Hybrid solar lighting doubles the efficiency and affordability of solar energy in commercial buildings

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This article describes a new hybrid solar lighting technology that may well result in a doubling of the efficiency and affordability of solar energy in commercial buildings and eliminate many of the negative attributes of existing daylighting strategies. A new R&D project, initiated by the Oak Ridge National Laboratory and industry partners in 1999, views solar energy from a dynamic, systems-level perspective, integrates multiple interdependent technologies, and makes better use of the entire solar energy spectrum on a real-time basis.

Background and prior art

Throughout the 1900s, use of the sun as a source of energy has evolved considerably. Early in the century, the sun was the primary source of interior light for buildings during the day. Eventually, however, the cost, convenience, and performance of electric lamps improved and the sun was displaced as our primary method of lighting building interiors. This, in turn, revolutionised the way we design buildings, particularly commercial buildings, making them minimally dependent on natural daylight. As a result, lighting now represents the single largest consumer of electricity in commercial buildings.

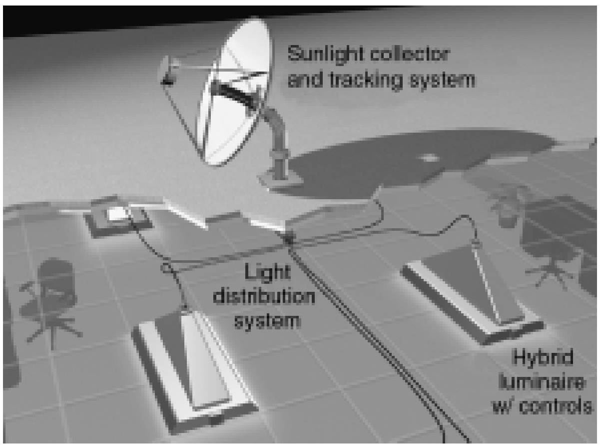


Figure 1: The proposed hybrid lighting system.

During the oil embargo of the 1970s, renewed interest in using solar energy emerged with advancements in daylighting, solar hot water heaters, photovoltaics, etc. Today, daylighting approaches are designed to overcome earlier shortcomings related to glare, spatial and temporal variability, difficulty of control, and over illumination. In doing so, however, these strategies typically waste a significant portion of the visible light that is available by shading, attenuating, and or diffusing the dominant portion of daylight, i.e., direct sunlight which represents over 85% of the light reaching the earth on a sunny day. Further, they do not use the remaining half of energy resident in the solar spectrum (mainly infrared radiation between 0.7 and 1.8 um), add to building heat gain, require significant architectural modifications, create wasted space, and are not easily reconfigured. Previous attempts to use sunlight directly for interior lighting via fresnel lens collectors, reflective light-pipes, and fibre-optic bundles have been plagued by significant losses in the collection and distribution system, ineffective use of non-visible solar radiation, and a lack of integration with collocated electric lighting systems required to supplement solar lighting on cloudy days and at night.

The hybrid lighting approach

We propose a systems-level strategy to solve the key problems discussed above. Our strategy is to improve the electrical power displacement efficiency of solar energy by integrating two solar technologies into multi-use hybrid systems that better utilise the entire solar energy spectrum. In **Figure 1**, the entire solar spectrum is concentrated by a primary mirror and the visible portion of the solar spectrum separated from the UV and near infrared portions at a secondary optical element. The two energy streams are used for different purposes, i.e. interior lighting and electricity generation.

This strategy takes advantage of the fact that new thermo-photovoltaics can very efficiently convert concentrated energy residing in the near-IR solar spectrum between 0.7 and 1.8 um. Similarly, analyses show that the visible portion of sunlight is inherently more efficient when used directly for lighting. The luminous efficacy of direct sunlight is 90 to 100 lm/W depending on the sun's orientation relative to the earth, atmospheric conditions, etc. Interestingly, the luminous efficacy of *filtered* sunlight approaches 200 lm/W and far exceeds existing electric lamps (15-90 lm/W). Unlike most comparisons with non-renewable alternatives where the energy density of sunlight is much lower, the luminous efficacy of filtered sunlight is more than double its only competition (electric lamps). Therein lies the primary motivation for using filtered sunlight for lighting purposes in buildings while using the remaining IR energy for electricity generation.

