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Hybrid Solar Lighting System for Energy Conservation: A Review

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Abstract—*Limited resources and increasing population have forced human being to develop newer energy saving technologies in order to fulfill the basic need of society. One of the burgeoning challenges in these human interventions is to avoid the adverse impact on the environment. Lighting is an area which consume a significant amount of energy and therefore it becomes essential to explore new areas in this field which can lower energy usage. Some technologies viz., Day lighting technology which if implemented properly can significantly reduce energy consumption. Moreover, it does not have any impact on environment and various health benefits. This paper review the development of solar lighting system, commercially available systems and latest technological advancement.*

1. INTRODUCTION

Before 20th century, daylight was the major source of lighting in buildings. But with the emergence of electric lamps and subsequent improvement in their performance, artificial lighting replaced the traditional source of lightings. The oil crisis of 1970s which caused increased energy prices generated a renewed interest in day lighting system as means to lower energy consumption. But drawbacks of these conventional day lighting system (example- skylights) such as excessive illumination, difficulty of control, glare, variability and architectural modifications for installation of the lighting system restricted their acceptability as a lighting system in buildings [1].

In our present times, artificial lighting has become the primary source of illumination in every residential or non-residential buildings which includes incandescent lamps, compact fluorescent lamps fluorescent tube, discharge lamps and high energy saving light emitting diode. A solar lighting system is a lighting system which tracks and collects sunlight and transmits it into light guides in the form of concentrated beam to provide luminance in indoor spaces of the building. Hybrid lighting uses optical fiber bundles to transmit light. These optical fibers terminate into luminaries where sunlight is combined with electric light to adjust the fluctuation in the sunlight and maintain a uniform brightness in the room.

2. IMPACT OF ELECTRIC LIGHTING ON ENVIRONMENT

Energy conservation in building is crucial because besides seriously affecting the operational cost, it has huge impact on the Environment. In 2010, Global Green-house Gas Emission reached a level of 49 Giga Tonnes as reported in fifth assessment report titled "Climate Change 2014: Synthesis Report" of Intergovernmental Panel on Climate Change (IPCC) [2]. Contribution of electricity and heat production sector in Global Green-house Emission is around 25%. Residential and commercial building uses a significant portion of electricity generation. Additionally, Commercial buildings have interior features which makes it difficult to illuminate interior space.

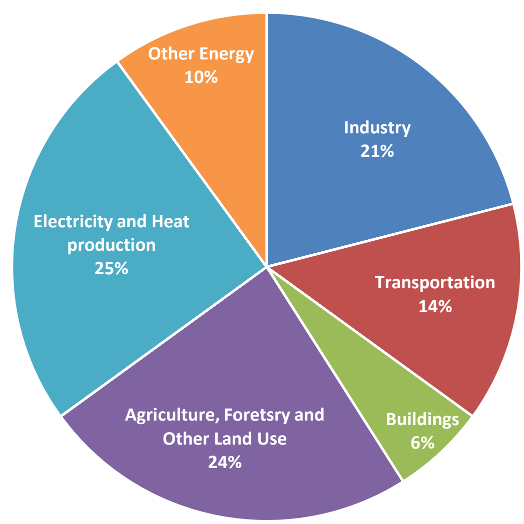

Fig. 1: Global Greenhouse Gas Emissions by Economic Sector [2].

As a result, most of the commercial building have huge electrical consumption. US department of energy reports that lighting consume 20% of electric power in commercial buildings [3]. Therefore, further technological advancement in the field of lighting system will significantly result in energy conservation.

3. SOLAR LIGHTING AS LIGHTING SYSTEM IN BUILDINGS

Solar energy being enormous source of energy can play a leading role in energy conservation. Use of solar light as lighting will have numerous advantages such as zero pollution, free availability. Over the last few decades, increasing awareness towards energy conservation and environment protection as well as technological advancement have made solar light harvesting a reality for lighting purposes in buildings. Benefits of using solar lighting system extends beyond energy conservation. Previous studies [4-6] have shown that natural sunlight is highly suitable for human body. Studies have also shown positive effect of sunlight exposure on human body instead of artificial such as reduced headaches and eye strains, reduced absenteeism and higher productivity [4, 5, 7].

