INNOVATIVE HYBRID SOLAR LIGHTING REDUCES WASTE HEAT AND IMPROVES LIGHTING QUALITY

Melissa Voss Lapsa
Christina Ward
Curt Maxey
David Beshears
James Parks
Oak Ridge National Laboratory
1 Bethel Valley Road
Oak Ridge, TN 37831-6054
lapsamv@ornl.gov
wardcd@ornl.gov
maxeylc@ornl.gov
beshearsdl@ornl.gov
parksjeii@ornl.gov

ABSTRACT

Artificial lighting is the largest component of electricity use in commercial U.S. buildings. Hybrid solar lighting provides an exciting new means of reducing energy consumption while also delivering significant ancillary benefits associated with natural lighting in commercial buildings. The system uses a roof-mounted collector to concentrate visible sunlight into a bundle of plastic optical fibers. The fibers penetrate the roof and distribute the sunlight to multiple "hybrid" luminaires within the building. The hybrid luminaires blend the natural light with artificial light to maintain a constant level of room lighting.

During 2005 and 2006 a field-trial demonstration program is being implemented across the U.S. By the year 2011, hybrid solar lighting should be saving the nation over 50 million kWh/year while also dramatically improving lighting quality in commercial buildings. A system cost goal of $4000 has been identified as necessary to meet the previously stated energy savings by 2011.

Fig. 1: Photos of hybrid solar lighting taken for Discover Magazine.

1. TECHNOLOGY OVERVIEW

When first developed, the hybrid solar lighting system employed a glass primary mirror that was heavy and

expensive. It relied on a third-party tracking system that was not optimized for the product and not easily adapted, and it used large-diameter optical fibers whose sustained availability was not assured by the manufacturer. The design used eight individual ½ inch in diameter fibers, each in a separate holder. Eight flat secondary mirrors were required as well. The design was costly and difficult to align.

Since that time the design of the hybrid solar lighting system has evolved to use a custom plastic mirror that is one-fifth the weight and one-tenth the cost of the original mirror. The eight individual fiber holders/adjusters have been simplified to a single holder for one bundle of 127 individual fibers, each 3 millimeters in diameter. This has also allowed the secondary mirror to be simplified from eight individual flat segments to a single elliptical mirror. The present tracking system consists of hardware and software that have been optimized to meet the product performance goals. The system design now uses a bundle of small optical fibers that are commodity items available from a variety of sources (Fig. 1). The patented hybrid solar lighting technology was licensed to Sunlight Direct, LLC, in August 2005. Sunlight Direct is installing ten systems in 2006 as part of a nationwide demonstration program, called "Sunlight Inside Initiative" (Fig. 3). Wal-Mart, Aveda Corporation, the Tennessee Valley Authority, Long Island Power Authority, San Diego Gas and Electric, and the Sacramento Municipal Utility District (Fig. 2) are among the early adopters participating in the demonstration program.

This year over 100,000 visitors to the American Museum of Science and Energy at Oak Ridge, Tennessee will see a hybrid lighting system operating as part of a permanent exhibit that was installed there in 2005 (sponsored by the Tennessee Valley Authority). Visitors to the Sacramento Municipal Utility District corporate center in California can now observe the effectiveness of hybrid lighting in a showcase display there (co-sponsored by the California Energy Commission). Shoppers at a Wal-Mart store in Texas will soon make their product selections in a portion of the store that is illuminated by a hybrid solar lighting system.

Hybrid solar lighting provides a flexible, efficient and easily integrated means for providing natural lighting in commercial buildings. An installed hybrid lighting system is so seamlessly integrated into the building architecture that it would go unnoticed, were it not for the strikingly improved quality of the light that it delivers. The hybrid lighting technology was originally developed for fluorescent lighting applications but recently has been enhanced to work with incandescent accent-lighting sources, such as the parabolic aluminized reflector lamps commonly used in retail spaces. Commercial building owners—specifically retailers—use the low-electrical-efficiency parabolic lamps because of their desirable optical properties and positive impact on sales. Yet the use of this inefficient lighting results in some retailers spending 55 to 70% of their energy budgets on lighting and lighting-related energy costs.

