along the window as shown in Fig. (5-A). A built-in light duct installed in the ceiling reflects and transports the diffused natural light to the back of the building [63,84,85].

5.5. Heliobus System

Heliobus, the Swiss manufacturing firm founded in 1999 has developed several solutions for daylighting systems over 20 years. A Heliobus light-pipe system is one of their own solutions offering commercially on demand. Therefore, there have been a few installations of Heliobus light-pipe systems on the market. Heliobus light-pipe system is a hybrid system for lighting and the first installation was composed of an optimized form fixed heliostat. On the other hand, the other installations use sun-tracking heliostats. The Heliobus light-pipe system only works with direct sunlight. As shown in Fig. (5-B), the sunlight is deflected into a hollow prismatic light pipe by means of a mirror that tracks the sun (heliostat), and transported over many meters to where it is needed [86-87]. It is one of the most costly SCDS, and no wonder then that the ideology of the manufacturer finds the "Heliobus light-pipes very sophisticated objects and built for images and PR reasons, more than for daylight illuminations. It's like a sort of daylight art [74,88]."

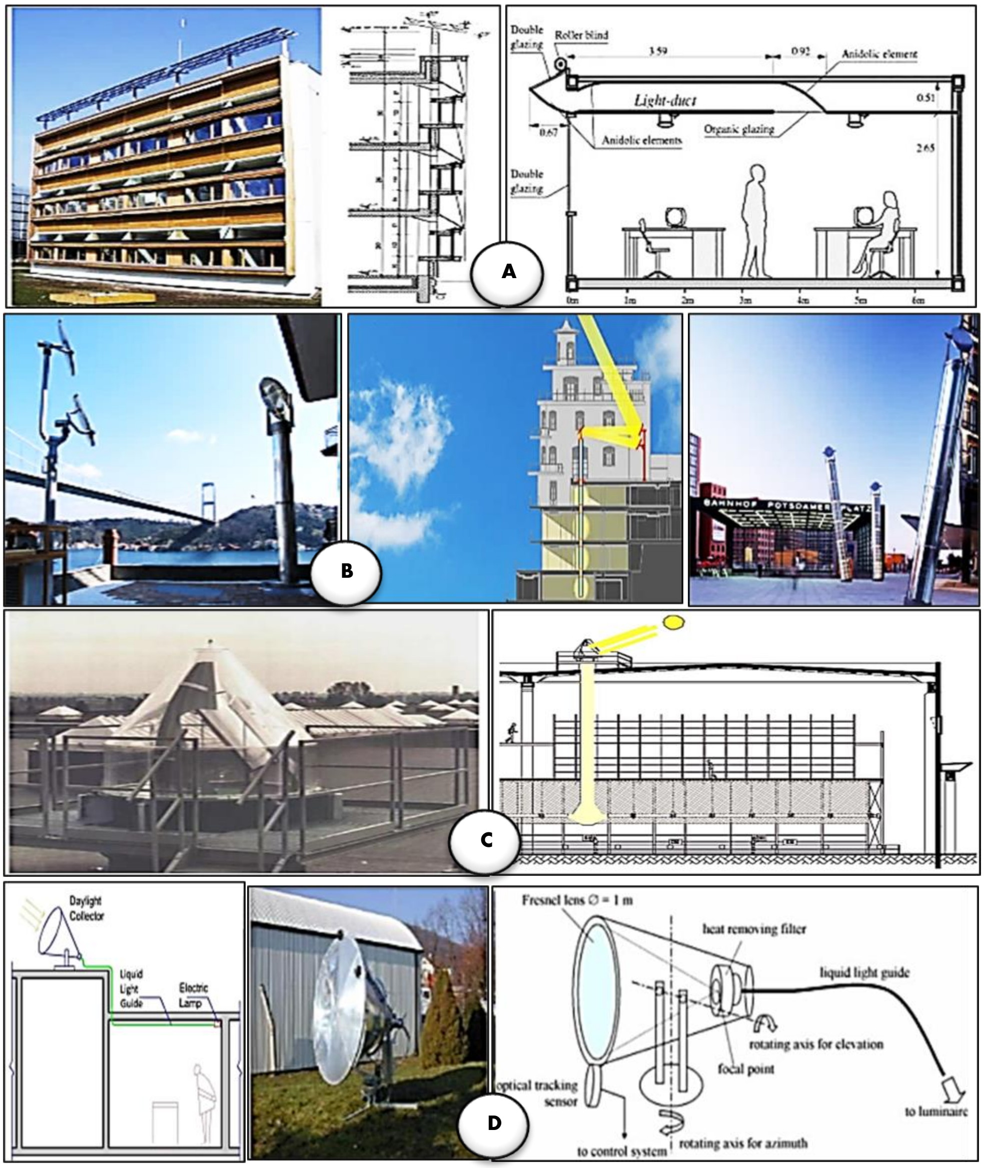

Fig. 5. *Picture and schematic representation of; (**A**) Anidolic Ceiling, (**B**) Heliobus, (**C**) Arthelio, and (**D**) Solux daylighting system [63,84-93].*

5.6. Arthelio System

From 1998 to 2001, the European Commission funded the "Arthelio" project to create a hybrid lighting system combining daylight and electric light from sulfur lamps. Only two prototypes were installed; one in Carpiano, Italy, and the other in Berlin, Germany [89-90]. As shown in Fig. (5-C), the heliostat of this system concentrates the light rays. Then, the light guide/pipe lined with prismatic material transports and distributes this light [91].

5.7. Solux System

In 2001, six prototypes of the 'Solux' daylighting system were mounted by a German company "Bomin Solar Research (BSR)" on the roof of the Berlin Museum of Technology [69]. The literature does not list any other installations from then to the present day. As shown in Fig. (5-D), it is a hybrid device consisting of a large Fresnel lens sun-tracking that focuses and filters sun rays onto the aperture of a guide of liquid light. To illuminate the construction entrance, the light from the guide is released into a diffusing tube that spreads the light in the construction [92-93].

