Energy Research and Development Division
FINAL PROJECT REPORT

HYBRID SOLAR LIGHTING DEMONSTRATION AT THE SACRAMENTO MUNICIPAL UTILITY DISTRICT'S CUSTOMER SERVICE CENTER

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Prepared by: Oakridge National Laboratory

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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Hybrid Solar Lighting Demonstration at the Sacramento Municipal Utility District's Customer Service Center is the final report for the Hybrid Solar Lighting project (SMUD ReGen Program, Contract Number 500-00-034) conducted by Oak Ridge National Laboratory. The information from this project contributes to Energy Research and Development Division's Renewable Energy Technologies program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

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ABSTRACT

Artificial lighting is still considered a poor substitute for sunlight despite impressive technology developments. Sunlight has superior color-rendering capabilities and is generally preferred by most people. The demand for more natural, higher quality indoor lighting is rapidly growing, however, since most individuals now spend an increasing amount of time working and conducting business indoors.

Oak Ridge National Laboratory installed a demonstration hybrid solar lighting system with a display kiosk at the Sacramento Municipal Utility District Customer Service Center. The system included a standard hybrid solar lighting collector/tracker and a fiber-optic bundle that transported sunlight from the rooftop collector to the display kiosk. The kiosk incorporated a three-tube fluorescent hybrid luminaire and three hybrid spotlights. Visitors could watch a video at the kiosk that explained the details of the technology. A computer graphic display continuously posted the energy savings for the fluorescent hybrid luminaire.

The Sacramento Municipal Utility District display kiosk demonstrated that hybrid solar lighting offers a flexible, efficient, and easily integrated means for providing controlled, natural lighting in commercial buildings. Hybrid solar lighting can be integrated so seamlessly into the building architecture that it would go unnoticed except for the dramatically improved light quality it delivers.

Keywords: Hybrid solar lighting, daylighting, commercial buildings, lighting, improved lighting quality, energy savings

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EXECUTIVE SUMMARY

Introduction

Lighting in United States residential and commercial buildings consumes close to five quadrillion British thermal units (Btus) of primary energy and one-fifth of all electricity. Lighting represents one-quarter of all energy demand in commercial buildings. The forecasted doubling of commercial floor space by the year 2020 highlights a growing need to find more efficient ways of lighting our nation's buildings. Typically, less than 25 percent of the electrical energy used for lighting actually produces light; the rest generates heat that increases the need for air-conditioning.

Hybrid solar lighting (HSL) is a technology that collects sunlight and distributes it into the interior of a building via optical fibers. A solar collector concentrates the light into an optical fiber bundle and transports that light into the building, where it is released in a controlled manner to replace a portion of the lumens required for lighting. Hybrid solar lighting increases the amount of lumens inside the building per watt of electricity being used to light interior space. Unlike conventional electric lamps, hybrid solar lighting systems produce virtually no waste heat.

Project Purpose

The goal of this project was to successfully demonstrate HSL technology in a commercial setting. The objectives of the demonstration were proving that HSL saves energy and provides higher quality lighting. Oak Ridge National Laboratory (ORNL) installed a demonstration HSL system with a display kiosk at California's Sacramento Municipal Utility District (SMUD) Customer Service Center. The system included a standard HSL collector/tracker and a fiber-optic bundle that transported sunlight from the rooftop collector to the display kiosk. The kiosk incorporated a three-tube fluorescent hybrid luminaire and three hybrid spotlights. Visitors could watch a video at the kiosk that explained the details of the technology. A computer graphic display continuously posted the energy savings for the fluorescent hybrid luminaire.

Project Results

ORNL installed the HSL 3000 system at SMUD's Customer Service Center in October 2005 (an HSL 3100 replaced the HSL 3000 in August 2006). The system consisted of the HSL 3000, a 65-foot long fiber bundle, and a display kiosk unit demonstrating HSL technology and explaining how it works. The HSL 3000 consisted of five major components: the system mounting base, the primary and secondary mirror-mount casting, the primary mirror, the secondary mirror, and the fiber/mixing rod holder. The fiber bundle was routed through the roof into the plenum area of the second floor and then down through a clear Plexiglas tube along the elevator shaft to the display kiosk. The system incorporated a three-tube fluorescent hybrid luminaire and three hybrid spotlights. At the kiosk, visitors could watch a video presentation on the details of the technology. The energy savings for the fluorescent hybrid luminaire were continuously displayed in a computer graphic to indicate the amounts of lighting being provided by sunlight and by electric lighting.

There is a significant market for a system that can deliver the benefits of natural lighting without compromising the convenience and control of artificial lighting. Starting in 2006 with the SMUD display kiosk, a 25-unit nationwide beta-testing program was conducted to evaluate system performance, quantify the benefits, and obtain user feedback related to the technology. ORNL will analyze and publish performance data, providing future consumers with a fact sheet on the full range of economic benefits associated with hybrid solar lighting.

The researchers were unable to obtain meaningful energy savings data for the installation because SMUD's hybrid solar lighting system was tied into a kiosk rather than an actual working environment. A standard hybrid solar lighting system that was identical to the SMUD system (except that it was tied into light fixtures in an office environment) was installed at San Diego State University. Initial results from the San Diego State University system indicated energy savings of better than 36 percent when compared to standard electric lighting alone. The sites are not set up to measure the savings from reduced cooling loads.

The researchers made several technical recommendations regarding HSL technology product development based on the first several months of operational data for the SMUD HSL system. Field experience demonstrated the need for improved moisture-proofing of the tracker body's mechanical and electrical components, an improved flexible coupling design for the tracker's azimuth drive to better handle wind loading, and an improved fiber holder design. Sunlight Direct, Inc. incorporated improvements related to these needs into its next-generation hybrid solar lighting system, the HSL 3100, which was beta-tested at SMUD and other test sites.