1.1 How It Operates

The hybrid solar lighting system houses a sun tracking control board that is used to calculate the sun's position based on latitude, longitude and time of day. The control board uses a microprocessor to compute the astronomical equations, obtained by the U.S. Naval Observatory, which are good to 1/60° for the next 300 years. This precision allows the system to track at 0.1° accuracy, required by the two-mirror geometry to keep the focused beam on the fiber bundle. The calculations represent positions in the Azimuth and Zenith Earth-Based coordinate system using latitude, longitude, and Coordinated Universal Time (UTC) from a Global Positioning System (GPS) receiver. The positions are then converted to units of encoder counts since an encoder is used to detect the location of the hybrid solar lighting system on each axis. The controller compares the actual position of the collector to the latest computed position of the sun and then determines if the move is to be in a positive or negative direction. The motors then move at a speed proportional to the difference in the actual and computed positions. This process is performed continuously throughout the day in order to track the sun accurately. The control board operates on a 12V or 24V dc supply and uses less than 2 Watts. A photovoltaic solar cell can also be used to power the board.

The control board allows a roof-mounted solar collector to concentrate visible sunlight into a bundle of plastic optical fibers[2]. The optical fibers penetrate the roof via a four-inch diameter pipe, and distribute the sunlight to multiple "hybrid" luminaires within the building[3,4]. The hybrid luminaires blend the natural light with artificial light (of variable intensity) to maintain a constant level of room lighting. When sunlight is plentiful, the optical fibers in the luminaires provide all or most of the light needed in an area. During times of little or no sunlight, a sensor controls the intensity of the artificial lamps to maintain a desired illumination level. Unlike conventional electric lamps, the natural light produces little to no waste heat and is cool to the touch. This is because the system's solar collector removes the infrared light—the part of the spectrum that generates a lot of the heat in conventional bulbs—from the sunlight. The hybrid solar lighting technology offers the potential to separate and use different portions of sunlight for various applications. Thus, visible light is used directly for lighting applications while the infrared and ultraviolet

light could be used for heating applications or to produce electricity. The optimal use of the energy in these invisible wavelengths is the focus of continued studies and development efforts within the solar technology program at ORNL.

1.2 System Advantages

One hybrid lighting solar collector can power 8 to 12 fluorescent hybrid light fixtures or 30 to 40 incandescent accent lighting fixtures, which can illuminate approximately 1000 square feet. Hybrid solar lighting systems are highly efficient and offer significant energy savings by reducing lighting costs. In addition, there are several other advantages that hybrid solar lighting provides:

• Infrared and ultraviolet energy in sunlight is separated from the visible light, rather than being transmitted into buildings. Heating, ventilation, and air-conditioning (HVAC) loads are thus reduced by 5 to 10%, compared with electric lighting systems.
• Hybrid solar lighting systems are readily adaptable to commercial buildings with multiple floors, relatively low ceiling heights, and interior walls. A single system can distribute enough sunlight to illuminate several small rooms in a typical office building.
• The concentrated light travels through optical fibers that require little plenum space (the area between the roof and drop ceiling), so there is little competition with other building services, such as HVAC ducts, sprinkler systems, and electrical conduits.
• Hybrid solar lighting can be used for diffuse ambient lighting (as in skylights) as well as focused task and accent lighting.
• In retrofit markets, hybrid solar lighting systems are easily incorporated into existing building designs, and the optical fibers can be rerouted to different locations as lighting needs change.
• When sunlight is plentiful, the fiber optics in the luminaires provides all or most of the light needed in an area. During times of little or no sunlight, a sensor controls the intensity of the artificial lamps to maintain a desired illumination level.
• When necessary, the solar lighting component is easily "switched off" by moving the solar collector to an “off-sun” position.