The approach we employ also integrates natural light and electric light in a hybrid luminaire that also contains electronic dimming ballasts and daylight harvesting controls. Depending on the intensity of emerging sunlight, collocated electric lamps adjust in real-time to provide a relatively constant level of illumination.

Technical issues

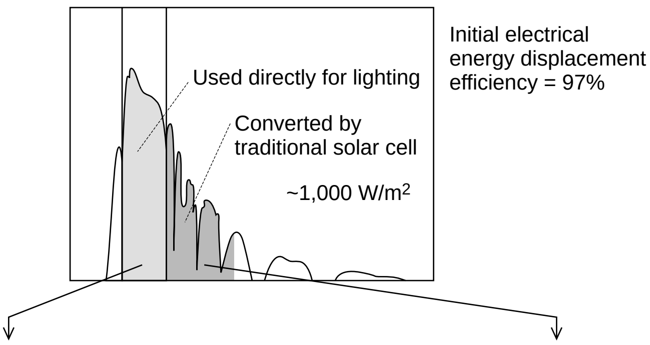
Although promising, several technical issues must be addressed before hybrid lighting will become a reality. Some of the remaining technical issues in the collection and distribution system include determining the maximum visible light-carrying capacity and long-term ageing of various large-core optical fibres, removal of residual thermal energy in the fibres and secondary optical elements, design of the thermo-photovoltaic and associated non-imaging optics, concentrator tracking accuracy, and installation/ maintenance requirements. Issues related to the hybrid luminaire include determining colour differences between collocated natural and electric illuminants, development of techniques to insure spatial and temporal uniformity, and development of integrated lighting control system strategies.

Anticipated outcomes

ORNL completed an initial optical design and performance analysis on the hypothetical system illustrated in **Figure 1**. Optical losses in the sunlight collection/distribution system were estimated and the results suggest that initial light collection and delivery losses in the proposed lighting system will be close to 50% for a single-story application and an additional 15% for second-story applications. These loss factors take into account losses attributed to the primary mirror, secondary UV cold mirror, large-core optical fibres, luminaires, and preliminary estimates for debris build-up and ageing of the various optical components. Optical analyses indicate light will enter the fibres at an average incident angle of well under 10°. This represents one of several advantages of the proposed system when compared to earlier fresnel-based designs. Further, the fibres are solid-filled rather than a fibre-optic bundle and packing fraction losses are eliminated. Also, the luminaire efficacy of fibre-based systems is anticipated to be much better than traditional lamp/luminaire combinations (85%-vs-70%) because the directional nature of delivered sunlight emerging from the fibres makes it much easier to control.

Figure 2 summarises the projected performance during peak use periods per 1,000 W/m^2 of incoming solar flux. Included in the performance summary are the following considerations:

1) the sunlight is filtered, the visible portion (approx. 490 W) is used for displacing much less efficient electric light and the near-IR radiation (approx. 360 W) is used for electrical energy generation;
2) the luminous efficacy of the displaced electric light (63 lm/W) includes the luminous efficacy of the lamp/ballast (approx. 90 lm/W) and the luminaire efficacy (70%);



Estimated Available Solar Energy/m^2

490 W		360 W	
x 200 lm/W	Luminous efficiency of filtred sunlight	15%	Collection losses
98,000 lm	Available visible light	25%	IR energy conversion efficiency
x 0.5	Passive distribution losses	90%	Power conversion efficiency (dc/ac)
50,000 lm	Distributed light	~70 W	Electrical energy generated
63 lm/W	Efficiency of electric lamp/ballast/luminaire		
+ 15%	Cooling load credit		
900 W	Electrical energy displaced		

Figure 2: Summary of the projected performance analysis.

3) the elimination of excess heat generated by electric lights in sunbelt regions, which reduces subsequent HVAC loads by as much as 15%.