The luminous efficacy (ratio of luminous flux to power) of direct sunlight ranges between 90 to 100 lm/W. The existing electric lamps have luminous efficacy within the range of 15 to 90 lm/W but luminous efficacy of filtered visible sunlight is around 180 to 200 lm/W [1]. This makes solar lighting highly beneficial for buildings illumination.

Use of sun light as controlled beam to illuminate indoor space of buildings was first proposed by Duguay et al. [8] in 1977. Their model used solar tracking concentrators to track and collect the sunlight. This beam of sunlight after passing through mirrors and lenses would be transmitted in the building. Dielectric mirrors separates the light into visible and infrared region of sunlight. The infra-red region could be used for generating electricity using solar cells. With the advancement in transparency of acrylic plastic optical fibers, Fraas et al. [9] used acrylic light guides to distribute the sunlight the interior of the building.

Optical efficiency of optical fiber bundle for solar lighting was studied by Kandilli et al. [10]. Their study conclude that optical efficiency of long optical fiber bundle varies between 69 to 80% for corresponding bending radii of 29.8 and 60.8 cm. A simulation study was carried out by Tsuei et al.[11] by combining natural lighting system with light emitting diodes (LEDs). The main conclusion was that illuminance of sunlight is not always uniform. Therefore, natural lighting system has to be incorporated with LEDs to provide a uniform lighting inside the buildings. Xue et al. [12] worked on a multi surface compound solar concentrator different from the conventional parabolic concentrator used in conventional day lighting system. Their concentrator focusses the captured sunlight in forward direction which offers simplicity in connecting optical fiber to the concentrator.

Gonzalez et al. [13] worked on numerical analysis of numerical aperture of optical fibers having different shapes at the end of optical fibers with a diameter of approx. 10 mm. They used fiber lenses having typical planar, convex, concave, conic, tilted planar shapes at the end. Their findings revealed that fiber lens having conical shape at the end with semi-angle ranging between 14 to 20 degree is the optimum shape for increasing the acceptance cone.

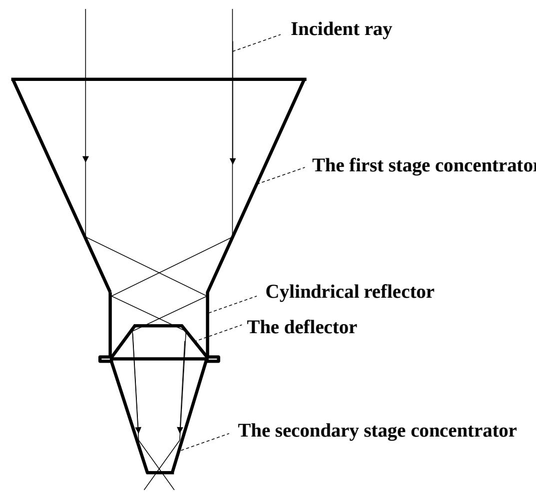

Fig. 2: Shows the working principle of novel solar light concentrator [12].

Fraas et al. [14] used a cold mirror to split the sunlight into visible and infra-red region. Visible region is transmitted to the interior of the building through light guides. The infra-red region of light is focused on the photo voltaic cell for generating electricity which could be used for electric lighting. Because of the very small diameter of optical fibers, it becomes important that tracking error for sun is less than 0.1 degree otherwise, it may result in fluctuation in output flux and unstable light quality.

Song et al. [15] developed a day lighting system having optical fibers for transmission and two stage sun tracking model. This two stage tracking model uses a high-resolution photodiode matrix for precise detection of focal point which ensures smooth tracking of sun over longer period of time. Moreover, their model showed tracking error of less than 0.07 degree and transmission efficiency of 37 to 40%. Most of the traditional fiber based day lighting system have been studied on small building.

Ullah et al. [16] worked on implementing solar lighting system on multi floor office buildings using highly concentrated sunlight. They used parabolic trough and linear Fresnel lens as two different method to capture sunlight. Also, a trough compound parabolic concentrator (CPC) is able to direct maximum collected collimated sunlight into the optical fibers in both the methods. The average illuminance achieved in their system were better than compared with other traditional system.