5.8. HSL System

In 1999, Oak Ridge National Lab. (ORNL) developed a conceptual design for the American 'Hybrid Solar Lighting, (HSL)' system [29]. The first installation on the field was in June 2002. Since then, nearly a hundred demonstration cases have been installed throughout the continental United States and Hawaii [94]. The second generation had been developed by 2004. The first market version was created by an ORNL spin-off firm, and beta systems were installed in more than eighty locations prior to returning the product to ORNL after a small number of years, all in 2006 [95]. This technology uses optical fibers and modified conventional luminaires to disperse sunlight within a building's interior. It uses a primary parabolic mirror to receive sunlight and concentrates it towards the secondary elliptical mirror as shown in Fig. (6-A). The secondary mirror is made of borosilicate, which has the ability to filter out the reflected radiation against harmful Ultraviolet and IR. The secondary mirror then focuses light at its focal point, where a fiber optic receiver collects sunlight and transmits it to the other end of the fiber through internal reflection [74,96,97]. While several attempts were made to solve serious issues with reliability, the developers lastly pursued another approach to design. The new configuration consists of a series of small Fresnel lenses [95].

5.9. SLP System

In 2001, a German company developed a special daylighting system called Solar Light Pipe (SLP), shown in Fig. (6-B). The only product was installed in an office building, in Washington DC (USA) [98]. 'SLP' is a hybrid lighting device that distributes sunlight along the 14-story building. It consists of a heliostat and a specially designed light tube. Therefore, it is one of the largest solar lighting fixtures on Earth. The designers of the system were not asked to construct an economic solution, but to design an aspect involving the people working in the building as they looked out into the dim, dreary atrium where the 'SLP' was built [98-100].

5.10. Sunflowers System

The collaborative 'Sunflowers' project was begun in 2001. Within this project, nine sunflower daylighting systems have been successfully installed in the Florence Stibbert Museum in Italy, to illuminate several showcases [101]. As shown in Fig. (6-C), each system comprises eight spherical lenses incorporating a solar collector, each of which is linked to an optical fiber bundle. The concentrated light can either be utilized for direct illumination or turned into electrical power for lighting [101].

5.11. UFO System

A prototype of the 'Universal Fiber Optic (UFO)' device was presented at the University of Athens during the summer of 2002 [102]. The device was the result of a multinational development under the Energy Program that was partly funded by the European Commission. It is a hybrid lighting system as shown in Fig. (6-D). It consists of a sun tracking Fresnel lens that focuses sun rays on the aperture of a liquid light guide. In turn, it delivers light to the output unit, which is a flat Perspex panel that has been specially made [102-103].

5.12. Parans System

According to the manufacturer's publications, several devices have been mounted in about thirty locations worldwide [104]. This system was developed in collaboration with the Chalmers University of Technology in Gothenburg, Sweden in 2003, and in 2004 the Swedish device became commercial. In the first two generations, the solar collector is a fixed square enclosure in which a set of small Fresnel lenses are installed. The enclosure is active and rectangular in the third generation. In the fourth generation, the enclosure is standard active linear. In the first two generations, each lens monitors the sunlight and concentrates it into the end of an optical fiber package. The entire solar panel, meanwhile, tracks the sunlight in both the third and fourth generations, as shown in Fig. (6-E) [105-107]. Moreover, each lens is coupled with a reflecting filter which filters out harmful UV and Infrared radiation which results in a reduction of heat. The light obtained by this system is beneficial for health and it also creates a relaxed atmosphere.

5.13. Sun/Solar (Canopy, Central, and Beamer) Systems

Solar Canopy Illuminance System was presented for the first time in 2003 as a new efficient tubular daylighting system for multi-floor buildings [108]. In 2005, the first demonstration device was installed [109-110]. Thereafter many demonstration cases of the 'Canadian-Solar-Canopy-Illuminance-System' (SCIS) have been installed in North America since 2010. In 2008, a Canadian company was launched as a spin-off of the University of British Columbia, where the system was developed. By then, the device called ‘Core Sunlighting System’ and numerous prototypes had been mounted in existing buildings [111]. The 'Canadian new system' was announced commercially in 2013 and the company already made drastic improvements to the 'Core System' components in 2014 to decrease the size of the system and to improve its performance. ‘Sun Central system’ is the brand name for the new product [112]. At the California lighting technology center, a prototype was tested in 2014. They concluded that the system is not commercially feasible, but there are still other demonstrations on operation [113]. The 'Sunbeamer system' is another product produced by the same company. For the 'Solar Canopy Illuminance System', the collector is a canopy running horizontally over the windows and includes a series of lenses and mirrors that monitor and focus sunlight (see Fig. (6-F)). Then, the light is deflected into a prismatic dual-function light guide operating above the interior of the structure [114-115]. The 'SunCentral system' contains redirectors for sunlight which is installed on the brink of the building at the ceiling level, as shown in Fig. (6-G). It tracks and redirects the sun rays towards a concentrator mounted on the building façades at the floor level. The concentrated light is then diverted to light guides to be distributed throughout the building [116]. The 'Sunbeamer system' – shown in Fig. (6-H) - uses the sunlight redirector solely via an atrium or skylight to project controlled sunlight. To achieve various effects or to deliver light to remote areas, different types of separate diffusers and reflectors can be integrated.