The expected installed system cost for a single-story application is estimated to be approximately USD 3,200 in commercial quantities, assumes a 2 m^2 collector, illuminating approximately 12 hybrid luminaires, covering close to 90 m^2 (900 ft^2) of floor space. This translates into peak performance of approximately USD 1.64/Wp.

It is often convenient to display the performance of energy efficiency measures in terms of cost per kilowatt-hour (kWh) displaced and or generated. In the case of our analysis, this method is dependent on several factors, including the regional availability of sunlight, building use scenarios, and the price of displaced electricity. **Table 1** provides the anticipated cost of hybrid lighting in cents/kWh of displaced electricity in different regions of the United States over a 20-year lifetime under differing building end-use scenarios and differing levels of sunlight availability. It also assumes that not all of the direct sunlight is necessarily used to displace electric light. The remainder of the sunlight will likely not be used in initial systems lacking adaptive controls because occupants do not always need lighting and insufficient colour matching between natural and electric illuminants may occur in the early morning and late evening.

The average cost of electricity during the day, during peak demand periods when sunlight is available, is projected by the American Solar Energy Society to be between 10-15 cents/kWh in a deregulated marketplace within this decade. In portions of California, electricity costs are already exceeding these values during peak demand periods. However, using an average value of 12.5 cents/kWh for the cost of displaced electricity, the simple payback in years is also provided in **Table 1**. Similar to cost-reductions in other solar technologies, the projected simple payback is based on a 50% reduction in system cost once the system is readily available in high volume quantities.

Comparisons with alternatives in buildings

Alternative 1:
Advanced electric lighting
Because a hybrid lighting system requires the use of electric lights when sunlight is not available, its cost is additive. As such it is not fully appropriate to compare them directly. However, in a "head-to-head" comparative analysis, the estimated additive cost of installed hybrid solar lighting systems (a clean energy alternative) in terms of cents/kWh displaced (5-12 cents/kWh) is typically lower than the cost of electric lighting systems in a deregulated market considering time-of-day rates (10-15 cents/kWh) during peak demand periods.

Alternative 2:
Conventional topside daylighting
Although there are countless daylighting strategies available offering value-added benefits beyond energy-efficiency, we limit this discussion to skylights, generally accepted as the most cost-effective form of conventional topside daylighting. On average, incident sunlight does not enter skylights normal to the horizontal plane. Depending on the type and configuration of skylight, light transmission varies dramatically and is attenuated significantly. This is due to several factors but is predominately determined by the efficiency of the light well and glare control media.

Comparatively speaking, several other factors must also be considered. First, the coefficient of utilisation (CU) of a single 1 m^2 tubular skylight will inherently be much lower than a system that distributes light from the same area to six or more luminaires in an office setting. Assuming that the room cavity ratio and other room parameters are identical, the CU of the more distributed hybrid system should be significantly better. If the single 1 m^2 skylight were replaced by approximately 6 much smaller skylights, the two systems CUs would be comparable, yet the cost of the skylight installation would increase prohibitively.

To reduce glare and over-illumination, skylights are typically not designed based on the maximum amount of light that can be supplied but rather designed to approximate that which is

Table 1: Projected cost of hybrid lighting in different regions of the United States.

Region	Building use scenario	Cost/kWh displaced Current	Cost/kWh displaced Projected	Years to payback at 12.5 ¢/kWh Current	Years to payback at 12.5 ¢/kWh Projected
Sunbelt (9 kWh/m^2/day)	Everyday	4.5	1.9	4.9	2.0
	300 days	5.5	2.3	6.0	2.5
	259 days	6.6	2.8	7.2	3.0
Average location (7 kWh/m^2/day)	Everyday	5.8	2.4	6.3	2.6
	300 days	7.0	2.9	7.6	3.2
	259 days	8.5	3.5	9.2	3.8
Suboptimal location (5.5 kWh/m^2/day)	Everyday	7.4	3.1	8.0	3.3
	300 days	9.0	3.8	9.7	4.0
	259 days	10.9	4.5	11.7	4.9

produced by the electric lighting system when the total exterior illuminance is 3,000 footcandles. This reduces over-illumination and glare. Because of this, all interior light produced by skylights beyond this value is typically not used to conserve electricity. Conventional skylights are also plagued by problems associated with heat gain and do not harvest non-visible light. Finally, conventional skylights are not easily reconfigured during floor-space renovations common in today's commercial marketplace. Once all factors are considered, the simple payback, efficiency, and unique features of hybrid lighting make it a potentially viable alternative to topside daylighting systems.