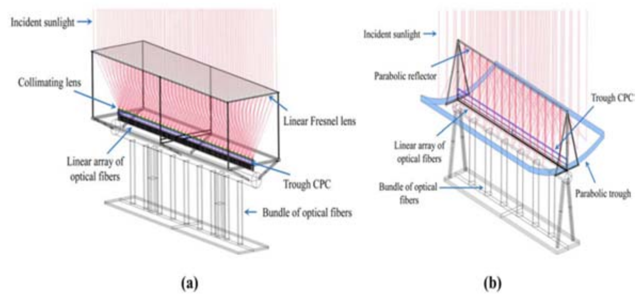

Fig. 3: Shows the layout of the system consisting of collimating lens and trough CPC placed between (a) linear Fresnel lens and optical fibers and (b) parabolic trough and optical fibers [16].

4. HYBRID LIGHTING SYSTEM

A hybrid solar lighting system combines solar light and electric light for illumination of indoor spaces. Hybrid system uses electric light when sufficient solar light is not available due to cloudy weather or during night. Also, Fluctuation in the intensity of solar light requires to be compensated by the electric lamp in order to maintain a constant illumination in the room. Otherwise these differences will be visible to the occupant in the room which will be highly undesirable. In these system, sun light is channeled into indoor spaces of the building where it is combined with electric light in luminaires. These luminaires transfer the light within the room. Further, these luminaires have control system for maximizing the available daylight and for on/off operation. This section discusses various types of hybrid systems which have been proposed and commercially available system.

4.1. Enhanced tubular daylight guidance system

Tubular daylight guidance system are the passive lighting system in which light is channeled through a rigid tubular guide. The interior surface of these tubular guide is of highly reflective material. These system have their main application in single storey buildings. The first development in hybrid lighting system was the modification of the tubular guidance system by using heliostats. These modified system combines light with electric light within the tubular guide rather than at the point of application. Example of enhanced tubular day lighting system are Arthelio. Heliobus etc.

Arthelio was a European research project which delivers day light to the lower floor of a multi storey building and also combines daylight with electric light to provide optimum illumination. Light collectors captures the sunlight and directs it into light guide. This system was installed in 3M Distribution Center building in Italy. It used a combination of Fresnel lens and a compound parabolic concentrator .The concentrator directs the collected sunlight into light guide of 28 m. This light guide delivers the sunlight into the lower floors of building. Electric light is mounted on the top of the light guide for provide uniform illumination. The installed system provides a illuminance of around 100 to 400 lux during daytime [17]. In Semperlux building in Berlin, Germany, a light collector of 6.25 m^2 was used and collected sunlight was directed towards Fresnel lens which concentrated it. A 13 m long light guide receives the concentrated light and delivers it into lower floors of building. The light guide was equipped with a sulphur lamp for providing illumination during fluctuation in sunlight intensity [18].

Heliobus lighting [19] is Swiss Company which produces lighting system such as light guide and light pipe. These system are a combination of heliostat which collects sunlight and sun pipe systems which deliver the collected sunlight into interior of the buildings. These system are equipped with electric light for use during cloudy weather or during night.

4.2. Hybrid solar system developed by Oak Ridge National Laboratory

Oak Ridge National Laboratory (ORNL) proposed a hybrid lighting system [1]. It consist of collection and tracking system (for collecting the sunlight and tracking the sun over whole day), Distribution system (for transmitting the collected solar light to the interior of buildings) control system (for dimming or on/off operation of natural light and electric light) and hybrid luminaires. A 1.22 m diameter parabolic acrylic collector concentrates the collected sunlight and directs it to a secondary elliptical mirror which re-directs it into a 3 mm diameter optical fiber bundle. These optical fiber bundles delivers the light to luminaires. It uses two sources of light which include natural solar light as the primary light source. Secondary light source such as electric lamps is required when sufficient sunlight is not available such as during cloudy day or at night. These two different sources of light are combined in luminaires which can distribute and blend light from both the sources. Fluctuation in the intensity of solar light must be compensated by the electric lamp in order to maintain a constant illumination in the room. Otherwise these differences will be visible to the occupant in the room which will be highly undesirable. It is estimated that the collector can capture up to 50000 lumens of sunlight which can illuminate 8 luminaires.

Three different design for collecting solar light have been developed. The first design involves the use of Fresnel lenses to focus sunlight directly on the optical fiber. This design is an improvement to a similar approach originally developed by Himawara Corporation, Japan in 1980s. The second design approach also in development stages of Synertech System Corporation, US. It uses a sunlight concentrator which focus the sunlight into reflective light pipe. The third design developed by ORNL in 1999 uses a primary mirror and a secondary optical element .In this design, visible solar energy is focused into optical fiber and the infra-red region light is focused on a photo voltaic cell. This design has two major benefits. Firstly, the light entering the room does not have infra-red part as result it does not heat up the room. Secondly, conversion efficiency of solar cells is much higher in infra-red region.