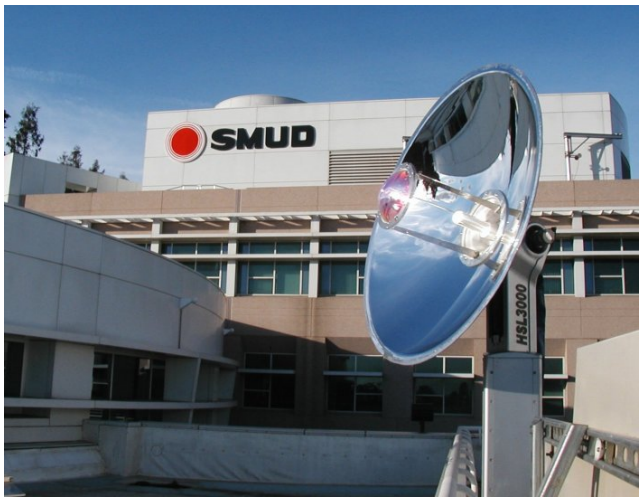

Fig. 2: Hybrid solar lighting system installed at SMUD.

2. MARKET POTENTIAL

The hybrid solar lighting commercialization goal based on market analysis for general consumer use is an installed price of $3000 per 1000 square feet. In the initial product offering from Sunlight Direct, the installed price of $24,000 is less than half of the early cost projections for the technology. Sunlight Direct has a development plan that aggressively targets the commercialization cost goal of $3 per square foot of illuminated space. When that target price is reached, regions of the United States where electricity is most expensive could pay for implementing the new technology in just 2 to 3 years with the savings on electricity bills alone (Table 1). Utility companies and their customers directly benefit form the offset in peak summer load. During peak demand periods (clear, hot summer days) hybrid lighting can reduce the amount of expensive supplemental power which must be provided.

In addition to the direct energy displacement savings from the solar lighting systems, there are a variety of other factors that enhance the economic benefits of hybrid solar lighting[1]. One of the initial target applications for hybrid lighting systems is in retail lighting applications that rely on direct lighting from incandescent sources.

During the sunlit day, those sources can be dimmed or turned off altogether. When incandescent lamps are dimmed, filament temperatures decrease, extending the life expectancy of the lamps and reducing maintenance costs associated with relamping.

Although skylights are widely used to include natural light inside buildings, they require large roof penetrations that add to the load on heating and cooling systems and are subject to water leakage. In contrast, the roof penetration for

a hybrid solar lighting system is a small pipe similar to the vent pipes that are used throughout the building industry. Smaller penetrations and less leakage save money on the building's heating, cooling, and maintenance bills.

3. ENERGY SAVINGS

On a sunny day, one hybrid solar lighting system will deliver 50,000 lumens of sunlight, or the equivalent of 55 60-watt incandescent lamps (Table 1). For buildings in the nation's sunbelt that use incandescent lamps, which have a luminous efficacy of 15 to 20 lumens/watt, this can result in two forms of energy savings.

First, there is an energy savings of approximately 6,000 kWh per year due to the reduced lighting needs. Second, there is an energy savings resulting from the buildings reduced cooling load. Because the hybrid solar lighting system delivers light with little to no infrared component, there is very little waste heat. The additional energy savings depends on the cooling technology utilized, but is on the order of 2,000 kWh per year, for a total energy savings of 8,000 kWh per year. The cost savings associated with this energy reduction will vary depending on local utility rates.

TABLE 1: COMPARISON OF LIGHTING EFFICIENCIES

Hybrid solar lighting technology could replace less efficient conventional electric lamps.	
Type of lighting	**Typical energy efficiency (approx. lm/W)**
Incandescent	15
Fluorescent	75
Hybrid solar	200

As an example, for areas with high utility rates, the cost per kilowatt-hour can be as high as $0.10. Therefore, over a ten-year period, a hybrid solar lighting system, working with incandescent lamps, can save a building occupant in these locations $8,000 per unit. Operation and maintenance savings—due to the reduced operating hours of the electric lighting and reduced costs for re-lamping of existing lighting fixtures—could account for another $2,500 over the same period. For large floor-spaces of 100,000 to 200,000 sq. ft., this translates into $1.1M to $2.1M of energy cost savings.