Alternative 3:
Solar electric technologies
The most relevant solar electric technologies include solar PV modules and solar thermal technologies. The advantages of these systems are obvious. First, PV modules require no moving parts, and they can be conveniently used for any electrically powered end use. Unfortunately, these advantages come with a penalty in terms of overall efficiency. For example, commercial PV modules typically have a total conversion efficiency of <15%, and only a small portion of the visible light into electricity. Further, losses attributed to electric power transmission/ distribution (approx. 8%) and dc-ac power conversion (10-15%) further reduce the overall efficacy of conventional solar technologies. Ironically, a large portion of the electricity produced in commercial buildings is used for illumination purposes. **Figure 3** compares the end-use efficiency of hybrid lighting and PV technology used for lighting.

Because of these and other reasons, conventional solar technologies have not displaced significant quantities of non-renewable energy and are expected to be used in the United States for residential and commercial buildings, peak power shaving, and intermediate daytime load reduction. The PV modules currently sell for between USD 3-5/Wp. The projected peak performance of hybrid lighting (USD 3,200 per 1,940 Wp or USD 1.65/Wp) have the immediate potential to more than double the affordability of solar energy when compared to these solar technologies.

Benefits in the buildings sector

In the 1999 financial year, the U.S. Department of Energy tasked an independent consulting firm (Antares Engineers and Economists) to conduct a preliminary technical assessment and market of hybrid lighting systems. Aside from the cost and performance of hybrid lighting systems, several other factors were considered prior to determining the expected market penetration values. Their estimates were based on comparing conceptual-level designs of:

a) a first-generation hybrid lighting system;
b) the most energy-efficient conventional daylighting strategy available (tubular skylights); and
c) state-of-the-art electric lighting systems.

Antares concluded that hybrid lighting has the potential to become more cost-effective than the most efficient traditional topside daylighting system commercially available and provided more flexibility within the context of current buildings designs and construction practices. Further, it concluded that hybrid lighting would likely compete favourably with other solar technologies used in commercial buildings.

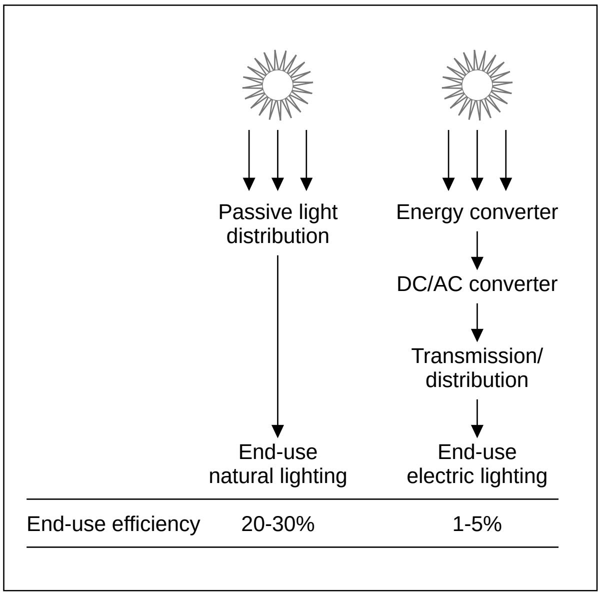


Figure 3: Comparison of end-use efficiency of hybrid lighting and PV technology used for lighting.

Summary

A co-ordinated R&D programme is still needed to develop and deploy commercial systems. However, if the different uses of solar energy are to include the reduction of energy use in buildings, peak power shaving, and intermediate daytime load reductions as many experts suggest, hybrid lighting reflects a new, potentially more efficient and cost-effective way of conserving non-renewable energy in commercial buildings.

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