DESIGN AND APPLICATION OF FIBER OPTIC DAYLIGHTING SYSTEMS

by

CHRISTOPHER G. WERRING

B.S., Kansas State University, 2009

A REPORT

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Architectural Engineering and Construction Science
College of Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2009

Approved by:

Major Professor
Rhonda Wilkinson, P.E., LEED AP

Abstract

Until recently sunlight was the primary source of illumination indoors, making perimeter fenestration essential and impacting the layout of buildings. Improvements in electric fixtures, light sources, control systems, electronic ballasts and dimming technology have influenced standard design practices to such a degree that allowing natural sunlight into a room is often seen as a liability. In the current climate of increasing energy prices and rising environmental awareness, energy conservation and resource preservation issues are a topic of governmental policy discussions for every nation on the planet. Governmental, institutional, social and economic incentives have emerged guiding the development and adoption of advanced daylighting techniques to reduce electric lighting loads in buildings used primarily during the day. A growing body of research demonstrates numerous health, occupant satisfaction, worker productivity and product sales benefits associated with natural lighting and exposure to sunlight. However, incorporating natural light into a lighting strategy is still complicated and risky as the intensity, variability and thermal load associated with sunlight can significantly impact mechanical systems and lead to serious occupant comfort issues if additional steps aren't taken to attenuate or control direct sunlight.

Fiber optic daylighting systems represent a new and innovative means of bringing direct sunlight into a building while maintaining the controllability and ease of application usually reserved for electric lighting by collecting natural light and channeling it through optical fibers to luminaires within the space. This technology has the ability to bring sunlight much deeper into buildings without impacting space layout or inviting the glare, lighting variability and heat gain issues that complicate most daylighting strategies. As products become commercially available and increasingly economically viable, these systems have the potential to conserve significant amounts of energy and improve indoor environmental quality across a variety of common applications.

Table of Contents

List of Figures

CHAPTER 1 - Fiber Optic and Hybrid Solar Systems

1.1 Setting the Stage

At the beginning of the twentieth century sunlight was the primary source of illumination within buildings but dramatic improvements in the efficiency, size and quality of electric light sources changed standard design practices in favor of easily controlled occupant responsive artificial lighting systems. Building shapes, room designs, light fixtures and lamps all transitioned toward high quality predictable electric lighting tailored to the owner's needs while allowing the intrusion of variable, dramatic and often overpowering direct sunlight was seen more and more as a liability. During the oil embargo of the 1970s increasing energy prices generated renewed interest in daylighting as a means to displace electric lights when possible and reduce energy consumption. However, the practice never gained widespread use as the quality of artificial lighting continued to improve and more complex daylighting designs failed to produce acceptable payback periods (Muhs(b) 6).

Over the last few decades government, institutional and private industry research has developed cost effective solutions to the myriad problems associated with designing an integrated, energy efficient and functional daylighting strategy. The evolution of codes and standard design practices, daylight modeling software, high performance glazing, fluorescent dimming technology and automated lighting control systems have made daylight harvesting systems easier to design, simpler to install and economically viable in a widening range of applications (Hybrid Solar Lighting). In a report presented at the Solar2000 Conference Jeff Muhs of the Oak Ridge National Laboratory explained the advances in, and limitations of, modern daylight harvesting technology.

> In recent years, however, a few technologies have made daylight harvesting a reality for some applications. For example, dimming ballasts are in widespread use in conjunction with perimeter fenestration systems to reduce electric lamp energy consumption. Today, topside daylighting approaches are

> designed to reduce glare and variability, minimize the need for control, and eliminate excessive illuminances. In doing so, however, they typically waste a significant portion of the natural light available by shading, attenuating, and or diffusing direct sunlight. Because more than 80% of the light available on a sunny day is in the form of direct sunlight, the energy end-use efficiency of state-of-the-art daylighting systems is therefore low, and the associated simple payback is relatively high in comparison to other energy-efficiency measures. This limits the market penetration of such systems and their utility to save significant amounts of nonrenewable energy (Muhs(a) 1).

Harnessing the power of sunlight for energy conversion, plant growth and lighting applications has been the focus of significant research by N.A.S.A., the U.S. Air Force, the Department of Energy and numerous other public and private institutions worldwide. In the 1970's optical fibers were first used to channel sunlight from a collector to light fixtures within a building. Collecting sunlight and guiding it to specific end uses with fiber optic cables represents the most effective method of harnessing the sun's power to displace electric lighting while solving many of the glare, heat gain, controllability and consistency issues that plague traditional daylighting designs using exterior glazing. Transmission of sunlight through optical fibers also facilitates natural lighting of a much larger building area without affecting the floor plan or requiring the large weatherproofing penetrations needed for skylights or clearstory windows. This paper begins with an explanation of the fiber optic daylighting concept and a description of the design and development of individual system components. In addition to design theory several governmental, institutional and private industry efforts to develop fiber optic daylighting components are presented as examples of the potential products further development can bring to lighting designers and building owners.

The second chapter is a discussion of the economic issues guiding initial market penetration of early generation solar lighting designs, identifying the geographic locations and occupancy types most likely to capitalize on the energy savings, lighting quality, worker productivity and occupant satisfaction benefits associated with properly designed fiber optic daylighting systems. A baseline fiber optic daylighting system cost estimate is established and compared to conventional natural and artificial lighting strategies in order to demonstrate the potential commercial viability of this technology compared to other lighting strategies.

The third chapter establishes basic criteria and performance parameters that can be used to compare solar harvesting design options and determine the effectiveness of a daylighting strategy. A properly designed daylighting system is critical to maximizing potential financial and environmental quality benefits while maintaining controlled and occupant responsive lighting for a given space. To demonstrate the lighting control and application benefits achieved by channeling sunlight to light fixtures using optical fibers the chapter concludes with a discussion of the primary lighting quality and occupant comfort issues that designers must consider when bringing sunlight inside.