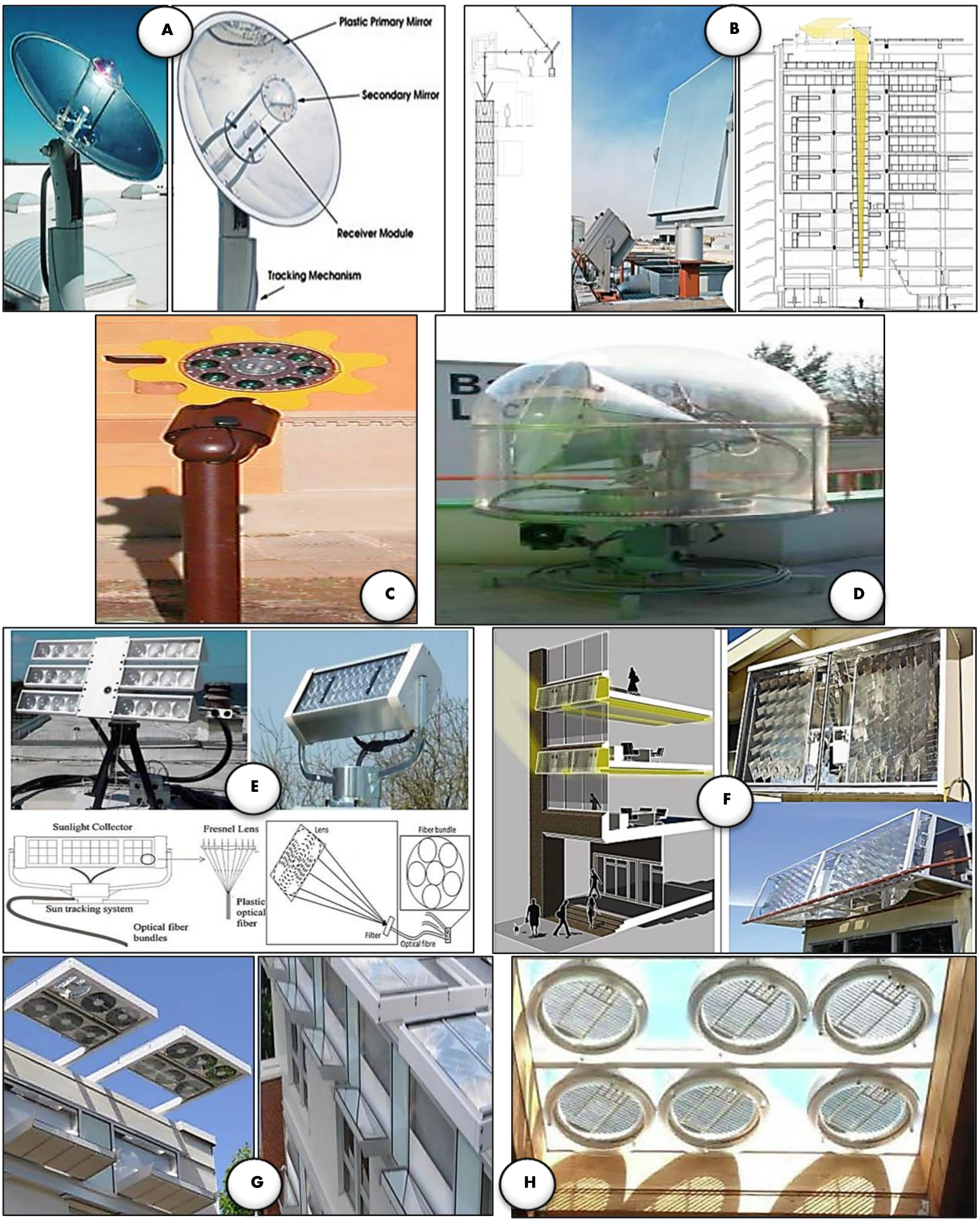

Fig. 6. *(**A**) HSL, (**B**) SLP, (**C**) Sunflowers, (**D**) UFO, (**E**) Parans (4^{th} & 3^{rd}) generation, (**F**) Solar Canopy, (**G**) SunCentral, and (**H**) Sunbeamer systems light collector [96-116].*

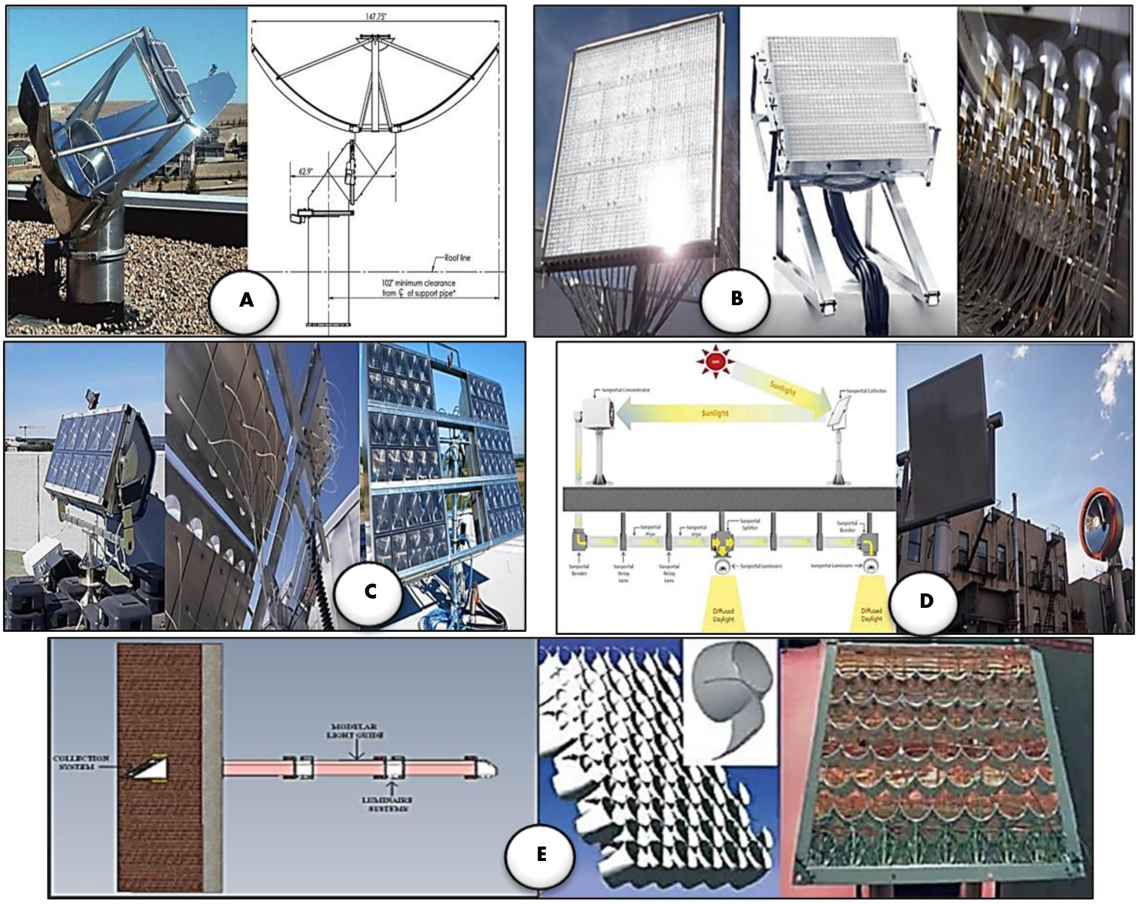

Fig. 7. *(**A**) Sundolier, (**B**) Sollektor (2nd & 3rd) generation, (**C**) Echy, (**D**) Sunportal, and (**E**) ADASY systems light collector [108,118-129].*

5.14. Sundolier System

Sundolier is an American company that specializes in the manufacture of daylighting systems. The company was established in 2004 and since then it has succeeded in installing many of its products for daylighting systems throughout the United States and many other countries [117-118]. Sundolier daylighting system aims to provide natural light on a larger scale than traditional skylights and without the drawbacks of high energy costs or heat issues. The system consists of specially shaped metal mirror tracks and focuses actively sunlight onto a 600 mm-diameter roof opening. By a Custom-made chandelier, daylight is distributed to large areas, and it is linked either immediately to the solar-collector or via light-pipe, as shown in Fig. (7-A) [108].