Project Benefits

- This technology demonstration provided SMUD customers, architects, lighting designers, and engineers with a new option for providing a cost-effective means of distributing controlled day lighting to interior space. The HSL development plan aggressively targeted the commercialization cost goal of $3 per square foot of illuminated space. Regions of the United States where electricity is most expensive, such as California, could pay for implementing the new technology in just two to three years once that target price is reached. Utility companies and their customers directly benefit from the offset in peak demand summer loads. During peak demand periods (clear, hot summer days), hybrid lighting can reduce the amount of expensive supplemental power needed, potentially eliminating the rolling blackouts California has experienced in the past and helping to reduce overall electricity prices.

Chapter 1: Introduction

Hybrid solar lighting (HSL) technology collects sunlight and distributes it in a controlled manner via optical fibers into the interior of a building. A solar collector concentrates the light into an optical fiber bundle and transports that light into the building, where it is released in a controlled manner to replace a portion of the lumens required for lighting (Figure 1). HSL technology increases the amount of lumens inside the building per watt of electricity being used to light interior space. HSL provides a new means of reducing energy consumption while also delivering significant ancillary benefits associated with natural lighting in commercial buildings. This natural form of lighting combines with artificial light sources, resulting in energy-savings and improved lighting quality.

Figure 1. Conceptual illustration of a hybrid solar lighting (HSL) system

The collector component (Figure 2) of an HSL system consists of a roof-mounted collector that tracks the sun and directs the focused sunlight into a bundle of polymer optical fibers. The sunlight is distributed via the optical fibers as needed throughout the building and terminates in a "hybrid luminaire fixture" (Figure 3). The luminaire integrates the light from the optical fibers with an artificial light source such as a fluorescent or incandescent lamp. This system incorporates a control system that monitors the light level in the room and adjusts the electrical lighting to maintain a constant light level in the room. On cloudy days, standard electric lighting will maintain the lighting level. On sunny days, the HSL system provides most of the lighting and maintains a constant level of room illumination regardless of solar fluctuations.

Figure 2. The solar collector tracks and directs sunlight into a fiber optic bundle

The concept for hybrid lighting has been around since the early 1970s, but it has been difficult to make the technology practical. Japanese researchers previously developed solar collectors with glass optical fibers, which are more heat-resistant, but also more expensive and more difficult to work with. The cost for the glass fiber alone is around $40,000 to illuminate 1,000 square feet (ft^2). ORNL has reduced system costs by using plastic optical fibers as well as plastic mirrors. The goal is to get the price to $3,000 for 1,000 ft^2, or $3 per ft^2. If this goal is reached, a building

Figure 3. Hybrid luminaire with solar diffusing rod

Photo Credit: Oak Ridge National Laboratory

owner in a sunny area in California could pay for implementing the new technology in two to three years with the savings on electricity bills. In other parts of the country, where sunlight is reduced and utility costs are less, this payback period would be longer.

1.1. HSL Background and Overview

HSL technology provides day-lighting to interior office space and can save energy in two ways: (1) by reducing the electrical loads required for lighting, and (2) by reducing the air conditioning requirements in commercial buildings (artificial lighting creates heat, resulting in increased air conditioning costs, which can be reduced in proportion to the amount of electrical energy saved in lighting). ORNL has developed a new HSL technology as a means of not only saving energy, but also providing higher quality lighting to help improve student performance, worker productivity, HSL system provides the visible portion of the sunlight spectrum, producing lighting with a higher color temperature as well as a higher color-rendering index (CRI). Color temperature is a simplified way to characterize the spectral properties of a light source. Low-color temperature implies warmer (more yellow/red) light, while high-color temperature implies a colder (more blue) light. The CRI is a figure of merit, on a scale of 0 to 100, used by lighting equipment manufacturers to describe the visual effect of the light on colored surfaces. Natural daylight is assigned a CRI of 100. Typical cool white fluorescent lamps have a CRI of 62. Lamps having rare-earth phosphors are available with a CRI of 80 and above.

In schools, offices, and stores, close to one-third of the electricity consumed is attributed to electric lights, most often during daylight hours when buildings are occupied and sunlight is abundant. Recent studies by researchers at the New Buildings Institute and the Heschong Mahone Group in California have found quantifiable improvements in student performance, worker productivity, and retail sales in buildings where daylight is used in place of electric lighting (for more information, see: **http://www.h-m-g.com/projects/daylighting/projects-PIER.htm**). Given these facts and the limitations of skylights, there is growing interest in exploring new methods of bringing sunlight into buildings.

The HSL technology being demonstrated at SMUD has been in development for approximately six years. The SMUD installation is one of several field-trial installations to establish operating experience and long-term feasibility. Initially, the HSL system employed a glass primary mirror that was heavy, expensive, and prone to cracking or breakage. Furthermore, it relied on a third-party tracking system that was not optimized for the product and not easily adapted. The early system used large-diameter optical fibers whose sustained availability could not be ensured by the manufacturer. The design used eight individual half-inch-diameter fibers, each in a separate adjustable holder used to align the individual fibers. The secondary mirror system was made up of 8 individual flat segmented mirrors. The original design required costly, labor-intensive machining; a difficult, time-consuming alignment process; and highly skilled technical personnel to assemble and align the overall system.

Figure 4. HSL fiber optic bundle

Since then, the HSL system design has evolved, using a custom plastic primary 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 mm in diameter (Figure 4). 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 optimized to meet the product performance goals. The system design now uses a bundle of small optical fibers available from a variety of sources.

1.2 Project Objectives

The goal of this demonstration is to give SMUD customers, architects, lighting designers, and engineers a new option for providing a cost-effective means of distributing controlled day-lighting to interior space. HSL can contribute to customers obtaining Leadership in Energy and Environmental Design (LEED) green building certification. In the United States and in many other countries around the world, LEED certification is the recognized standard for measuring building sustainability. Achieving LEED certification is the best way for building owners to demonstrate that their building project is truly “green.”