Integrating hybrid solar lighting with fluorescent applications has the potential to save building managers $500 per system annually with a life cycle of 20 years and a system price of $4 per square foot (estimated for 2008). During 2005 and 2006 a field-trial demonstration program entitled the "Sunlight Inside Initiative," is being implemented across the U.S. To-date 12 sites have signed up to participate in the field trial program. Performance data from the field trial program will be collected and published. By the year 2011, hybrid solar lighting should be saving the nation over 50 million kWh/year while also dramatically improving lighting quality in commercial buildings.

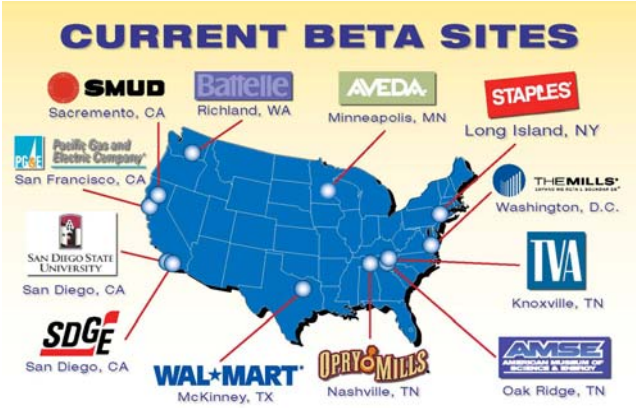

Fig. 3: Hybrid solar lighting demonstration sites.

Through commercialization efforts with industry partners, over 5,000 hybrid solar lighting systems will be installed by 2011 in regions of the U.S. where solar availability and electricity rates make this technology cost effective to consumers. Developing an initial system tailored to commercial buildings with mixed fluorescent and incandescent lighting (commonly found in retail applications) has been identified as the most likely first market for this technology. Given that market, a system cost goal of $4,000 (installed) has been identified as necessary to meet the previously stated energy savings by 2011.

4. LIGHTING QUALITY

With respect to lighting systems, quality is a term that has special meaning and it is quantified in various ways. For example, Color Rendering Index (CRI) is used to quantify how accurately colors are revealed under a given source. Lamps are typically identified with respect to their "color temperature", in degrees Kelvin, to indicate whether the lamp has "warm" red tones or "cool" blue tones in the emitted light (though ironically the "warm" tones come from the lamps with lower color temperatures). In addition, some light sources have smooth and continuous spectra while others emit all of their light in a few distinct color bands and there are ongoing discussions about the influence this may have from a human factors perspective.

From a practical point of view, the key features of lighting quality can be captured with the following observations. Almost all artificial light sources emit light that is more reddish than natural sunlight (i.e. their emission spectrum is peaked at a wavelength greater than 500 nm). As the relative proportion of blue light increases, the sources tend to more closely mimic natural sunlight and are often preferred in term of aesthetics and illumination comfort. This preference is validated by the fact that that lamps with more "solar-like" spectra command higher prices. There is also a lot of evidence[5,6,7] to suggest that retail sales, student scores, and productivity may all improve in the presence of natural sunlight.

Fig. 4 shows the comparison between outdoor sunlight and light exiting the fibers of a hybrid solar lighting system. The peak in the solar spectrum occurs at around 500 nm and diminishes smoothly to either side of that peak. As expected, the light exiting the fibers very closely matches the solar spectrum. By design, the ultraviolet and near-infrared wavelengths are omitted by the hybrid solar lighting system. There is also a small amount of absorption loss around 625 nm. Though unintended, this reduction in red light may actually enhance the perceived quality of the transmitted light.

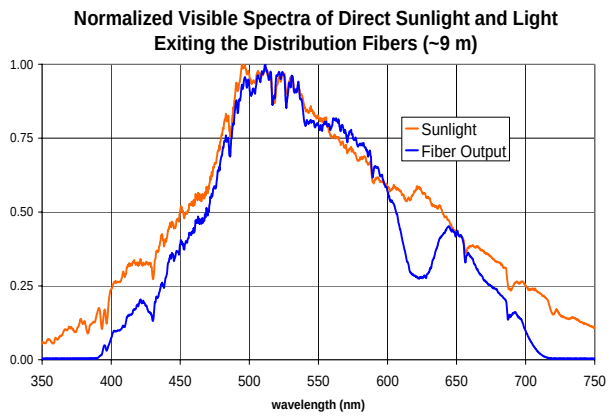

Fig. 4: Natural solar spectrum compared to light exiting hybrid solar lighting system fibers.