5.15. Sollektor System

The Sollektor daylighting system is a hybrid lighting system developed at the Polymer Optical Fiber Application Center in Nuernberg, Germany. The system was commercially produced in 2010 by a German company. By the end of June 2017, the producing company announced that it had halted production of the system due to high production costs in Germany, [119]. As shown in Fig. (7-B), the Sollektor daylighting system consists of a sun tracking system that contains a plastic injection-molded concentrator optic arrangement, and a polymeric optical-fiber-bundle that directs and transmits the collected sunlight. To spread the channeled light, a custom-designed hybrid luminaire was used. The solar collector of the 1st generation contains 600 lenses. The 2nd generation consists of 4 panels with 224 lenses each; connected to 8 fiber bundles. One square solar collector was used in the 3rd version that contains 900 lenses [120-121].

5.16. Echy System

Echy system is a hybrid daylighting system that was initiated for the first time at Ecole Polytechnique in France, in 2010. Later, in 2012, the company was founded. At the end of 2013, the first version, named "ESCHYSSE", was lunched. The second version, named "ECHYNOXE", was lunched at the end of 2017. The system was installed in more than 20 locations in France until mid-2018, with plans to be sold internationally in 2019 [122]. Echy system consists of modular assemblies of small sunlight-collecting Fresnel lenses that are mounted on a tracker which follows the path of the sun (see Fig. (7-C)). After that, the concentrated light is transported by optical-quartz-fibers and then distributed by innovatively designs luminaires [123-124].

5.17. Sunportal System

The hybrid daylighting system, Sunportal system has been produced by a South Korean company founded in 2011. The system was initiated after 5 years of research and development and after establishing three successful large commercial pilot projects in South Korea [125]. It had become commercially available since 2012. In addition to a demonstration site in Lowline Park in the

USA, the few installations available exist in industrial and public spaces (e.g., underground tunnels, etc.) in South Korea [88,126]. As shown in Fig. (7-D) the system comprises a Heliostat with a unique parabolic dish to actively collect and concentrate sun rays and transport them through side-emitting light-pipes connected to a series of special optical relay lenses [127].

5.18. ADASY System

In 2012, the first prototype of the 'Active Daylighting System' (ADASY) was built in an office building in Spain. ADASY system was developed by University Complutense of Madrid and other Spanish partners in the context of the European EUREKA 3575 project led by the Lledó Group. Within this project the Lledó Group put some future plans to commercialize the ADASY product [128-129]. As shown in Fig. (7-E), the ADASY system comprises a light collection system consisting of a set of anidolic-optical components located outside the vertical facade of the building. The collection system collects sunlight and redirects it into a modular light guide that runs along the horizontal false ceiling and light extractor luminaires strategically positioned along the guide [128-130].

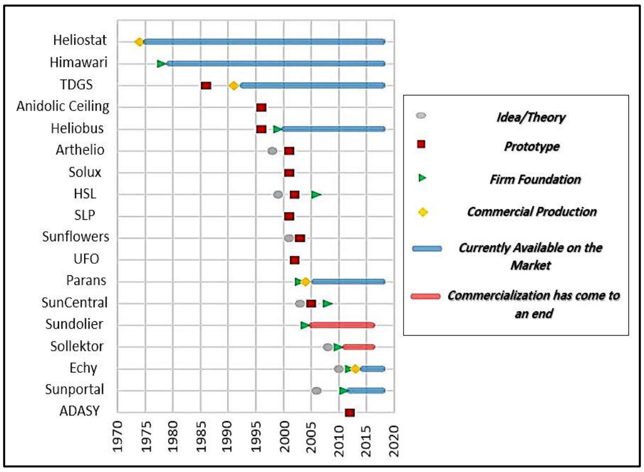

Fig. 8. Summary of the SCDS's historic advance and market situation till 2019.

Table 1. SCDS/IDS construction and current market situation.

Item / SCDS	Components			Market Situation
	1. Collection	2. Transport	3. Distribution	
Heliostat	Collection of active/static optical elements	Free spaces - Completing a collection of mirrors	No exit component	Commonly commercially provided
Himawari	Array of lenses for sun-tracking	Optical Fiber Bundle	Custom designed luminaire - like devices	Commercially provided; fundamentally in the Far East Asian market
TDGS	Transparent dome	Light tube	Various luminaire - such as diffusers	Widely/Most commercially available IDS
Anidolic Ceiling	Parabolic fixed concentrator	Light duct	End emitting light duct	Fully sophisticated - No commercial manufacturing
Heliobus	Sun-tracking Heliostat	Light-pipe	Side & end emitting light-pipe	Accessible commercially upon demand
Arthelio	Sun-tracking Heliostat	Light-pipe	Side & end emitting light-pipe	No market production - Fully developed
Solux	Fresnel lens sun-tracking	Liquid light guide	Side emitting light-pipe	Fully sophisticated - No commercial production
HSL (Original design)	Sun-tracking parabolic mirror	Bundle of optical fiber	Traditional luminaire combined with PMMA side-emitting rods	Issues with technical reliability
SLP	Sun-tracking Heliostat	Light-pipe	Side & end emitting light-pipe	There is only One Installation
Sunflowers	Group of sun-tracking lenses	Bundle of optical fiber	Not Available	Fully developed - No market production
UFO	Sun-tracking Fresnel lens	Liquid fiber optics	Custom designed hybrid luminaire	Fully sophisticated - No commercial manufacturing
Parans	Array of sun-tracking lenses	Optical Fiber Bundle	Custom designed luminaire - like devices	Fourth product generation; commercially available – Low sales volume
Solar Canopy	Sun-tracking mirrors	Light-pipe	Side emitting light-pipe	System development stopped
SunCentral		Free space & Light duct	Side emitting light duct	Fully developed - No commercial production
Sunbeamer		Free space	No output device	Commercially available – Low sales volume
Sundolier	Sun-tracking Heliostat	Ceiling opening or Light-pipe	Simple diffuser or custom designed chandelier	Because of high manufacturing costs, commercial production came to a halt
Sollektor	Array of sun-tracking lenses	Bundle of optical fiber	Custom designed hybrid luminaire	Commercial production stopped due to high manufacturing cost
Echy	Array of sun-tracking lenses	Bundle of optical fiber	Custom designed luminaire -like devices	Commercially available – Low sales volume
Sunportal	Sun-tracking parabolic mirror	Light-pipe	Side emitting light-pipe & end emitting diffusers	Commercially available upon request
ADASY	Parabolic static concentrators	Light duct	Apertures covered with flat glass	Fully developed - No commercial production