In 2007, ORNL installed hybrid lighting system at Customer Service Center of Sacramento Municipal Utility District in California [20]. During several months of operation, recommendation were made which included improvement in the waterproofing of the mechanical and electrical components of the tracking system, improvement in coupling design of the tracking system to better handle the high speed wind and better holder design of fiber bundle.

4.3. Universal fiber optics

Universal fiber optics was a project conceived by European Commission Energy Programme [21]. It consist of heliostat which collect the sunlight and 1 m diameter Fresnel lens which concentrates the collected towards the 10 m long and 20 mm diameter liquid-core optical fibers. These optical fibers delivers light to the indoor spaces in the building via luminaires. Two metal halide lamps (150 W each) are mounted adjacent to the heliostat and light from them is delivered to the luminaries through plastic optical fibers. A prototype of this system was installed in Athens which had an output of 3060 lumens. The system had an overall efficiency of around 3.4% because of the large number of optical stages.

4.4. Solar canopy illumination system (SCIS)

This hybrid system is developed by University of British Columbia, Canada [22]. It consist of 70 flat 16 cm wide squares mirrors which are enclosed inside a weather proof transparent enclosure known as Adaptive Butterfly Array (ABA). ABA is controlled by a microprocessor which moves all the mirrors with sun movement throughout the day. Sunlight from the flat mirror is directed towards two parabolic mirror at constant angle. These mirror concentrates the light and again redirects it to a second parabolic mirror which redirect the re-collimated light into the light guide. The light guide delivers the sunlight light into the interior spaces. Electric lights is located side the light guide to supplement the daylight as required. Two prototypes of this system were installed in institute of University of British Columbia. It was reported that the installed system were able to deliver an average illuminance of 500 lux for floor area of 15m^2.

4.5. Optical fiber based solar lighting system (Parans System)

The SP3 lighting system is a third generation solar lighting system developed by Swedish company Parans [23]. The first system was SP1 patented in 2004 followed by SP2. SP3 has the ability to track sun every hour of the day. This system can be mounted on the roof or facades of the building. It consist of receiver and optical fiber cabling. The receiver consist of a matrix of Fresnel lenses tracking the sun over the whole day to collects its light. This solar light is focused by lenses into the optical fiber through a filter which removes the ultraviolet and infrared parts of the solar light. The light is then guided through these optical fibers by various custom designed luminaries to the interiors of the building. Hybrid luminaires combines sunlight with LED so as to provide a uniform brightness during fluctuation in intensity of the sunlight. Further, these LEDs also provide lighting during night time.

4.6. Sunportal system

Sunportal system [24] have developed a lighting system can provide more than 60000 lumens of daylight. It can deliver up to a distance of 200 m using a series of compact optical lenses. It also has provision a of LED lighting system for use during cloudy, rainy weather.

5. COMMERCIALLY AVAILABLE SYSTEM IN MARKET

A number of solar lighting system are available in the market. Important one have been discussed below.

5.1. Himawari solar lighting system:

This system was developed by Japanese company and it [25] consists of three main components – a collector (for tracking sun and collecting sunlight) , optical fiber cable (for transmitting sunlight to the interior of building) and light fitting at the terminal. The Himawari collector are of two version, one having 12 lenses and other having 36 lenses. Light after passing through optical fibers enter the indoor space using various custom made light fittings.

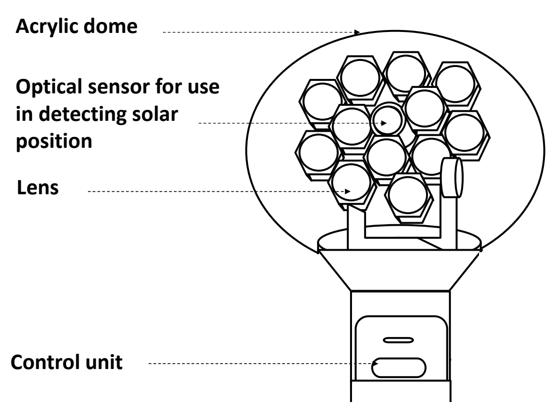

Fig. 4 Shows the collector of Himawari solar lighting system [25].