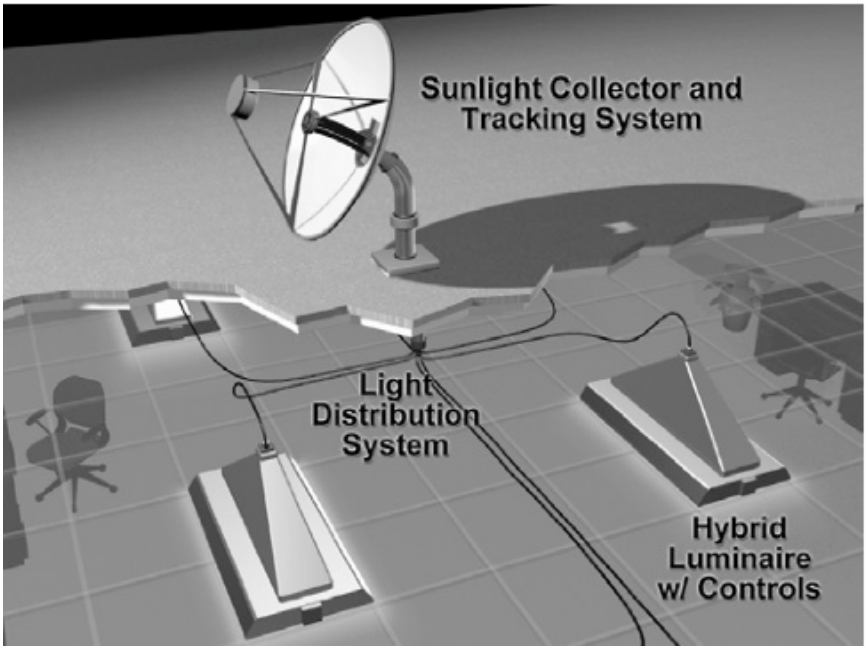
The fourth chapter further justifies the use of solar harvesting systems by reviewing several studies into the effects of sunlight exposure on humans as well as the occupant productivity impacts of daylighting in educational, office, retail and healthcare facilities. Occupant satisfaction is the ultimate gauge of any lighting design and scientists are continuing to develop our understanding of the role light plays in the body's regulatory processes and the maintenance of both mental and physical health. Numerous medical studies have linked a connection with the outdoors and exposure to full spectrum sunlight with myriad physiological, psychological and productivity benefits that may provide less tangible incentives to install fiber optic daylighting systems.

In order to quantify the tremendous amount of power used for electric lighting and illustrate the potential to displace this load with high quality natural light, the final chapter is dedicated to building electrical consumption in the United States. Declining fossil fuel supplies, increasing energy prices and global climate changes have lead to mounting public and private pressure to improve resource utilization efficacy and minimize production and operation inefficiencies. As social pressures and energy prices increase, the cost of designing more complex and ultimately more energy efficient lighting systems grows progressively easier to justify. The chapter discusses industry programs to incentivize environmentally sustainable design and concludes with a summary of benefits possible using passive or hybrid solar systems to improve lighting quality, increase occupant satisfaction and reduce building electrical consumption by making a concerted effort to implement this new and promising 'green' technology.

1.2 Fiber Optic Daylighting System Overview

Fiber optic daylighting systems are divided into passive and hybrid solar lighting categories. Passive solar lighting systems are composed of three main components: the sunlight collector and tracking mechanism, optical fibers and associated connections and finally luminaires to distribute light within the space. Hybrid solar lighting systems contain the same components as passive designs, however electric lamps and a dimming control system are incorporated to determine when adequate direct sunlight is unavailable and modulate the electric sources to supplement natural light. The figure below illustrates the components of a fiber optic daylighting system developed at the Oak Ridge National Laboratory in association with the Department of Energy. The collector is located on the roof with an unobstructed view of the sun while the optical fibers and luminaires distribute captured light within the building.

Figure 1.1 Hybrid Solar Lighting System Schematic



Copyright 2000. ASME (Muhs(a) 3)

1.3 Solar Collectors

Solar collectors for passive or hybrid daylighting systems are responsible for capturing direct sunlight and channeling it into one or more optical fibers for transmission to end uses within the building. The functionality of a solar collector is primarily dependent on its collection efficiency, the quantity of sunlight gathered consistently and the duration over which design light levels can be maintained. Designs are continuously evolving to minimize light losses within the collector and increase luminous flux entering the optical fibers, enabling each collector to support higher space illuminance levels and a larger number of fixtures, lighting a greater area and reducing overall system cost.

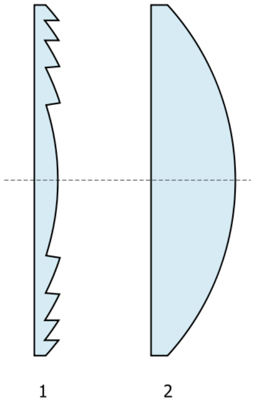
Advances in microprocessor technology have facilitated increasingly accurate tracking motor control systems, consequently improving collection efficiency and duration. Some collector designs even include photovoltaic cells capable of powering the solar tracking control circuitry and motors allowing the entire system to function without any electrical connection. Commercialization and use of advanced materials manufacturing have made the collector system viable for a variety of lighting applications where improved indoor light quality and reduced daytime power consumption are primary design goals (Lapsa, Maxey, et al. 11; Soydan, Engin 1).

Through the research and development of many public and private groups two basic collector designs have proven to be the most effective, reliable and cost competitive. The first strategy uses Fresnel lenses to refract and concentrate sunlight into optical fibers; the second design captures incoming light by reflection off parabolic mirrors.

1.3.1 Collectors Using Fresnel Lenses

The Encyclopedia Britannica describes a Fresnel lens as a “succession of concentric rings, each consisting of an element of a simple lens, assembled in proper relationship on a flat surface to provide a short focal length.” Figure 1.2 shows the cross-section of a Fresnel lens (1) compared to that of a simple lens (2), and illustrates the dramatic difference in material volume and overall depth required to achieve the same optical characteristics.

Figure 1.2 Fresnel Lens Cross-Section



Applied to solar collection, Fresnel lenses refract incident sunlight from the entire face of the lens to a single focal point behind the opposite side of the lens. To transmit collected sunlight the exposed end of an optical fiber, or a bundle of several small fibers, is mounted behind each lens at its focal point. Early in the 1970s Dr. Kei Mori of the Himawara Corporation developed a concept solar collector using a single Fresnel lens to harness and concentrate direct sunlight for a variety of end uses (The Inventor). The collector was named the ‘Himawari’ after the Japanese word for sunflower. By 1979 Mori had further developed the solar collecting and tracking system into a prototype containing a series of hexagonal Fresnel lenses mounted in a honeycomb pattern to form a single circular collector array that refracted incoming sunlight into optical fibers for transmission. “[Originally]… light distribution losses in polymer optical fibers were high, and different portions of sunlight were attenuated more than others, making emerging light look different from natural sunlight” (Soydan, Engin 1). These and other problems made the system impractical, inefficient and cost prohibitive for commercial application.