6. PREFERENCES AMONG STRUCTURE CORE DAYLIGHTING SYSTEMS

In this section, in Table (2) and Table (3), a comparison was made between the parts made up for SCDS/IDS in connection with the elements of collecting and distributing solar energy. Also, the systems were categorized and grouped depending on the proximity of the design and the method of collecting/distributing solar energy between them, which helps us to extract the mutual features of the SCDS/IDS, successful or failed.

Looking at Table (2), the SCDS/IDS solar collectors are classified from five perspectives. First; it is distinct using an unfocused dome that allows direct and diffused sunlight in addition to the diffuse skylight. Second; it is distinct using a group of large low or medium-concentration optical components. Third; it is distinct using an arrangement of small low/unfocused optical components. Barring the Anidolic-Ceiling which uses a single concentrator. Fourth; it is distinct using a large, highly concentrating optical component. Fifth; it is distinct using an array of small high-focused lenses.

Looking at Table (3), the SCDS/IDS solar carriers/distributors are classified from three perspectives: The first is the transmission of daylight through Free Spaces (Fig. 9, L), the second is through Light Tubes (Fig. 9, A-J), and the third is through Optical Fiber bundles (Fig.9, K). Since the Sundolier system has two different kinds, it was categorized under the first two approaches.

Table 2. *SCDS collection components.*

Item	SCDS	1. Type/shape	2. Formed material	3. Dimensions/Area	4. Motion/Inclination
Clear glazing without concentration	**TDGS**	• Spherical/Diamond dome ▪ Flat rectangle surface	• Plastic (e.g., Polycarbonate-Acrylic), or Glass ▪ Glass	• The most popular range from Ø0.23 m to Ø1.0 m ▪ Vary	• Static ▪ Static {Mostly horizontal, but perhaps inclined to face the sun, depending on the position of the site}
Group of large optical components with low/mid-concentration	**Heliostat**	• Various forms of; (Flat, concave, convex, circular, or rectangular) reflectors	• Different types	• Mostly range from 0.8 m^2 to 5.5 m^2	• Static/Active (i.e., dynamic) {Any angle between horizontal and vertical}
	Heliobus	• Mirror specially shaped ▪ Multiple mirrors circular/rectangular	• Aluminum plate with the specularly reflective material coating ▪ Not Available	• 2.25 m (H) × 1.0 m (Ø) ▪ Not Available	• Static ▪ Axial/Dual-axis tracking
	SLP	• Multiple mirror system	• Glass	• Not Available	• Axial tracking system
	Arthelio	• Mirror, set of Fresnel lenses, and specially designed reflectors	• Not Available	• Area of the primary mirror = 6.2 m^2	• Axial tracking system
	Sundolier	• Banana-shaped primary concave mirror paired with a secondary convex mirror	• Aluminum	• ~3.8-4.45 x ~0.3-0.6 m (~1.5–1.8 m^2)	• Bi-axial tracking {Inclined to face the sun according to the site location}
Arrangement of small low/unfocused optical components	**Solar Canopy**	• Rectangular structure contains a set of small flat mirrors and a collection of large parabolic mirrors	• Glass	• 3 m (H) × 1.3 m (W) × 0.8–1 m (D)	• Static structure & Dual-axis tracking mirrors
	SunCentral	• Rectangular enclosure houses (3) modules of array of mirror slats	• <u>Roof level part</u>: Laminated mirror • <u>Floor level part</u>: Aluminum mirror and tempered glass	• <u>Roof level part</u>: 1.58 x 0.52 × 0.15m • <u>Floor level part</u>: 1.58 x 0.6m	• Static enclosure, Bi-axial tracking mirrors {Horizontal} • Fixed {Almost horizontal}
	Sunbeamer	• Array of mirror slats	• Laminated float glass	• Ø 38–67 cm	• Dual-axis tracking
	Anidolic Ceiling	• Two-dimensional parabolic concentrator	• Anodized aluminum foil, glass	• ~0.7m × 0.7m × Window width	• Static
	ADASY	• Array of truncated compound parabolic concentrators covered with glass	• The concentrators treated by PVD metallization	• Not Available	• Static
A large, highly concentrating optical component	**Solux**	• Fresnel lens	• Not Available	• Ø 1 m	• Dual-axis tracking
	UFO	• Fresnel lens	• PMMA	• Ø 1 m	• Bi-axial tracking
	Sunportal	• <u>Collector</u>: flat, circular, or rectangular mirror ▪ <u>Concentrator</u>: parabolic mirror	• Not Available ▪ Not Available	• Ø 0.8 m or 1.5 × 1.5 m ▪ Ø 1 m	• Active {Any angle between horizontal and vertical} ▪ Static {Vertical}
	HSL (Original design)	• Parabolic primary mirror + secondary elliptical mirror	• Plastic + • Borosilicate	• Ø 1.1 m	• Dual-axis tracking
Array of small high-focused lenses	**Himawari**	• 12-198 Hexagonal honeycomb-patterned Fresnel lenses	• <u>Enclosure</u>: Acrylic dome • <u>Lenses</u>: Not Available	• From 0.52m × 0.81m to 2.35m × 2.5m • Lens Ø 95 mm	• Bi-axial tracking {Inclined to face the sun according to the site location}
	Parans	• Modular rectangular panel contains 4 or 8 Fresnel lenses; Tracker consists of 4 – 10 panels	• <u>Enclosure</u>: Tempered glass • <u>Lenses</u>: Not Available	• From 1.10m × 0.34m to 1.95m × 0.88m • Lens Ø 100 mm	• Dual-axis tracking {Oriented to look at the sun based on the site location}
	Echy	• Modular rectangular panel includes 10 Fresnel lenses; Tracker consists of 1 – 10 panels	• Not Available	• From 1.5m × 0.65m to 3.8m × 3.0m	• Bi-axial tracking
	Sollektor	• 800 Plastic injection molded concentrators	• Plastic	• ~0.5 × 0.5 m	• Dual-axis tracking
	Sunflower	• 8 Spherical compacted lenses	• PMMA with anti-reflection coating	• Ø ~ 0.275 m • Lens Ø 55 mm	• Dual-axis tracking