5.2. American Sundoiler daylight harvester :

It is skylight of 0.6 m roof penetration. It creates a concentrated collimated beam of sunlight with up to 100000 lumens of daylight which can be used for deep core, two floor or large open space day lighting applications. [26]

5.3. Suncentral system:

It is lighting system developed by a Canadian company which can track sunlight at the roof of the building and transmitting it down to every floor in the building. It consist of sunbeamer which tracks the sun and transmits a collimated beam of light along any side of the building. This sunlight beam is intercepted by sunshade (installed on every floor of the building) and directed towards a sunspandrel which channels the sun light into sun luminaire and transported to the interior spaces of the building. This system can reduce electricity consumption by 75% of daytime hours. Although these system have high cost and their pay-back period is long but they can reduce the energy consumption considerably. [27]

5.4. Solatube day lighting system:

It captures sunlight on the top of the floor and transmit it through a highly reflective tube into interior space.[28] Fig. 4 shows the schematic view of the solatube lighting system. It is available as 160 DS which has 6 m length, 250 mm tube diameter, and 6 m of tube length. 290 DS has a size of 350 mm, and length of 9 m.

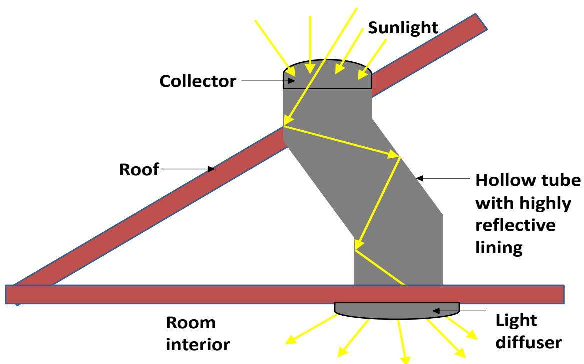

Fig. 5: Shows the schematic view of the Solar tube lighting system [28].

5.5. Ciralight Sun Tracker:

It [29] consist of three highly reflective aluminium and their movement is controlled a solar powered global positioning system based motor. This motor keeps the mirror in perfect alignment with the sun throughout the day. Sun light from the mirror is directed towards a highly reflective light well into the indoor spaces of the building.

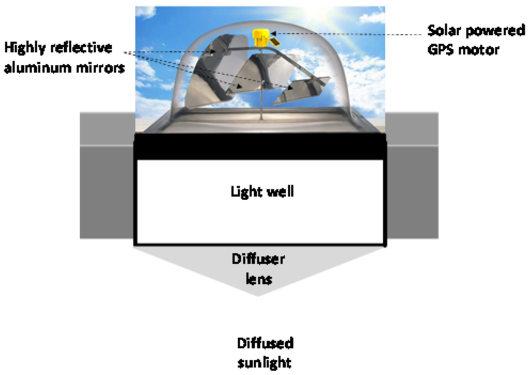

Fig. 6: Shows the Ciralight sun tracker [29].

6. LATEST TECHNOLOGICAL ADVANCEMENTS

Ullah et al. [30] proposed the concept of solar tower for day lighting in multi office building. Since conventional day lighting system have difficulty in illumination of indoor space of large building. Their proposed model consist of large number of heliostat arranged in circular arc around mirror light pipe (MLP). A focusing mirror is mounted on the MLP and sunlight form the heliostats is directed to the focusing mirror which re- directs into the MLP. At each floor, directing mirror were installed which directed the sunlight into the light guide. Sunlight is then distributed into the indoor space through light guide. They reported that high intensity of light was achieved using heliostats and uniform lighting was achieved. Fig. 7 shows the proposed model layout.

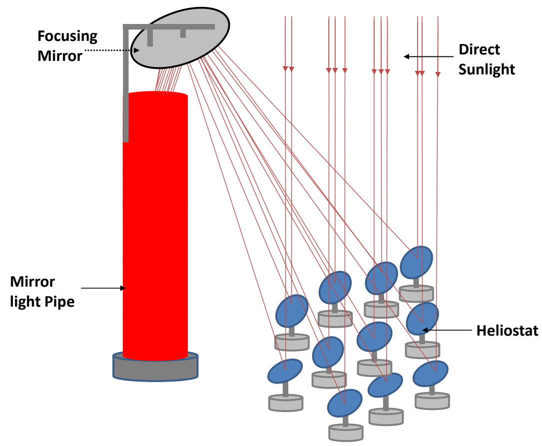

Fig. 7: Shows proposed model day lighting system [30].