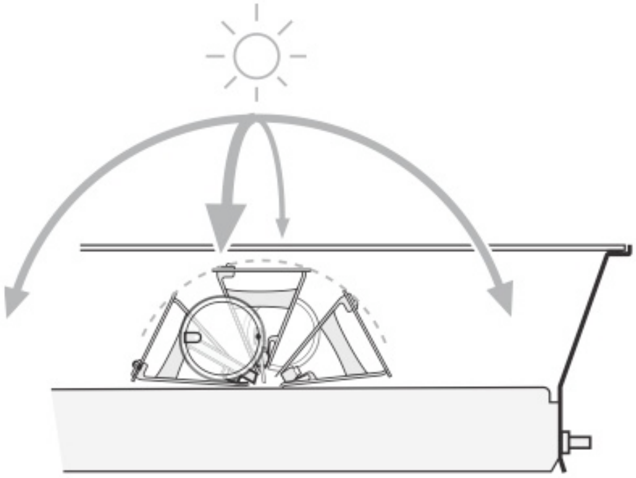
Later design iterations used progressively more complex arrangements of Fresnel lenses and optical fibers to supply a greater number of light fixtures with brighter and more consistent light. Smaller collectors were adapted to use fewer Fresnel lenses, each made circular to improve individual component collection efficiency above that of the hexagonal array (History of the Himawari). The Himawari's success spawned an entire line of solar collectors, each designed to capture more light than the last and support a greater number of fixtures. The largest Himawari, shown on the left in Figure 1.3, contains 198 lenses mounted in a honeycomb pattern and is capable of supplying thirty-three luminaires with a total luminous flux of 53,790-lumens (lm). On the right in Figure 1.3 is the smallest Himawari with only twelve circular lenses capable of supplying two luminaires with a total flux of 3,840-lm (Products Line-Up; Specifications).

Figure 1.3 Himawara's 198 Lens (Left) and 12 Lens (Right) Fresnel Solar Collector

Copyright 2006. La Forêt Engineering Co., Ltd (Products Line-Up)

Parans, a solar lighting systems manufacturer based in Sweden, developed a collector using a series of Fresnel lenses, however, the design uses a much different organizational pattern than that of the Himawari. The collector is about one meter square and 180-mm deep, containing a series of sixty-two circular Fresnel lenses mounted across the face of the collector. Each lens is held in place by a small V-shaped metal frame secured to a pivot point at its base. This mounting design allows each lens to pivot in a cone around the frame's base point as illustrated in Figure 1.4.

Figure 1.4 Parans Fresnel Lens Mounting



Copyright 2008. Parans Solar Lighting AB (Parans 11)

The circular lenses are mounted in a grid across the collector's face, each surrounded by enough open space to accommodate uniform movement as a group in response to changing sun position. The supports are interconnected with a grid of struts linked to actuator motors controlled by a photocell-based tracking system which continuously points the lens array in the direction of maximum solar intensity. Articulation of each Fresnel lens allows for tilt angles of 60º in any direction, forming a 120º active cone capable of capturing direct sunlight for an eight-hour period (Parans 12).

Each circular Fresnel lens is mounted above a 0.75-mm optical fiber with the exposed end located at the focal point. The small fiber optic cables are bundled to form four separately jacketed large cables, each 6-mm in diameter and capable of supplying a separate luminaire with natural sunlight (Parans 12). This modular optical fiber configuration allows Parans' designers to work backwards from the light fixture layout to determine the number of collectors required to support every fixture with the required 6-mm fiber bundle connections. Each collector can supply multiple light fixtures or provide four connections to a larger fixture, increasing system flexibility without complicating the optical fiber distribution system. Whatever the collector configuration, newer iterations of Fresnel lens collectors still contain the same basic components as the original: a series of lenses coupled to dedicated optical fibers routed out of the collector and into the building.

Figure 1.5 Parans 'SP2' Solar Collector

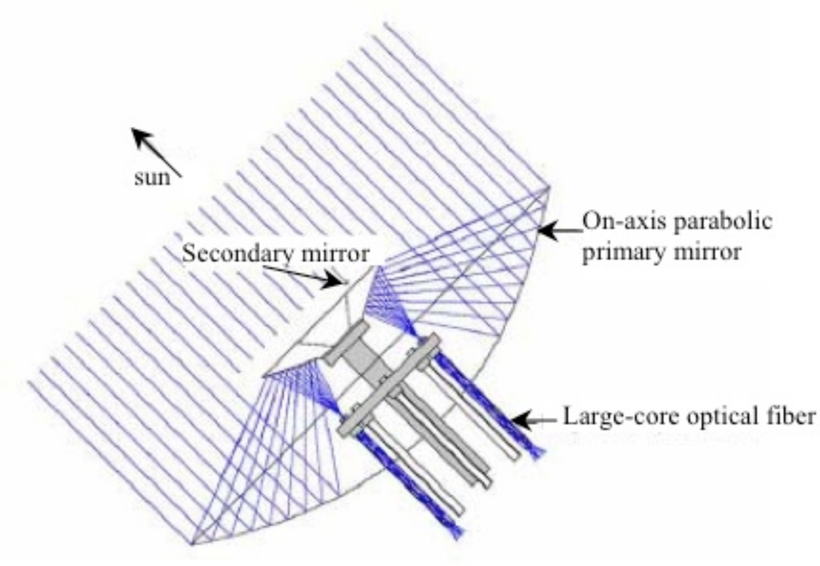
Copyright 2008. Parans Solar Lighting AB (Parans 11)

1.3.2 Collectors Using Parabolic Reflectors

Like the first reflecting telescopes, the first collectors to channel sunlight into an optical fiber using a mirror were very simple. A parabolic mirror was pointed at the sun and an optical fiber was located at the mirror's focal point to collect reflected light. Single mirror designs reflected sunlight from the mirror's outer edge to the focal point at relatively high angles of incidence, restricting transmission efficiency within the fiber as high entrance angles diminish the total internal reflection of captured sunlight. Controlling the angle at which captured light entered the optical fiber became the focus of reflecting collector design, eventually leading to a dual mirror approach capable of concentrating and directing incoming sunlight into a fiber nearly parallel to its center axis.