With this in mind, the project objectives included:

- Giving SMUD customers, architects, lighting designers, and engineers a new option for providing a cost-effective means of distributing controlled day lighting to interior space;
- Demonstrating how HSL can provide direct controlled day-lighting and eliminate the problems of glare, variation in intensity, and thermal impact that typically plague conventional day-lighting systems;

- Demonstrating a new disruptive technology (a technological innovation, product, or service that eventually overturns the existing dominant technology or product in the market) that uses solar energy for direct lighting applications with no conversion of solar energy to electricity;
- Educating California building owners as to how HSL can be used to help achieve LEED certification; and
- Providing initial energy monitoring data to illustrate how HSL technology can save energy in California.

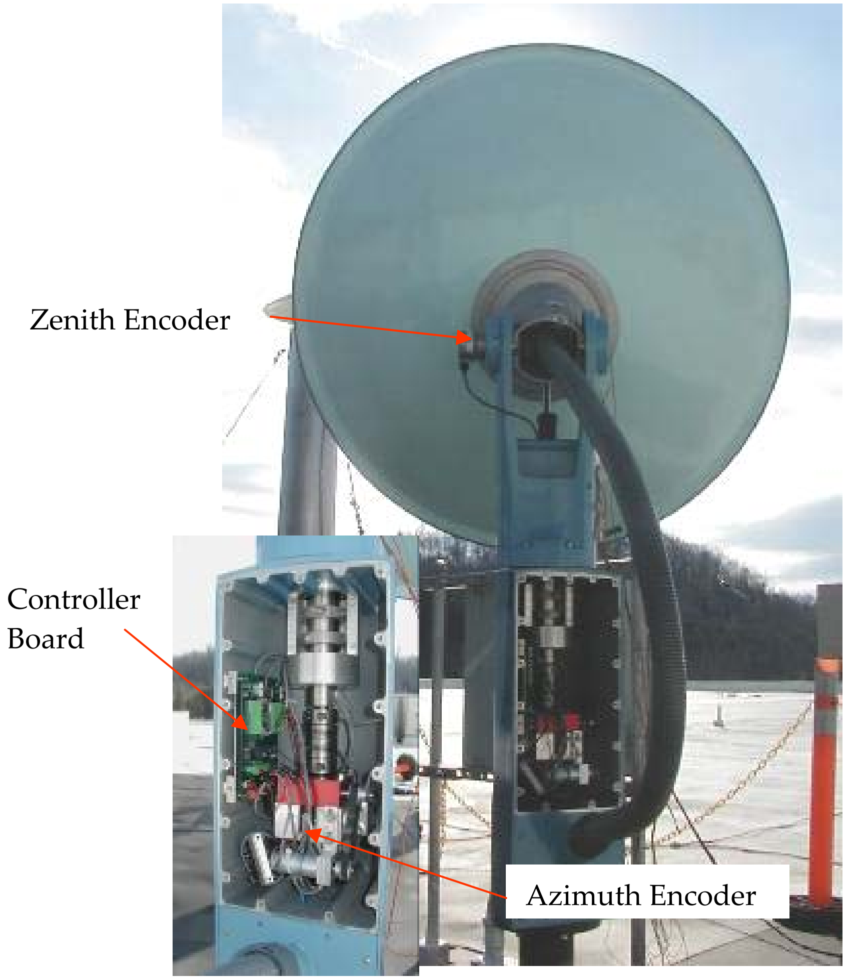


Figure 5. HSL collector

1.3. How HSL Works

The HSL collector (Figure 5) houses a sun-tracking control board (Figure 6) used to calculate the sun's position based on latitude, longitude, and time of day (Figure 7). The control board uses a microprocessor to determine the positions in the azimuth and zenith Earth-based coordinate system. The microprocessor computes the United States Naval Observatory's astronomical equations. These calculations, which determine the positions in the azimuth and zenith Earth-based coordinate system using latitude, longitude, and coordinated universal time from a global positioning system receiver, are accurate to 1/60th of a degree for the next 300 years. This precision allows the system to track at 0.1° accuracy. The coordinates are then converted to units-of-encoder counts for the two encoders that detect the collector's location on each axis. The control board allows a roof-mounted solar collector to concentrate visible sunlight into a bundle of plastic optical fibers. The optical fibers penetrate the roof via a 4-inch-diameter collector mounting post and distribute the sunlight to multiple "hybrid" luminaires within the building. The hybrid luminaires blend the natural light with artificial light (of variable intensity) to maintain a constant level of room lighting.

Figure 6. HSL controller board

The controller compares the actual direction in which it is pointed to the computed position of the sun and then determines if the collector needs to be moved in a positive or negative direction to match its position with the sun's position. 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 to track the sun accurately. The control board operates on a 12-V or 24-V dc supply and uses less than 2 watts. A PV solar cell can also be used to power the board. (PV cells were not used as part of the SMUD installation).

Photo Credit: Oak Ridge National Laboratory

When sunlight is plentiful, the distribution rod fed by the luminaires' optical fibers provides all or most of the required lighting. 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"