Table 3. *SCDS distribution/transport components.*

	Item / SCDS	1. Type	2. Material	3. Size
Free space	**Heliostat**	• Free space – Various supplementary distribution systems can be used	• Vary	• Vary
	Sunbeamer	• Free space	-	-
	Sundolier	• Ceiling opening	-	• Ø 60 cm
Light-pipe	**TDGS**	• Mostly circular light tube	• High reflective materials; mostly Aluminum	• The most common sizes range from Ø 20 cm to Ø 1 m
	Anidolic Ceiling	• Rectangular horizontal light duct	• Anodized aluminum foil	• 50 cm (H) ~ 4.5 m (D)
	ADASY	• Rectangular horizontal light duct, extractor within the duct	• High reflective material	• 57 cm (W) × 30 cm (H) × 5.79 m (D)
	Solar Canopy	• Dual function horizontal hollow light duct	• Prismatic film for bottom surface – High	• 60 cm (W) × 25 cm(H) × 10 m (D)
	SunCentral	• Dual function horizontal hollow light duct	• Prismatic film for bottom surface – High reflective material for the others	• 28 cm (W) × 1 m (H) × 15 m (D)
	Arthelio	• Dual function hollow light-pipe, foil extractor inside the pipe	• Inner surface lined with Prismatic film	• 12.5–20 m length Ø30 cm or less
	Heliobus	• Dual function hollow light-pipe	• PMMA lined with prismatic film • Glass	• 10 m length Up to 0.62 × 0.62 m • 14–24 m length Ø0.8–1 m
	SLP	• Double skin tapered light pipe	• Outer skin: Tensioned translucent Lycra fiber • Core: prismatic glass panels with optical film	• 36m length Ø1.75m at the top and Ø0.5m at the bottom
	Sunportal	• Hollow light-pipe contains relay lenses	• Acrylic	• Ø200mm - Up to 200 m long Ø100mm - Up to 30 m length
	Solux	• Hollow liquid light-pipe	• The pipe filled with an optical clear liquid	• 50 m length Ø2 cm
	UFO	• Liquid fiber optic	• Optical clear liquid	• 10 m length Ø20 mm
	Sundolier	• Hollow light-pipe	• Not Available	• Vertical: up to 75 m add horizontal: up to 18 m
Optical fiber	**Himawari**	• Optical fiber	• Highly pure quartz glass fibers	• Up to 50 m length Core size Ø1mm
	HSL (Original design)	• Optical fiber	• PMMA fibers	• 15 m length Core size Ø3 mm
	Parans	• Optical fiber	• Not Available	• Up to 100 m length
	Echy	• Optical fiber	• Quartz glass fibers	• Up to 160 m length Core size Ø1.5 mm
	Sollektor	• Optical fiber	• Polymer fibers	• Up to 40 m length Core size Ø0.75 mm
	Sunflower	• Optical fiber	• Plastic fibers	• 30 m length Core size Ø1.5 mm

As mentioned earlier, several SCDS/IDS systems have been installed. Most of such installations are for research purposes and in public and non-residential buildings. However, few of them have been commercially launched. There are many restrictions that hinder the widespread use of the SCDS/IDS daylighting systems, such as the extremely high-cost, low efficiency, utilization difficulties, and application restrictions.

Table (4) shows the efficiency and initial cost for different SCDS/IDS systems based on the available information published by the developers [54,131,132]. As shown in Table (4), the TDGS system has achieved the best efficiency comparing with other SCDS/IDS under the specified conditions, whereas its cost is much lower than other systems due to its formative simplicity. Knowing that these are the initial costs (i.e., they do not include the costs of delivery, installation, and taxes), noting that the greater the amount of daylight required from the innovative system, the higher the level of technology or system development required, and thus this will lead to an increase in the initial price. On the contrary, in the case of TDGS, the auxiliary devices that have been integrated into some versions to improve its performance did not significantly increase its cost compared to the rest of the innovative systems [91]. Importantly, it was evident from previous studies that TDGS achieved the largest electricity savings in nearly all different climatic regions (tropical, arid, temperate, and cold) - (average 55%), followed by Solar Canopy (39%), HSL (33%), and Parans (31%) [132]. Moreover, when the SLP or Heliobus is used for a distance of 30 m and in the case of overcast skies, the energy savings can reach up to 39%.

In absolute general terms, to determine the capabilities of SCDS/IDS for collecting daylight, it is necessary to know the operating conditions (geographical location, sky condition, measurement time, etc.) under which measurements can be made as well as collector size and collector distance from the measurement point. To give a rough idea of the amount of daylight collected and delivered by some innovative systems, as well as Table 4 (approximate ranges for efficiencies values), here are some of the following values which are examples cited from developers' publications. Depending on the number of lenses, the total luminous flux of the Himawari system ranges from 3,840 lm to 63,360 lm measured under direct sunlight of 98,000 lux [72]. Under clear sky conditions at mid-latitudes, the collecting capacity of the HSL system is up to 160,000 lm [96]. Sundolier system can hold 100,000 lm [118]. The Sunportal system delivers over 66,000 peak lumens [125]. Based on a center spacing of 1.5 m and 100,000 lux of reference input illumination, the SunCentral system provides a peak of 350 lux [112]. At 10 meters from the collector, the total output flux of the Parans system is approximately 4,600 lm, which was measured under direct sun illuminance of 130,000 lux [106].