Parabolic reflecting solar collectors using two mirrors are based on the design of a reflecting telescope, originally developed by Newton in 1668, using a primary collection mirror to concentrate light onto a smaller secondary mirror located at the primary mirror's focal point (Telescope). Unlike a reflecting telescope, the secondary mirror of solar collector is composed of several small sections of a parabolic mirror arrayed around the collector's center axis, each designed to focus the concentrated sunlight from the primary mirror down onto one of several optical fibers passing out the center of the primary mirror and into the building. The size of each secondary mirror section is dependent on the number of optical fibers arrayed around the center of the collector. Figure 1.6 shows a ray diagram illustrating the path of direct sunlight incident on the primary mirror. Notice the shallow angle at which light enters the fiber compared to range of angles at which reflected light strikes the secondary mirrors.

Figure 1.6 Parabolic Reflector Ray Diagram



(Soydan, Engin 3)

Researchers at the Oak Ridge National Laboratory (ORNL) developed an exceptional parabolic solar collector system in 1999 with several noteworthy improvements over the basic design. The collector, shown in Figure 1.7, uses a four-foot diameter acrylic parabolic primary mirror that is substantially lighter, less expensive and more durable than a traditional glass mirror to dramatically reduce system cost while maintaining collection efficiency. The primary mirror reflects direct sunlight onto one of eight spectrally selective secondary optical elements, or cold mirrors, that allow near infrared radiation to be transmitted while reflecting visible solar energy (Soydan, Engin 3). Each cold mirror focuses non-diffuse visible light into one of eight large-core optical fibers, or bundles of smaller fibers, and transmits the infrared radiation through the mirror onto a photovoltaic cell mounted behind. This design takes advantage of the fact that photovoltaic cells are more efficient at generating electricity from light in the near-infrared portion of the spectrum while simultaneously protecting the optical fiber bundle against excessive heat gain from the concentrated sunlight. By channeling only visible light into optical fibers for use indoors and simultaneous generating power to operate the collector's tracking mechanism, this design further improves end-use efficiency by allowing the collector to deliver 50,000-lm of luminous flux while consuming very little power during operation (Lapsa, Maxey et al. 8; Muhs(a) 4).

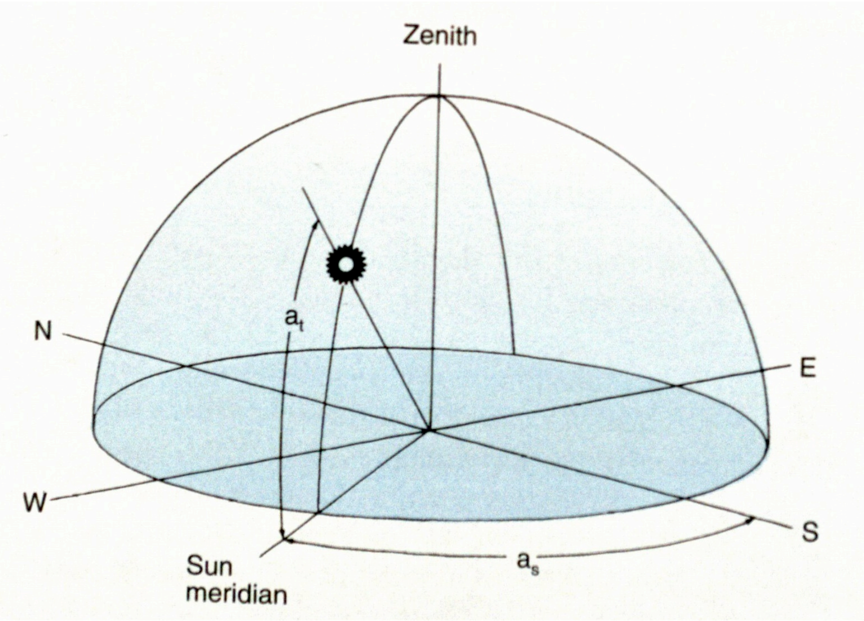
Figure 1.7 ORNL Parabolic Reflecting Collector

From *Energy Engineering* Vol. 4, No. 104 (Lapsa, Maxey, et al. 8)

1.4 Tracking Systems and Collector Alignment

Proper operation of a passive or hybrid solar lighting system requires direct sunlight focused into the end of an optical fiber, a task made difficult by the sun's constantly changing position in the sky. In order to provide consistent light levels solar collectors employ tracking mechanisms to maintain constant alignment with the sun while mirrors or lenses reflect or refract light into a group of optical fibers. Tracking systems have been developed with the goals of maintaining precise alignment with the sun and maximizing operational hours thus minimizing power required for electric lighting and shortening payback periods associated with the solar lighting system. Alignment errors outside tight tolerances correspond to significant reductions in collection efficiency and system efficacy (Beshears, Capps, et al. 2-3). Maintaining proper collector alignment with the sun requires a mechanical tracking system capable of tracking both vertically and horizontally relative to the earth. Two-axis tracking designs contain one actuator to rotate the device around a vertical axis perpendicular to the earth, controlling the ‘azimuth’ angle (measured from due south), as well as an actuator to adjust the collector’s angle of tilt measured from the horizon known as the ‘altitude’ or ‘zenith’ angle.

Figure 1.8 Sun’s Azimuth (a_s) and Altitude (a_t) Angle Relative to Primary Compass Directions

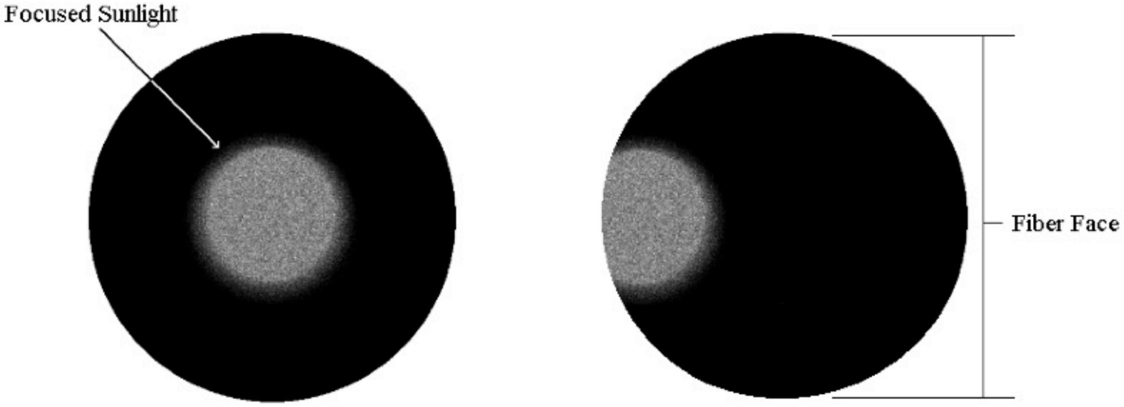


Copyright 2006. IESNA (Rea 8-22)