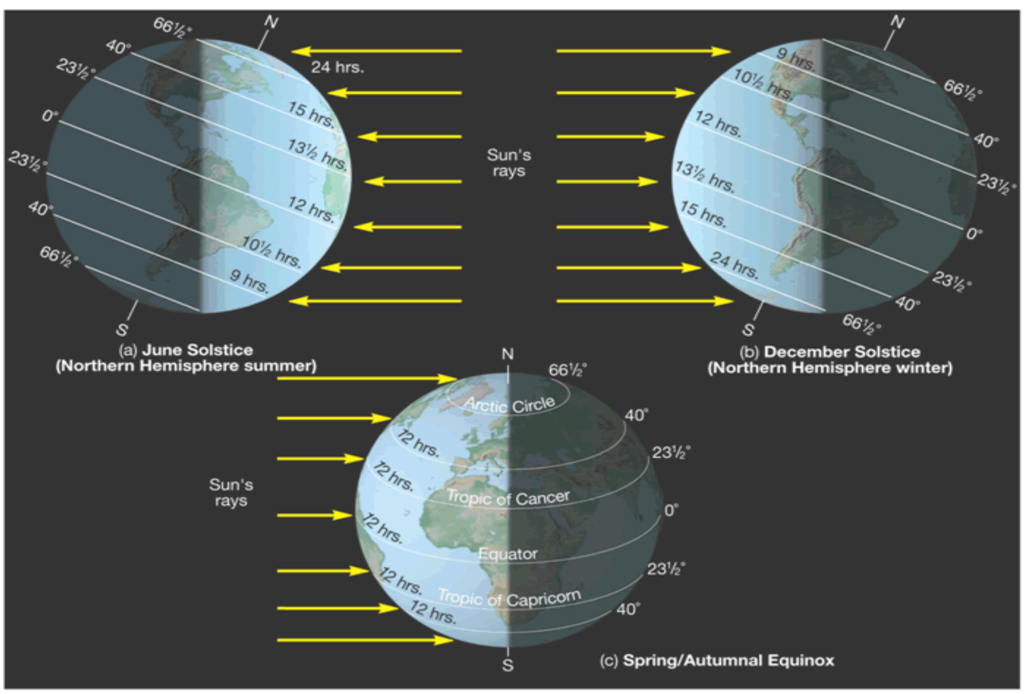
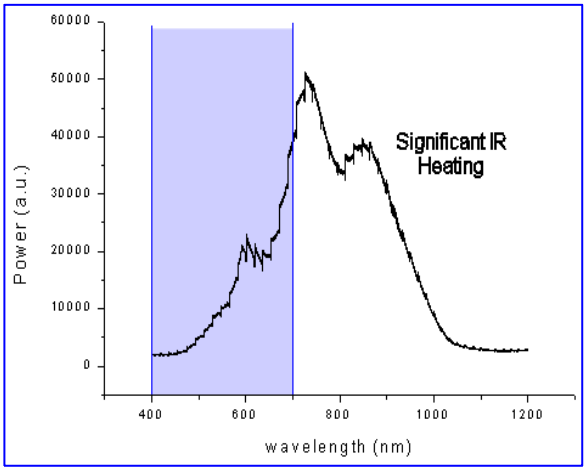


Figure 7. Hours of sunlight vary with latitude and season

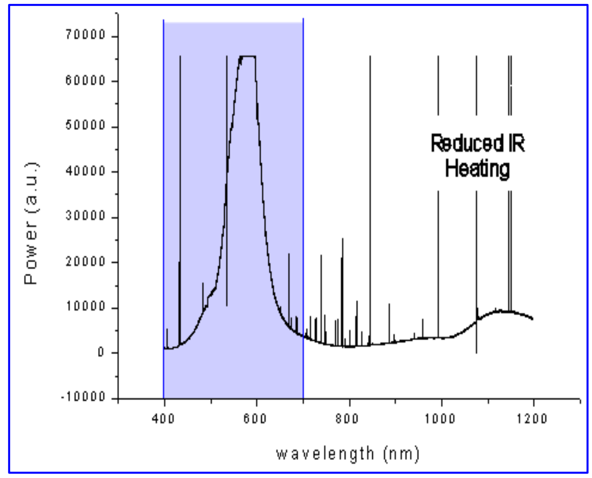
Photo Credit: Oak Ridge National Laboratory

al sunlight provided produces little or no waste heat and is cool to the touch. This is because the system's solar collector filters and removes the infrared, heat-producing light and the ultraviolet light from the spectrum, leaving only the desired visible light.

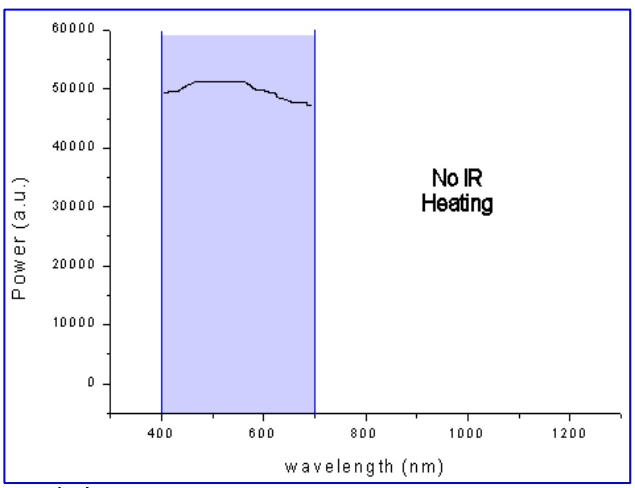
HSL technology offers the potential to separate and use different portions of sunlight for various applications. Thus, visible light can be used directly for lighting applications while the infrared and ultraviolet light could be used for heating applications or to produce electricity via a concentrated PV cell. Figure 8 compares the output spectrums in arbitrary units produced by incandescent, fluorescent, and HSL technologies. The infrared portion of the spectrum, invisible to the human eye, serves no lighting function and creates waste heat, which increases the need for air conditioning.



Incandescent (15 lumens/W)



Fluorescent (75 lumens/W)



HSL sunlight 200 lumens/W)

Figure 8. Comparison of heat production: incandescent, fluorescent, and HSL technologies

Photo Credit: Oak Ridge National Laboratory

1.4. HSL Energy Savings

On a sunny day, one HSL system will deliver 35,000 to 50,000 lumens of sunlight, or the equivalent of approximately 55 60-watt incandescent lamps. For buildings in the nation's Sunbelt that use incandescent lamps, which have a luminous efficacy of 15 to 20 lumens/Watt, the energy savings benefits of HSL technology are twofold. First, there is an energy savings of approximately 6,000 kilowatt-hours (kWh) per year due to the reduced lighting needs. (Table 1 illustrates how HSL could replace less efficient conventional electric lamps.) Second, there is an energy savings resulting from the buildings' reduced cooling load. Because the HSL system delivers light with little to no infrared component, there is very little waste heat. HVAC loads are thus reduced by 5 to 10 percent, compared with electric lighting systems. The additional energy savings depend on the cooling technology used, but are 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

(Source: Oak Ridge National Laboratory)

Type of lighting	Typical energy efficiency (approx. lm/W)
Incandescent	15
Fluorescent	75
Hybrid solar	200

As a cost saving example, for areas with high utility rates, the cost per kilowatt-hour can be as high as $0.15. Therefore, over a 10-year period, an HSL system, working with incandescent lamps, can save a building occupant in these locations $12,000 per unit. Operation and maintenance savings—due to the reduced operating hours of the electric lighting—could account for another $2,500 over the same period. For large floor spaces of 100,000 to 200,000 ft^2, this translates into $1.1 million to $2.1 million of cost savings.