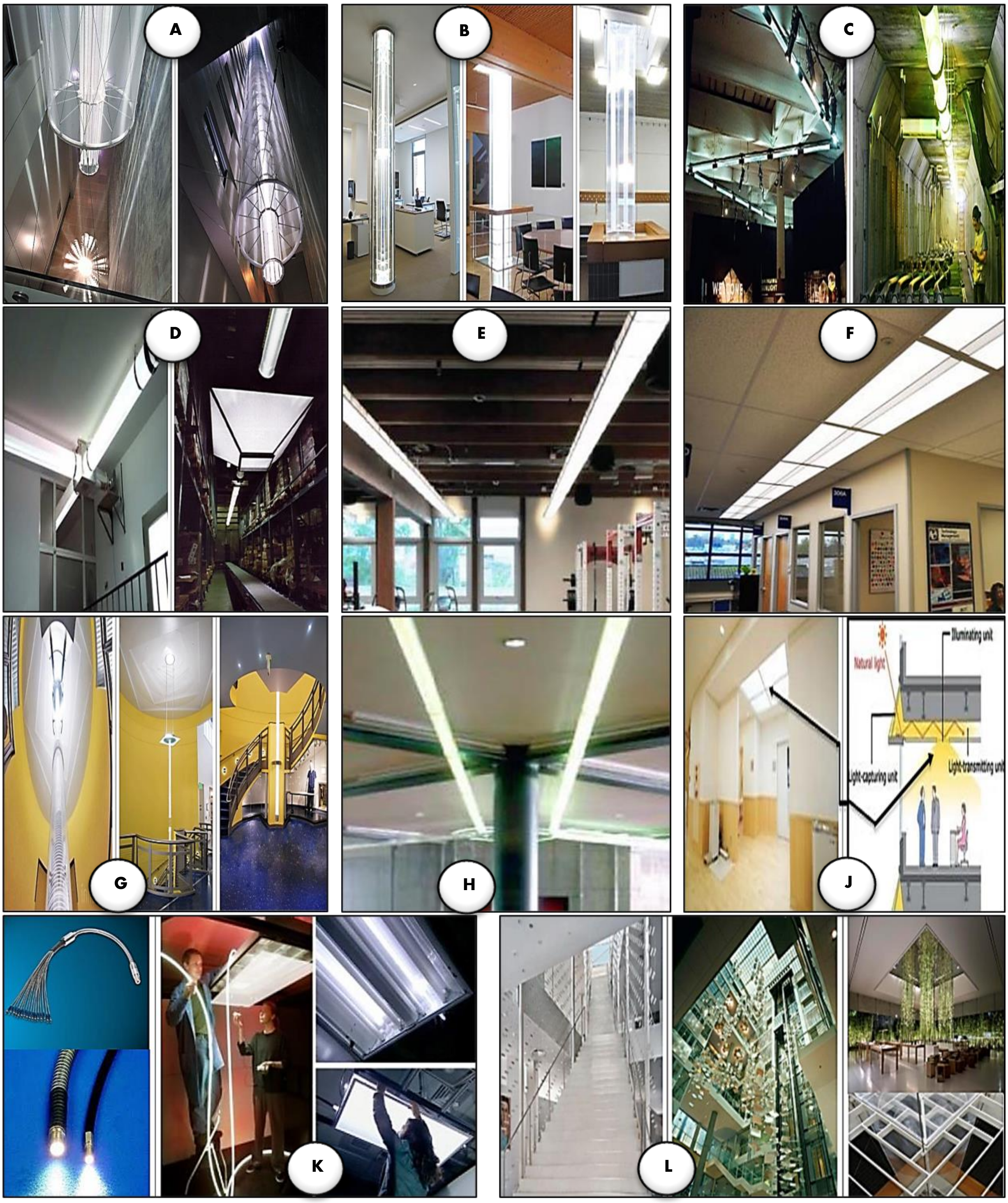

Fig. 9. *Various types of SCDS light distribution/transport devices;* ***A****: SLP light-pipe,* ***B****: Heliobus light-pipe,* ***C****: Sunportal light-pipe,* ***D****: Arthelio light-pipe,* ***E****: SunCentral light duct,* ***F****: Solar Canopy light duct,* ***G****: Sundolier light-pipe,* ***H****: Solux liquid light guide,* ***J****: Anidolic Ceiling/ADASY light duct,* ***K****: Fibre Optics Bundle/Cable, and* ***L****: Free space/vertical void [88,91,99,108,112,118,125-127].*

***Table 4.** Overall efficiency and initial price of some SCDS/IDS.*

IDS/SCDS	Sky condition	Efficiency	initial cost/price Details
Solux	Clear	5%, but (80-90%) after 10m length	-
UFO	Clear and overcast	3.4%	-
Himawari	Clear	23%	5,750 EUR [1] A small Himawari system package (includes 12-lens collector, two 5 m-optical fiber cables, two luminaires, and mount)
Solar Canopy	Clear and overcast	25%	-
Heliobus	Clear and overcast	20-30%	200,000 EUR The cost of the custom-made system is often estimated based on the case details, but starts from 200,000 EUR
Anidolic Ceiling	Overcast	32%	-
Arthelio	Clear and overcast	8%-overcast, 55%-clear sky	-
HSL	Clear and overcast	30-50%	-
Parans	Clear and overcast	60-80%	5,000 EUR Parans system package (includes SP3 collector, six 5 m-optical fiber cables, two medium luminaires)
TDGS	Clear and overcast	(80-90%) for 99.7% Rf of tube and after just 20 bounces	400 EUR A TDGS package (includes 350 mm dome, 1.2 m sun pipe, and diffuser)

[1] Currency exchange rates: (1.00 EUR) ~ (1.1 USD) ~ (144 JPY) ~ (26 L.E.) [133].

As for the thermal aspect, the SCDS/IDS have the potential to provide or deliver daylight with minimal attendant heat gains. This work is welcome in the cooling season as opposed to the heating season. There are two factors by which the thermal properties of these systems are determined. First, the amount of heat associated with the channelled daylight, as IDS makes extensive use of cold-mirrors and spectrally selective optical-materials to eliminate the infrared wavelengths. IR-cutting-coating-technology is used in the Sunportal system [125]. In the SunCentral system, gain of heat and glare from reaching the lower floors is prevented by the Sun Shade. Furthermore, in order to maintain adequate thermal resistance of the building, the Sun Spandrel is insulated [112]. In the Parans system, a reflective filter is used, which according to its name, reflects and blocks NIR and UV, but allows and transmits visible light [106]. In TDGS, to enhance the U-value, a double-glazed dome can be used in addition to a diffuser. This value was rated at (1.66 W/m^2. K) based on a typical application of 1.5 m length of the light guide. This compared favorably with a double-glass-skylight [134]. The last factor, heat loss or solar gain due to light guide penetration of the insulated spaces as the penetration apertures required in fiber optic-based systems are very small and do not cause a significant impact on the thermal balance of the building. Unlike light guide-based systems that require relatively large roof holes and are often topped with a transparent or protective glass cover, which is comparable to conventional skylights in terms of roof area and thermal performance. The surface area of the light guide is typically much smaller than that of skylight panels, and presumably, the thermal performance is almost the same as that of traditional glass.