The spectrum in Fig. 5 is typical of what is seen in many commonly used fluorescent lamps. The majority of light is emitted in a band that is centered around 575 nm and falls off rapidly on either side of that peak. There are also substantial spikes in the spectrum at other wavelengths.

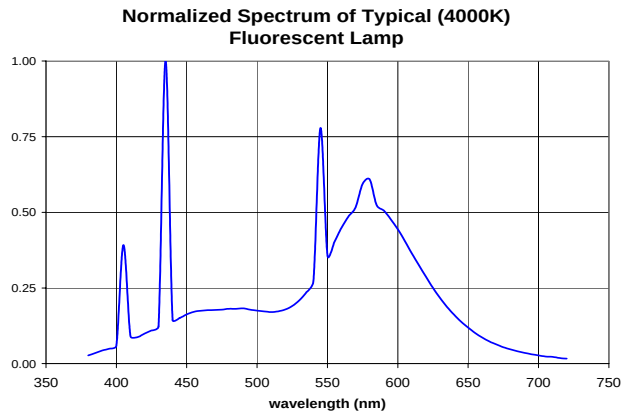

Fig. 5: Spectral output of typical (4000K) fluorescent lamp.

The difference in lighting quality between natural sunlight and fluorescent lighting will be apparent to those who work with spectral curves on a regular basis. However, for those who do not, the photo in Fig. 6 illustrates the difference more clearly. This photo, taken in the hybrid solar lighting laboratory, shows one half of the lab illuminated only by sunlight via the distribution fibers. The other half of the lab is illuminated only by 3500K florescent lamps. The photo is an accurate representation of the differences we observed in the laboratory. The artificially illuminated half of the room seemed noticeably pink compared to the naturally illuminated half (however, we had not particularly noticed the pinkish cast until the natural light was available for side-by-side comparison). The measured light levels were comparable in the two halves of the room. Subjective observations were that the light was more comfortable, visual acuity for task work was improved, and colors seemed to be truer on the naturally illuminated side of the room.

Fig. 6. Comparison of distributed sunlight and electric light.

5. CONCLUSION

5.1 Other Applications

There has been significant interest in using hybrid solar lighting technology for growing plants/microorganisms in condensed-volume growth chambers. Growing organisms in a condensed volume cannot be done without the collection and controlled distribution of sunlight. The hybrid solar lighting system allows sunlight to be piped deep into a growth chamber and distributed as necessary. A hybrid lighting collector was used in an algae growth bioreactor as part of a carbon sequestration program at Ohio University. New solid state lighting (LED) hybrid luminaires are also being researched for increased energy efficiency. Exciting new areas of R&D for ORNL with industry and university partnerships include integration of photovoltaics with the hybrid solar lighting system for other technology applications, including space heating and water heating.

5.2 Market for hybrid solar lighting

Artificial lighting is the largest component of electricity use in commercial U.S. buildings. In the United States, there is 72 billion square feet of commercial building space. Electricity use for artificial lighting in commercial building space costs building owners nearly $17 billion a year (personal communication, Energy Information Administration). Despite the high energy consumption, natural lighting from conventional options, such as skylights and windows, illuminates only a tiny fraction of the available commercial space. This limited use of natural lighting is a result of the architectural limitations of skylights and windows and the uncontrollable nature of the sunlight itself (i.e., it fluctuates in intensity, and it can be highly directional, producing glare and unwanted heating).

A significant market exists for the hybrid solar lighting system, a natural lighting product that can offer the benefits of natural lighting seamlessly integrated with existing lighting technology.

5.3 Deployment Status

During 2006, the licensee, Sunlight Direct, LLC, will install ten hybrid solar lighting systems in buildings across the United States in a demonstration program called “the Sunlight Inside Initiative.” Performance data will be analyzed and published by Oak Ridge National Laboratory, providing consumers with a fact sheet on the full range of economic benefits associated with hybrid solar lighting.

6. REFERENCES

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