Linear fluorescent lamps are much more efficient (75 lumens/watt) than incandescent lamps, which translates to lower savings and a longer payback period. As the HSL system costs fall and electricity costs increase, HSL could potentially become cost-competitive in most indoor-lighting scenarios. The HSL commercialization goal, based on market analysis for general consumer use, is an installed price of $3 per square foot (by 2010). In its initial product offering, Sunlight Direct's installed price was $24 per square foot, less than half of the early cost projections for the technology. The company has a development plan that aggressively targets the commercialization cost goal of $3 per square foot of illuminated space in the next five years. 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 two to three years with the savings on electricity bills alone.

Chapter 2:
Project Approach

HSL technology has developed rapidly. The first generation system demonstrated the concept; the second achieved a cost reduction in the solar tracking equipment as well as improved flexibility in distributing the light. In this, the fifth year of development, a third-generation system was licensed to Sunlight Direct, Inc. This company, working with ORNL, is currently beta-testing the HSL 3000 and HSL 3100 at beta sites across the United States (Figure 9). The SMUD demonstration site was the first beta site outside the Oak Ridge, Tennessee, area. Although the HSL was installed first, it was eventually replaced by the HSL 3100. This beta system significantly reduces the manufacturing and assembly costs associated with the technology and makes future use of the system for various lighting applications possible (target installed system cost in 2007 is $8 per square foot.

Figure 9. Sunlight Direct, Inc., working with ORNL, is currently beta-testing the third-generation HSL system at sites across the United States

Photo Credit: Oak Ridge National Laboratory

2.1. Sacramento Municipal Utility District HSL 3000 Installation

ORNL installed the HSL 3000 at the SMUD's Customer Service Center and began operation November 4, 2005. The system consisted of the HSL 3000, a fiber bundle 65 feet long, and a display kiosk unit produced by SMUD to demonstrate the HSL technology and explain its operation.

The HSL 3000 system consists of five major components: the system mounting base, the primary and secondary mirror-mount casting, the primary mirror, the secondary mirror, and the fiber/mixing rod holder. The assembly sequence is depicted below in Figure 10 (a–e). SMUD provided the mounting post, a 4-inch schedule-80 pipe with a mounting flange that served as a platform for the HSL mounting base as well as a feed-through point for the fiber optical bundle. The mounting base houses the tracker control system and motor drives as described in Section 1.3.

Figure 10. HSL 3000 assembly sequence, clockwise from top left: (a) HSL mounting base, (b) primary and secondary mirror mount, (c) secondary support rods, (d) primary mirror, (e) secondary mirror and fiber/mixing rod holder

Photo Credit: Oak Ridge National Laboratory

The fully assembled HSL 3000 system at the SMUD Customer Service Center is shown on the following page in Figure 11a. The fiber bundle was routed through the roof into the plenum area of the second floor and then down through a clear Plexiglas tube along the elevator shaft to the display kiosk (Figure 11b). The system incorporates a three-tube fluorescent hybrid luminaire (11c) as well as three hybrid spotlights (11d). The energy savings for the fluorescent hybrid luminaire are continuously displayed in a computer graphic (11e) to indicate the amount of lighting being provided by sunlight and the amount being provided by electric lighting. Visitors can view a video presentation at the kiosk that explains the details of the technology (11f).

The HSL 3000 was one of three ORNL-produced, limited-production units. Two were installed in the Oak Ridge area and the third was installed at SMUD. ORNL experienced numerous reliability problems with the prototype HSL 3000 units, but gained valuable operational experience and ultimately modified the design, which vastly improved system reliability.

Figure 11. HSL 3000 at SMUD's Customer Service Center, clockwise from top left: (a) fully assembled HSL 3000 at SMUD's Customer Service Center, (b) fiber bundle routing through a Plexiglas tube along the elevator shaft, (c) hybrid fluorescent luminaire, (d) SMUD's educational HSL kiosk, (e) HSL spotlights, (f) screenshot of early display

Photo Credit: Oak Ridge National Laboratory

Design issues related to the HSL 3000 and the SMUD installation included:

- The housing, which contains the sun-tracking control board, the azimuth and zenith drive motors, and the required gear drives, allowed moisture into the cavity, which created oxidation on the control board, resulting in its failure to properly track consistently.
- The flexible coupling joining the gear drive to the main azimuth shaft was inadequate to provide the required torque and was thus prone to slippage, causing the primary mirror to be misaligned with the sun.

- The fiber holder incorporated a compression fitting to hold the fiber bundle, which, over time with the normal heating and cooling cycles (both daily and seasonal cycles), allowed the fiber bundle to slip, reducing the amount of light being captured at the front face of the fiber bundle.

Because of these design issues, the HSL 3000 was unreliable, and as a result, from November 2005 to July 2006, the system was taken out of service numerous times. The flexible coupling resulted in the system being out of service twice. Then oxidation of the controller board resulted in the system being taken out of service twice, with the second instance of oxidation causing the primary mirror hub to overheat, which in turn overheated the fiber bundle. The fiber bundle was repaired in place but the repair was inadequate for long-term service. Also, the fiber bundle compression fitting allowed the fiber to slip twice, resulting in a significant reduction in the light transmitted to the kiosk.