TDGS is the most widely (or commercialized) of "innovative passive systems", used, and also studied [135]. As shown in Table (5), it is effective in all-sky conditions, unlike "innovative active systems", which are mainly limited to regions with a distinct solar climate due to the presence of moving parts that follow the solar path by directing the collector in the direction of the sun to obtain the maximum amount of available light as possible at any time of the day, besides, they need regular maintenance because they have mobile elements, which makes them more expensive than their already high cost. There is also an important drawback of passive systems, which is that their collectors require a large collection area, which may cause negative effects on the building structure.

When talking about the cost of these systems, submitting the prices in expressions of €/m^2 or €/kW for the objective of comparing is challenging. However, a previous study was able to estimate the initial costs (including system and installation costs) for some SCDS/IDS under specified conditions and compared them to an equivalent electrical lighting system. It found that the cost of the TDGS per square meter was 76% more than the electric lighting system, noting an important thing that the electric lighting system will also be required to use it in times of absence or insufficient daylight. Moreover, the cost concerning the Parans system is about six times that of the equivalent electric lighting system, assuming a large production volume [41].

In addition to the above, the equilibrium between the cost of their components and their performance efficiency is one of the great fundamental decisions that an engineer designing for these systems must make. Therefore, the previously mentioned limitations and disabilities encourage researchers, developers, and companies to consider more research and other new design approaches to address these issues, which cannot conquer whole at once. Hence, in this paper, we have presented the most recent scientific findings or the latest design approaches to find out their shortcomings.

***Table 5**. Summary of the main challenges associated with the produced or demonstrated SCDS/IDS.*

IDS/SCDS	Technology	Initial price	Utilization		Applicability		Light quality			Light delivery		Perception as daylight possibility
			Guide installation	Collector impact on building image	Sky case	Building form	Uniform distribution over time	Uniform distribution over space	Retaining daylight spectrum	Amount	Distance	
TDGS	Simple	Low	Difficult	Low	All	Upper storey	Excellent	Good	High	Small	Medium/ long	Medium
Heliostat	Medium	High	Medium	Medium	All/ clear[a]	Central void	Good	Good	High	Medium/ big	Medium/ long	Medium/ high
Heliobus	Medium	Very high	Very difficult	Medium/ high	All/ clear[a]	Central void	Good	Good	Medium	Medium/ big	Medium/ long	Low
Himawari	Complex	High	Easy	Low/ medium	Clear	All	Bad	Medium	Low	Big	Extreme	Very low
Parans	Complex	High	Easy	Low	Clear	All	Bad	Bad	Low	Big	Medium	Very low
Sundolier	Complex	High	Medium	Medium	Clear	Upper storey	Bad	Good	High	Big	Short	Low
Sunportal	Very complex	Very high	Difficult	Medium	Clear	All	Bad	Good	Low	Extreme	Extreme	Low
SunCentral	Medium	Medium	Very difficult	Very high	Clear	Multi-storey	Medium	Good	High	Medium	Medium	Low
HSL	Complex	High	Easy	Low	Clear	Upper stories	Bad	Medium	Low	Big	Medium	Very low

[a] According to the mirrors type used in the system.

7. CONCLUSIONS AND PERSPECTIVES

There are two solutions or strategies that can be followed, either separately or together in different building types, in order to save electric lighting energy: (i) new energy-efficient artificial lighting technologies, and (ii) different daylighting applications/systems, whether traditional or innovative. The use of a lighting control system is a necessary and a key component when the daylighting system is combined with artificial lighting systems (i.e., the hybrid system), and previous studies have shown how effective the result is in saving energy.

The interior spaces of multi-storey buildings (i.e., taller and deeper) are often not illuminated by natural light during the daytime, due to the distance from these spaces to the nearest traditional general application through which daylight must enter and therefore the electric power for lighting is entirely dependent. Moreover, these applications cause glare, heat gain, high contrast, and excessive brightness, so they are improved and developed.

IDS/SCDS are resorted that can direct daylight into the interior spaces/core of the built environment (such as modern buildings, underground spaces, tunnels, deep staircases, etc.) in a more controlled manner and increase uniformity, resulting in higher lighting energy savings and a more comfortable visual environment.

Current work chronologically reviewed the development of IDS/SCDS and its current or post-prototype status only. The design concepts and main elements are briefly described, and comparisons are made between the elements of collecting and distributing /transmitting sunlight. In the end, we can deduce some important lessons learned from the review and discussion of SCDS as follows:

(1) Despite the huge variability of the IDS, none of them is likely to overcome all the challenges associated with it, but a number of systems that fit different ambient conditions efficiently are the most practical approaches.

(2) Although there is no reliable information regarding the market share of each system, there is a fact that TDGS is the most commercially successful and widely accepted of SCDS, being the cheapest, simplest to configure, most efficient, and greatest studied. In addition, it is the most energy-saving for all different climatic zones.

(3) The type of SCDS should be selected according to the characteristics of the climate (i.e., the prevailing type of sky and the latitude of the building site). Therefore, optical fiber-based systems are more suitable for use where clear skies predominate, while light ducting systems are suitable for all-sky conditions. Accordingly, light duct-based systems promise to be more viable, but the difficulties of using them have made the possibility of their widespread use under expectations.

(4) Cost remains the main problem that needs further development to come up with more creative solutions. Despite ongoing efforts to reduce costs for systems components and optical materials, the SCDS remains an uneconomically attractive option for lighting.

(5) IDS/SCDS represents a great opportunity to provide electrical energy in two main forms; saving lighting energy due to the reduction of electric lighting and saving cooling energy due to the heat rejection feature that allows separation of infrared and ultraviolet rays from the spectrum.

(6) Despite the limited commercial success of some systems over the past few decades, new design approaches are being developed to overcome technical difficulties and market penetration barriers, i.e., continuous attempts to reduce component costs, improve system routing longevity, improve system controls, and maintain lighting quality and increased user's acceptance.

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