Daylight guiding system has optimum illumination performance when sun light falls vertically on the sunlight collector but it has low performance when the sunlight falls obliquely on the collector. Chang et al. [31] designed a heliostat which can direct sunlight vertically on the day lighting system. They proposed a 3 x 3 mirror heliostat in comparison to a single mirror in traditional heliostat. They reported a 3.32 times increase in system efficiency. Fig. 7 shows the matrix heliostat.

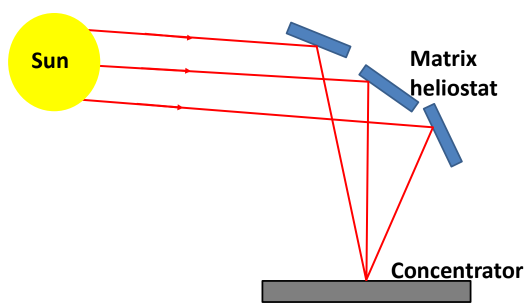

Fig. 8: Shows matrix heliostat directing sunlight in the acceptance of the concentrator [31].

Installation of solar lighting system need modification in architecture of the building and also occupy significant amount of space. This may be undesirable for the user. Integration of lights ducts with the heating, ventilation and air conditioning (HVAC) ducts is innovative solution. Mayhoub et al. [32] proposed a dual duct system for lighting and HVAC in the building. Majority of the commercial building have HVAC systems installed and HVAC network is able to reach most of the interior spaces within the building. Also, HVAC ducts are of comparable size to light ducts. Thus, integration of HVAC system with lighting system is significant way of cost reduction and simplified installation. Their study reported that installation of AC system and day light guidance system requires 97m/ floor and 70 m of horizontal and vertical ducts respectively. But implementing the proposed model would save 44% of the horizontal duct.

In 2015, Song et al. [33] fabricated a parallel mechanism day lighting system. The advantages of using a parallel mechanism is its compact and flat shape which makes it suitable for placing on roof for horizontal settings or hanging on walls for vertical settings. Their experiments demonstrated a transmission efficiency of 25% for a distance 10 m.

Tonghui et al. [34] worked on reducing the cost and improving efficiency of a day lighting system by designing a parabolic trough solar lighting with thermal system. Their design involved splitting up of sunlight spectrum into visible and infra-red region using a cold mirror. The visible region light is passed through a second stage Fresnel lens which concentrate it again and finally though optical fibers it reaches the indoor space of the building. The infra-red portion of light is used in heat generation. For optimum illumination of 500 m^2 office space, 8 m^2 of PTC is required. The payback period of their proposed system is less than 10 years in cities like Los Angeles.

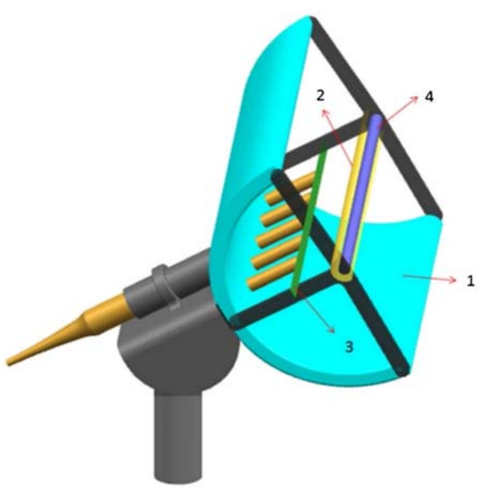

Fig. 9: Shows the layout of the lighting system consisting of (1) parabolic trough solar collector, (2) cold mirror, (3) Fresnel lens, (4) thermal system [34].

7. CONCLUSION

The solar lighting systems studied in this paper can significantly assist in reducing the overall energy consumption of building. For example, annual lighting energy conservation using Parans, Sunportal and Sun central lighting system is estimated at 55%, 60% and 75% respectively [27, 30, 35]. Cost of these system is a major issue for their widespread acceptability in the society and therefore, further development is required to reduce the cost through creative approaches. Integration of the lighting system into building requires architectural modification which may not be convenient for the user. Maintenance of these lighting system, especial keeping optical lenses clean to ensure good quality in indoor spaces, is vital to attain satisfactory system efficiency.

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