By July 2006, ORNL had developed and successfully tested a new HSL design. Rather than continuing to repair the prototype design, it was agreed that replacing the HSL 3000 with the new HSL 3100 model would be a better option; this was done in August 2006. The HSL 3100 (Figure 12) incorporated a new fusing technology along with a redesigned fiber holder, a moisture-tight tracker enclosure, conformal coating on the tracker control board, and other improvements from lessons learned from the operation of the HSL 3000 installations. As of December 2006, the HSL 3100 has been operating continuously since its installation with no service interruptions.

The original HSL 3000 system was equipped with minimum remote monitoring and control equipment. ORNL equipped the new HSL 3100 with updated remote monitoring and control equipment as well as a web-enabled camera (Figure 13) that allows the system performance to be monitored over the Internet. The system allows remote maintenance and diagnosis of the tracker unit and provides real-time video and energy savings data.

Figure 12. HSL 3100

Photo Credit: Oak Ridge National Laboratory

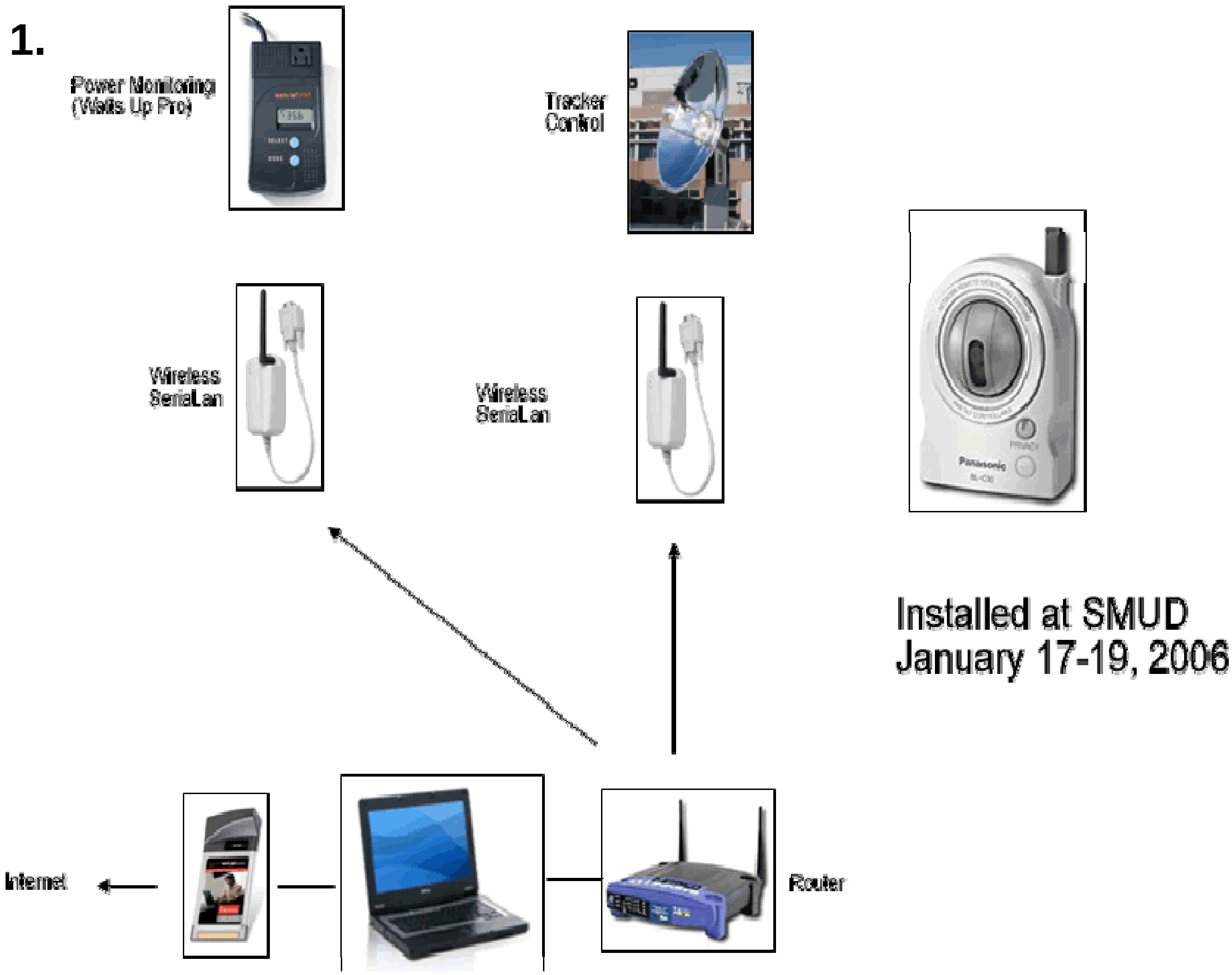


Figure 13. Remote monitoring system installed at SMUD

Photo Credit: Oak Ridge National Laboratory

Chapter 3: Project Outcomes

The commercialization of HSL technology officially began with the start of the beta-testing effort being conducted jointly between ORNL and Sunlight Direct, Inc., in 2006. Sunlight Direct plans to launch a new product in early 2007 and expects total sales of roughly 1,000 units by the end of 2009. Continued R&D efforts are also underway to increase the size of the system's primary mirror and thereby extend the illuminated space from 1,000 ft^2 to 2,000 ft^2 per system. In addition, the maximum recommended length of the optical fiber run, currently specified at 45 feet, is expected to be increased to 65 feet by the end of 2006 and to 90 feet by late 2009. Ultimately, as system performance is improved and cost is reduced, an HSL system for general illumination is expected to make significant market penetration into the commercial building sector and, eventually, the residential sector.

The SMUD HSL demonstration has provided SMUD customers, architects, lighting designers, and engineers with a hands-on experience of how HSL can be used to provide *controlled* day-lighting to interior space where there is no access to sky-lighting or other conventional day-lighting techniques. The key to the HSL technology is the fact that it provides controlled day-lighting were the light can be spatially distributed to mimic standard conventional electric lighting. The challenge with conventional day lighting techniques such as skylights, light pipes, and windows is to collect day lighting from a source that varies in both intensity and position and distribute the luminous flux comfortably with minimal glare and thermal impacts. The SMUD HSL system demonstrates how this can be accomplished.