1.4.1 Critical Alignment Parameters

First, the solar collector must be properly configured to minimize internal alignment errors between the lenses or mirrors and the optical fibers. An ideal configuration will focus incoming direct sunlight precisely into the center of the exposed end of each optical fiber thus maximizing the quantity and intensity of light directed into the building. However, if the alignment of collector components is not perfect, as is usually the case, collected sunlight will be focused off the center of the optical fiber as shown in Figure 1.9 and could potentially miss the fiber altogether. The quantitative decrease in light captured by the collector is proportional to the percentage of focused sun image incident on the optical fiber ends. Light is transmitted through optical fibers via total internal reflection of light rays within the fiber core and light focused off the fiber center is less likely to be totally reflected, which can intensify transmission losses discussed further in Section 1.5.

Figure 1.9 Concentrated Sunlight Properly and Improperly Focused Into Optical Fiber



Copyright 2003. ASME (Beshears, Capps, et al. 2)

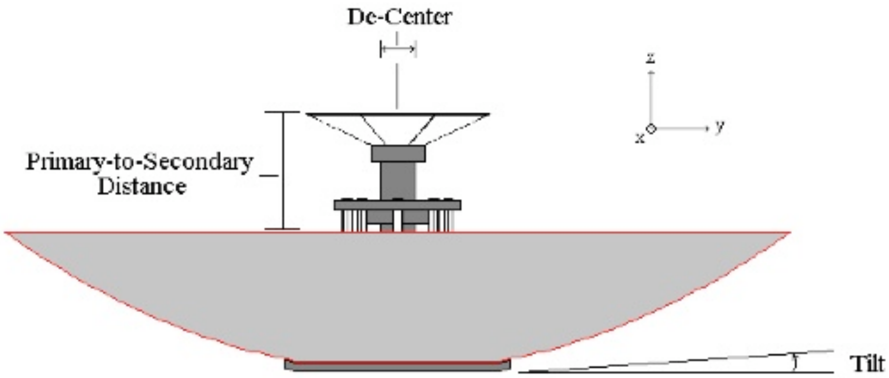
Research conducted by the Oak Ridge National Laboratory tested two potential tracking systems for the parabolic reflecting solar collector developed at ORNL. Five alignment parameters critical to proper collector function were established and acceptable tolerances were determined with the goal of fully capturing the reflected sun image within each of the eight optical fibers mounted above the center of the primary mirror (Beshears, Capps, et al. 2). In order to quantify alignment variations the team established an X-Y-Z coordinate system around a test collector mounted facing straight up in a bowl shape as shown in Figure 1.10. The X-Y plane was established parallel to the ground as a tangent plane touching the center of the primary mirror. The Z-axis was defined extending vertically through the center of the primary and secondary mirrors. The first two critical parameters complement each other and together describe the primary mirror's angle and direction of tilt off true vertical. The third and fourth critical parameters are also related and measure horizontal differences in mounting position between the primary and secondary mirrors, measured in the X-Y plane. The fifth and final critical parameter simply measures the vertical separation of the primary and secondary mirrors.

The first parameter is X-Tilt, or the angle of the primary mirror's tilt off the vertical Z-axis relative to the secondary mirror, measured along the X-axis. The second parameter is called

Y-Tilt, or the primary mirror's angle of tilt off the Z-axis relative to the secondary mirror, measured along the Y-axis. The third parameter is called X-De-Center and measures the horizontal distance along the X-axis between the center points of the primary and secondary mirrors. The fourth parameter is called Y-De-Center and measures the distance between the center points of the primary and secondary mirrors along the Y-axis. The fifth parameter is called the Primary-to-Secondary distance and is simply the offset between the primary and secondary mirrors measured along the Z-axis (Beshears, Capps, et al. 2).

Allowable alignment tolerances were calculated by limiting variations in the established parameters to ensure that all focused sunlight was captured by the optical fiber array. "If a misalignment caused any portion of the focused sunlight to exceed the reach of the fiber optic cores, the misalignment was deemed unacceptable" (Beshears, Capps, et al. 2). X-Tilt and Y-Tilt angles of ±0.125° off true vertical were deemed acceptable. Mounting misalignments between the primary and secondary mirrors, X and Y-De-Center distances, were found be acceptable if kept within a 3-mm variance in either direction. Divergence in Primary-to-Secondary mounting height distance was acceptable if kept within a 2-mm variance (Beshears, Capps, et al. 2).

Figure 1.10 Critical Internal Alignment Parameters



Copyright 2003. ASME (Beshears, Capps, et al. 2)

The same alignment parameters used on parabolic reflectors can be simplified and applied to collectors using Fresnel lenses though refracting collectors are simpler to configure than reflecting designs, especially those using multiple mirrors. In most Fresnel lens collectors each lens corresponds to a single optical fiber, making individual adjustment of lens-fiber pairs relatively simple by reducing possible sources of internal alignment error compared to reflecting collectors. Additionally, the smaller component size and shorter distances between lenses and fibers reduces the impact of alignment errors, making tolerances less exacting. Proper configuration of a Fresnel lens collector depends primarily on the alignment of each individual optical fiber with the focal point and center axis of the corresponding lens. The X-Tilt and Y-Tilt parameters are now measured relative to a vertical axis passing through the center of the optical fiber and the Fresnel lens. X and Y-De-Center parameters also correspond to the centers of the Fresnel lens and the optical fiber. The Primary-to-Secondary parameter discussed earlier is no longer titled appropriately but the distance between the Fresnel lens and optical fiber is still crucial as each lens is designed to refract incoming light at a specific focal length. In every collector design minimizing internal alignment problems will increase the allowable margin of tracking error, however, even a perfectly calibrated collector requires a highly precise tracking control system to achieve ideal operating efficiency.