The demonstration allows individuals to see first-hand HSL system components and operation. At the SMUD kiosk, visitors can learn in detail how this disruptive technology compares to other solar technologies such as solar PV. Unlike solar PV technology, HSL requires no conversion of energy from one form to another but rather uses solar energy in the form of light directly for lighting purposes.

Electricity is conserved during daytime peak demand periods in proportion to the amount of sunlight available. The HSL approach is to provide the user with a high quality day-lighting system. In addition to cost savings, the day-lighting character of HSL can greatly improve the lighting quality by providing full spectrum, high-color-temperature lighting. Studies have shown that day-lighting not only increases worker productivity but also positively affects the wellbeing of people who work or spend time in a day-lit environment. ORNL, in conjunction with SMUD, will be hosting an HSL Summit where end users, architects, lighting designers, and engineers will convene to evaluate the technology and help determine how best to introduce and promote it in California.

Because SMUD's HSL system is tied into a kiosk rather than an actual working environment, meaningful energy savings for the SMUD installation cannot be calculated. Because the beta-testing phase is not yet completed, there are insufficient data for comprehensive results; however, we can examine the data from San Diego State University, one of the beta sites, to see an example of the benefits of HSL. These data show a typical operation cycle at the university for an HSL 3100 on a normal work day. In the figure, the light is turned on early in the morning (we will assume little or no sunlight is available and all the light is being provided by the electric lights). As the sun rises, it supplies more and more of the interior lighting via the HSL system, and the power usage begins to decline. The electric lights are dimmed by approximately 60 percent during the brightest part of the day; as the sun goes down in the afternoon, the electric light use increases until the lights are turned off in the evening.

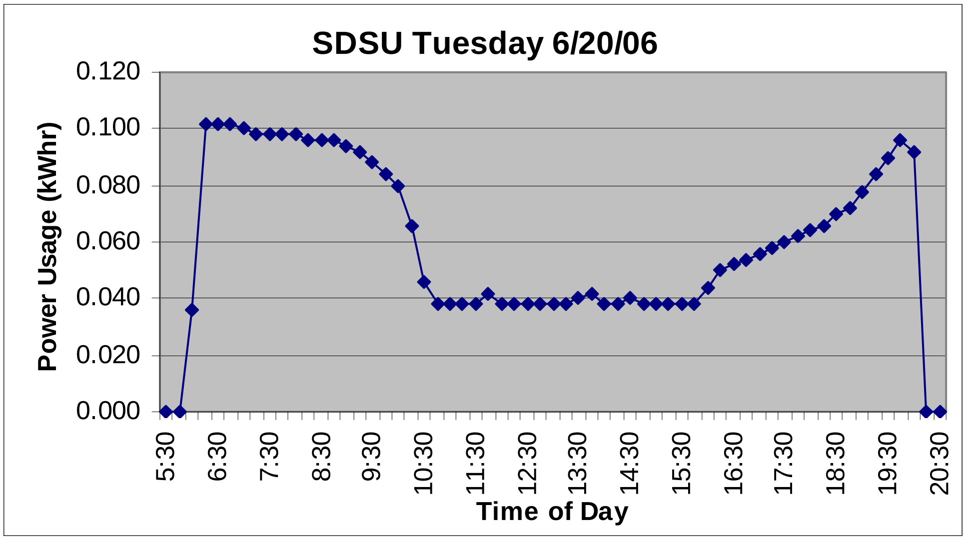


Figure 14. Energy usage at San Diego State University (Source: Oak Ridge National Laboratory)

The calculations below show that on a typical day in June at San Diego State University, the HSL system was able to reduce the power used for lighting by 36 percent. The baseline power usage (power used without the benefit of HSL technology) is equal to the power used in a 15-minute interval times the number of 15-minute intervals in an hour times the total number of hours the lights were on. Thus, the baseline power usage

= 0.102 kWh × 4 × 14 hr

= 5.712 kWh or 5712 Whr

Actual power used = sum of power used in each 15-minute interval (area beneath curve)

= 3.630 kWh or 3630 Whr

Total power saved = baseline power usage – actual power used

= 5712 Whr – 3630 Whr

= 2082 Whr

Percent savings = (Total power saved / Baseline power usage) × 100

= (2082/5712) × 100

= 36 percent

3.1. Market Potential

At first, the most probable candidate for the first commercial use of HSL will be multi-story buildings (upper two floors) that (1) are Sunbelt locations where daytime electricity prices are highest; (2) are occupied daily, including weekends; and (3) use lighting applications where lighting quality (color temperature and CRI) is important and less-efficient electric lamps are currently used.

As Figure 15 illustrates, federal facilities in the Sunbelt region are an excellent first market for HSL. The first chart illustrates that 77 percent of all federal facilities are in the Sunbelt region; the second chart illustrates that 72 percent of all federal building square footage is in the Sunbelt region. More in-depth analysis of savings potential by market segmentation is planned for 2007.

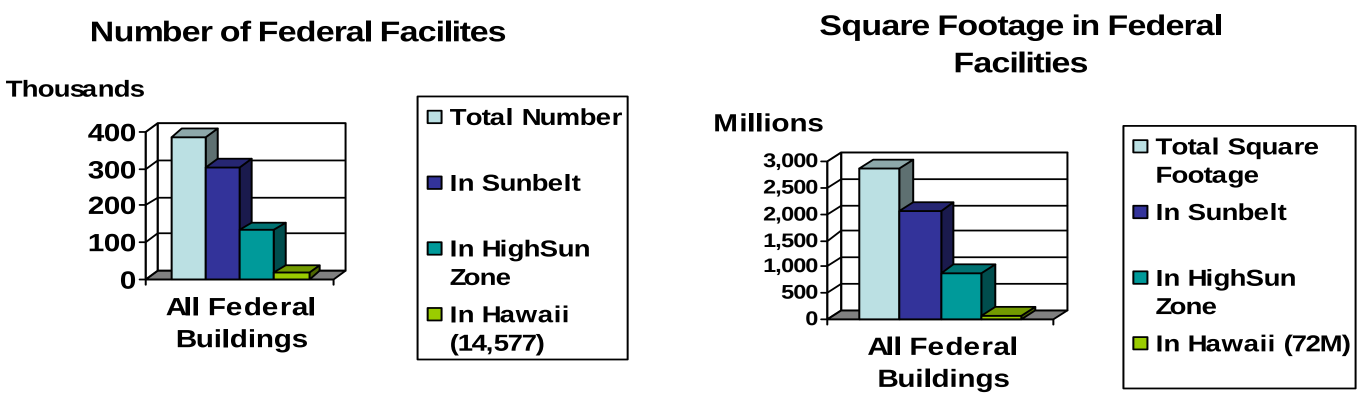


Figure 15. HSL market statistics for federal facilities in the Sunbelt

Photo Credit: **http://fempgis.pnl.gov/**

Chapter 4: Conclusions and Recommendations

4.1. Conclusions

Artificial lighting is the largest component of electricity use in the 72 billion ft^2 of commercial building space in the United States. Commercial building owners spend nearly $17 billion a year in electricity costs for artificial lighting. 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—it fluctuates in intensity and is highly directional (produces glare and unwanted heating).

There is a significant market for a lighting system that can deliver the benefits of natural light without compromising the convenience and control of artificial light.

Begun in 2006 with the SMUD display kiosk, a 25-unit nationwide beta-testing program is underway to evaluate system performance, benefits, and user feedback related to the technology. ORNL will analyze and publish the performance data, providing future consumers with a fact sheet on the full range of HSL-associated economic benefits.

ORNL looks forward to feedback on the HSL system installed at the SMUD Customer Service Center and is excited about the upcoming opportunities to increase awareness of HSL through the upcoming SMUD-sponsored HSL workshop in spring 2007. Additional field trial deployments are ongoing in California.

4.2. Recommendations

Based on the first several months of operational data for the SMUD HSL system, several technical recommendations were made regarding HSL technology product development. Specifically, field data demonstrated a need for improved waterproofing of the mechanical and electrical components in the tracker, an improved flexible coupling design for the azimuth drive of the tracker to better handle wind loading, and a new fiber bundle holder design. Sunlight Direct, Inc., has incorporated these recommendations into the new HSL 3100 currently being beta-tested at SMUD and 15 other sites throughout the country.

4.3. Benefits to California

The HSL commercialization goal based on market analysis for general consumer use is an installed cost of $3 per square foot of illuminated space. In Sunlight Direct's initial product offering, the installed price of $24 per square foot is considerably more than the target price, thus providing the primary challenge to market penetration. Sunlight Direct is aggressively targeting the commercialization cost goal of $3 per square foot of illuminated space. Once installed cost of $6.30 per square foot is reached, regions of the United States where electricity is most expensive could pay for implementing the new technology in just two to three years (see Tables 2 and 3—Calculation provided by Sunlight Direct).

Utility companies and their customers directly benefit from the offset in peak demand summer loads. During peak demand periods (clear, hot summer days), HSL can reduce the amount of expensive supplemental power that must be provided, potentially eliminating the rolling blackouts California has experienced in the past and helping to reduce overall electricity prices.

Table 2. Return on investment for hybrid solar lighting for incandescent lighting (Source: Sunlight Direct, Inc.)

Installation Cost	Incandescent
System price	$8,000.00
Installation price	$1,000.00
Total price	$9000.00
Total price w/ federal tax credit (30%)	**$6,300.00**
Installed cost per square foot per year	$6.30
Energy savings per year	**$1,209.60***
No. of bulbs to replace for coverage area	40
Cost per bulb	$1.50
Bulb replacement labor, per bulb	$1.00
Frequency of bulb replacement (in months)	2
Total Bulb Replacement Costs (Annually)	$600.00
Life Extension of Bulb with HSL (factor of months)	12
Bulb Replacement Savings per year	**$550.00**
Savings on HVAC per square foot	$0.57
HVAC savings per year	**$568.26***
Total cost savings per year	**$2,327**
Return on investment (months)	**32**

***see Table 3 for supporting calculations**

Table 3. Energy savings calculations supplement to Table 2	
Lighting Savings	
Average daily available direct solar energy per square meter ($kWh/m^2/day$)	5.3
Collector area (m2)	1.0
Collector and distribution efficiency	50%
Total delivered light (lumens)	50,000
Efficiency of electric lighting (lumens/W)	12
Amount of displaced wattage (W)	4,167
Annual electricity displacement (kWh)	8060
Cost of electricity ($/kWh)	$0.15
Annual energy savings (lighting)	**$1,209.06**
HVAC savings	
HVAC heat removal efficiency (kW of electricity required to remove kW of heat)	0.5
Efficiency of artificial lamps (lumens/W)	12.0
Efficiency of hybrid solar lighting (lumens/W)	200.0
Waste heat displaced with HSL (kW)	3.9
HVAC load reduction (kW)	2.0
Annual HVAC load displaced (kWh)	3,788.40
Cost of electricity ($/kWh)	$0.15
Annual energy savings (HVAC)	**$568.26**
[a]DOE National Renewable Energy Laboratory (Sunbelt U.S. Region Data)	
[b]Assumes incandescent lighting	
[c]Assumes business is open during daylight hours, 7 days a week	
[d]Annual savings agree with conclusions of National Energy Technology Laboratory Report #41164R06, *Adaptive Full Spectrum Solar Energy System*, pg. 10, Figure 1.6.	
[e]Varies with building design, HVAC system, and environment.	

Source: ORNL ; Source: Sunlight Direct, Inc.

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