1.4.2 Tracking Motor Control Systems

Although the motor technology needed to physically move a collector with the accuracy required by a solar concentrating collector was a design challenge many years ago, highly precise stepping motors are seeing widespread use in a variety of applications. Development of actuator control systems capable of precisely tracking the sun's motion and aligning a collector accordingly pose more current and complex problems. Microprocessor technology has revolutionized research into tracking control and enabled designers to pack enormous computing power into control boards small enough to be mounted almost anywhere. While sun's arch across the sky is steady and easily predictable, variations in location, elevation, reflection and obstruction from nearby objects, as well as weather and sky conditions can interfere with proper operation of tracking controllers. Two different approaches have been developed to control solar collector tracking systems: the first uses a photocell to measure the intensity of incoming light and modulates the tracking motors to point the collector in the direction of maximum light intensity, the second strategy utilizes electronic micro-controllers to calculate the celestial bearing of the sun relative to the earth and align the collector accordingly.

1.4.2.1 Sensor Based Tracking Control

As part of the effort to develop a solar lighting system the Oak Ridge National Laboratory tested a photocell based tracking system manufactured by Array Technologies for use with sun tracking photovoltaic arrays. The WattSun Solar Tracker is an advanced example of photocell-based tracking as it combines the basic principle of photocell control with advanced circuitry to accurately position the collector within tight tolerances. A microprocessor uses input from a proprietary, closed loop, optical sun sensing system consisting of four individual photocells to align the collector with the sun. The sensors are mounted on each side of a square post positioned at roughly a 45° angle to the vertical face on which it's attached, as shown in Figure 1.11.

Figure 1.11 Photocell Array From WattSun Solar Tracker

Copyright 2003. ASME (Beshears, Capps, et al. 4)

The photocell array is fixed to the solar collector such that its vertical axis is parallel to the center axis of the collector. The sensor array provides input for controller circuitry programmed to compare the signals from each photocell and adjust alignment of the array to balance sensor input, theoretically centering the collector on the position of the sun. In a report prepared for the 2003 International Solar Energy Conference D. L. Beshears explains the WattSun Solar Tracker's control system:

> The closed loop system feeds information to the controller electronics about the direct component of sunlight available, the diffuse amount of sunlight, the total amount of sunlight as well as the differential amount of sunlight on the opposing sensors. The control electronics then provides a signal to the azimuth-elevation motors to move the optical sun sensor until the individual optical sensors balance (Beshears, Capps, et al. 3).

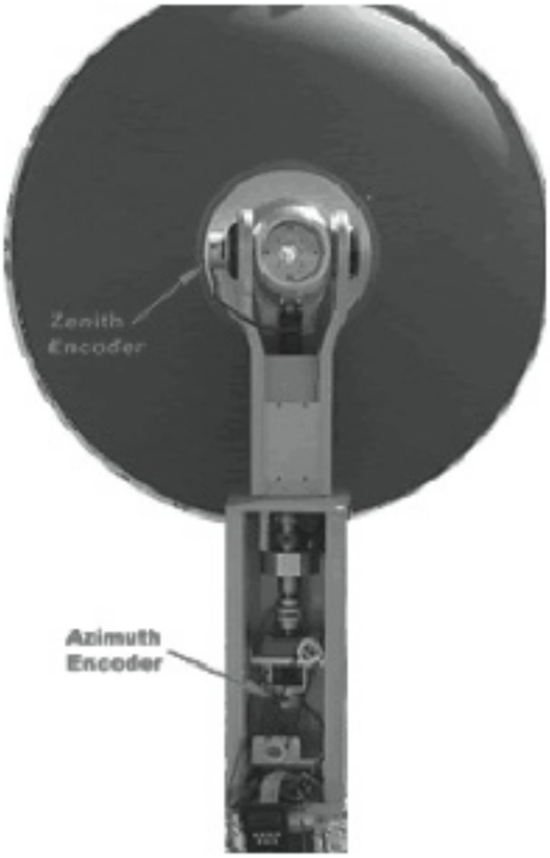
Photocell-based tracking controllers function reasonably well under clear sky conditions and lightly overcast skies, though even under ideal conditions the WattSun controller did not consistently align the collector within the tight tolerances required for maximum collection efficiency. This control strategy is suitable for applications with predominately clear skies or less stringent alignment parameters such as photovoltaic panels or Fresnel lens collectors, however, on hazy or cloudy days the system will not accurately or consistently track the sun with the precision required for a parabolic reflecting collector. During overcast conditions the control algorithm attempts to balance input from opposing sensors so dark clouds in portions of the sky can cause improper tracking adjustments, reflections and shadows from nearby buildings and landscape can intensify this effect and further reduce collection efficiency (Beshears, Capps, et al. 10). Calibrating the control processor to account for unusual sensor input due to terrain and surrounding structures can reduce tracking errors in combination with more advanced control algorithms and limiting tracking motor adjustment speed. Though further development and more accurate situational calibration of photocell-based tracking controllers has the potential to reduce tracking inaccuracies, currently sensor-based strategies can't attain the precision achieved by astronomical tracking control.

1.4.2.2 Astronomical Tracking Control

Astronomical control systems function by calculating the celestial bearing of the sun relative to the collector and adjusting the tracking motors to match the required azimuth and altitude angle. Astronomical equations developed by the U.S. Naval Observatory are accurate enough to compute the sun's position within 1/60th of a degree for the next 300 years, which is well within the strictest alignment tolerances found for reflecting collectors (Lapsa, Maxey, et al. 9). The tracking strategy is a micro-controller based system that computes the sun's astronomical bearing relative to the earth while compensating for latitude, longitude, elevation, date and time of day. When properly calibrated with the relevant geographic location and time data the microprocessor computes current sun position in terms of azimuth and zenith alignment angles and then analyzes actuator position information to determine the current location of the collector and if system alignment adjustment is needed. The control algorithm modulates the two-axis actuators, referred to as the zenith and azimuth encoders in Figure 1.12, proportionate to the discrepancy between actual and calculated collector alignment. The microprocessor evaluates current positioning and calculates required adjustments at one-second intervals throughout the day (Lapsa, Maxey, et al. 9).

The astronomical tracking control system on ORNL's Hybrid Solar Collector can consistently position the array to within one-tenth of a degree of actual sun position using input from a global positioning system and Naval Observatory equations (Lapsa, Maxey, et al. 9). When tested on the ORNL parabolic reflecting collector the SolarTrack astronomical tracking controller was able to consistently track the sun within the tight tolerances required to maintain maximum sunlight collection throughout the day. The SolarTrack controller performed well under a variety of atmospheric conditions and was not affected by nearby buildings or terrain. Another advantage of the control processor is ease of configuration and flexibility as the root programming can be upgraded with more advanced control algorithms. The system can be interfaced with additional sensors or control switches as well as connected to other devices through a data network, allowing one microprocessor to control multiple collectors or talk to a building management system (Beshears, Capps, et al. 9).

Figure 1.12 Astronomical Tracking System on ORNL Parabolic Solar Collector



From *Energy Engineering* Vol. 4, No. 104 (Lapsa, Maxey, et al. 9)

1.5 Optical Fibers

"In essence, optical fibers are lightguides: channels along which electromagnetic radiation of optical frequency can be conducted efficiently" (Driggers 534). In its most basic form an optical fiber is simply a core of dielectric material having a refractive index greater than that of the surrounding cladding material, resulting in total internal reflection of light entering the fiber's end. The second layer of transparent cladding material is similar to that of the core and is used to improve transmission efficiency by capturing any light scattered out of the fiber core by imperfections in the material or other factors. Typically, the fiber core and cladding are circular in cross-section and protected by a flexible jacket, often with a reflective inside surface (Driggers 535).

1.5.1 Optical Fiber Core and Cladding Materials

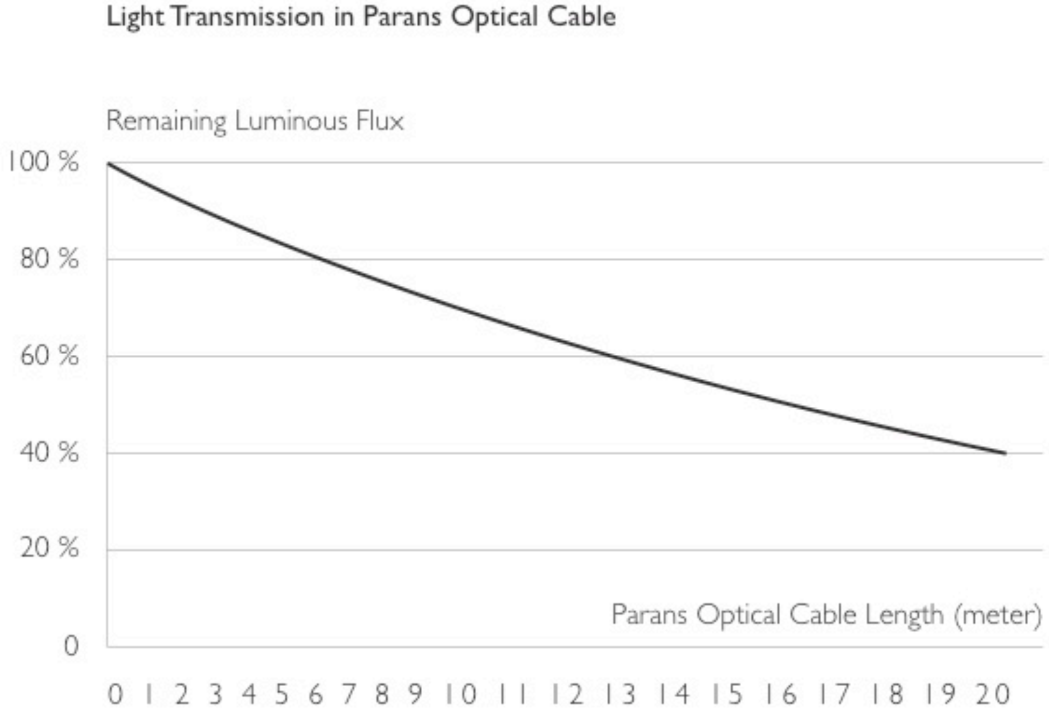
Suitable materials for optical fibers are compared based on their transparency, the ease with which they can be drawn into continuous strands, and the frequencies of radiation most readily absorbed and transmitted by the material. Analogous to steel alloys, the material used to make the core of an optical fiber is dependent on the intended application, wavelengths of the light source, transmission distances and many other issues. However, in all cases the crucial parameter is quantity of signal attenuation across the relevant wavelengths of light per unit length of material. For data transfer applications optical fiber attenuation is typically measured in decibels lost per one kilometer of length (dB/km) but for studies of visible light transmission for lighting applications meters may be used as the unit length. Signal attenuation is caused by absorption within the fiber material, core/cladding interactions, scattering and dispersion due to variations in material density and other physical imperfections on a microscopic scale. In addition to use of high quality materials a minimum bend radius must be sustained along the entire length to minimize losses due to dispersion from local density variations and to maintain total internal reflection of light within the fiber core (Driggers 535). Three primary materials are used to make optical fibers for solar lighting applications.

The first core material used in optical fibers for solar lighting is silica-based glass. Chosen for its high transparency and correspondingly low attenuation across a wide range of wavelengths, purified glass is the standard material used in most data transfer applications. Manufacturing techniques have been developed to create ultrapure, ultra-transparent glass with attenuation coefficients as low as 0.2-dB/km at a wavelength of 1550-nanometers (nm). Glass manufactured for optical fibers is so pure it must be infused with other elements like germania or fluorine to adjust the refractive index for specific applications (Driggers 521). Though glass is the standard against which all other core materials are judged the relatively high cost of production, wide bend radii required and fragile nature of glass make these fibers impractical for most solar lighting applications, although if light must be transmitted a great distance glass-core fibers may be advantageous compared to other options.

The second core material considered for solar lighting applications is a mixture of highly purified liquids, typically water and methanol and/or ethanol. The liquid is contained inside a protective jacket with two transparent end caps with a similar refractive index to that of the fiber core. Liquid core fibers are advantageous do to their durability and long life as well as low production cost relative to that of glass. Also, liquid core fibers have attenuation coefficients below 2-dB/m across most of the visible spectrum, making the material better for transmission of visible light than other wavelengths (Altkorn 8997). However, liquid core fibers are not easily coupled or spliced and cannot be field cut to length, complicating installation and reducing versatility.

The third, and most commonly used material, is a synthetic polymer called Polymethylmethacrylate or PMMA. Though polymer fibers using different chemical compounds allow efficient transmission across wider ranges of wavelengths, PMMA is preferable within the visible spectrum making it ideally suited to solar lighting applications. PMMA fibers have attenuation minima of 64, 73 and 130-dB/km occurring at 520, 570 and 650-nm respectively. These wavelengths indicate that PMMA fibers will transmit green, yellow and red light particularly well. Only the yellow-orange portion of the spectrum is attenuated significantly more than other wavelengths of visible light, this is due a spike in light absorption within the polymer at a wavelength of 625-nm (Driggers 522). Though polymer-core fibers have substantially higher attenuation coefficients than those of silica glass and liquid-core fibers, the relatively low cost of production, tighter minimum bend radii, ease of installation and durability make PMMA preferable in solar lighting applications as the effect of higher attenuation coefficients is mitigated by the short transmission distances and high intensity of direct sunlight. Parans uses PMMA optical fibers with their solar lighting systems and produced Figure 1.13 to illustrate the anticipated percent reduction in transmitted sunlight intensity as a function of fiber length.

Figure 1.13 Light Attenuation Per Meter of Parans PMMA Optical Fiber



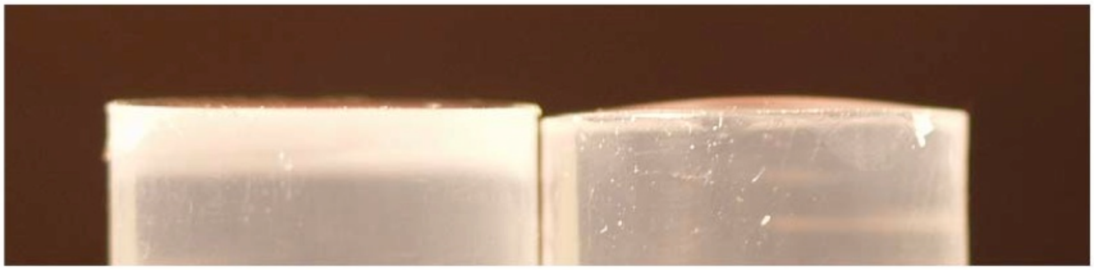
Copyright 2008. Parans Solar Lighting AB (Parans 14)

1.5.2 Coupling of Optical Fibers

Besides attenuation of light within the optical fiber, coupling losses account for the most significant reductions in transmitted light intensity. Traditionally, multiple optical fibers were connected by hand sanding and polishing the ends of each fiber and simply coupling the polished ends together as tightly as possible, often resulting in light intensity losses of about fifteen percent per coupling. Intensity reductions occur primarily as a result of imperfections in end-face geometry and axial alignment as well as Fresnel reflection losses (Maxey, Cates, Jaiswal 1).

When light passes through a continuous optical fiber the beam is contained in the fiber core through total internal reflection, resulting in signal attenuation only from absorption within the material itself. Optical fiber couplings are intended to match the configuration of a continuous fiber as closely as possible, but this is simply not achievable by hand polishing. Achieving proper end-face geometry and axial alignment across a fiber coupling requires the exposed ends be finished with a specially design jig similar to a carpenter's miter box. This jig holds the fiber and polishing material so that the end is polished perfectly flat and perpendicular to the fiber's axis. Polished fiber ends allow light to pass cleanly out of one fiber end and into another without scattering light and creating losses. Properly finished ends will meet without creating visible air gaps and will maintain the fiber's axial alignment across the coupling, minimizing light loss and maximizing internal reflection. It is important to properly prepare coupled fiber ends as well as provide adequate support to maintain connection alignment over time.

Figure 1.14 Fixtured (Left) and Freehand (Right) End-face Preparation Comparison



Copyright 2003. ASME (Maxey, Cates, Jaiswal 3)

No matter how well the fiber ends are prepared and held together Fresnel reflection losses will result in significant attenuation within the coupling. Fresnel reflection losses occur when light exits the optical fiber material and enters a medium with a different refractive index, such as air. Fresnel losses are relatively constant no matter what distance is involved, resulting in an approximately four percent loss of light intensity leaving the first fiber and an additional four percent reduction in remaining light intensity upon entering the second fiber, even when the air gap is microscopically small. To mitigate these losses researchers have developed 'Index Matching Media' designed to fill the air gap with liquids, gels or adhesives that match the refractive index of the fiber as closely as possible. It has been experimentally determined that the media's index of refraction is less important than the mechanical properties of the substance. Liquids and gels can seep out of the joint unless a reservoir is provided to reliably contain them, while some gels and adhesives are comparably very easy to work with and durable (Maxey, Cates, Jaiswal 4). During an experiment conducted at the Oak Ridge National Laboratory using an index matching gel to couple two large-core PMMA fibers, Fresnel losses across the coupling were reduced from 7.8 percent using no media to 0.03 percent with the gel was in place. Maxey, Cates and Jaiswal summarized the results of their experiment to minimize losses within fiber joints, “With the existing degree of development in end-face preparation, connector designs and the use of index matching media, losses are routinely being contained to between 2% and 5% per coupling” (Maxey, Cates, Jaiswal 5).

1.6 Passive and Hybrid Solar Luminaires

Once sunlight has been collected and transmitted into the space, effective utilization of the natural light is the final step in any solar lighting system. Providing relatively uniform illuminance levels at the work surface, maximizing utilization of available light, minimizing glare, increasing horizontal light levels and improving surface rendering are just a few of the relevant luminaire design goals. Effective daylighting design criteria are discussed in more detail in Chapter 3. Conventional light fixtures are developed to control the light they emit in order to provide an even and predictable luminous flux suitable to a specific application and solar light fixtures share the same objectives. Solar lighting fixtures benefit from the point-source supply provided by fiber optic emitted daylight and as a result are able to avoid many of the variability and controllability issues present in traditional daylighting strategies. Though typically proprietary and designed for use with a specific manufacturer’s fiber optic lighting system, solar lighting fixtures have been developed for accent, linear, ambient and decorative lighting applications.

Passive solar light fixtures are intended for use only when adequate direct sunlight can be collected but hybrid solar luminaires are equipped with dimmable electric lamps and a photocell to supplement natural light during cloudy periods or nighttime operation. Hybrid solar fixtures have the additional concern of blending natural and artificial light evenly while modulating electric lamp output seamlessly so as not to disturb occupants. D. D. Earl and J. Muhs summarize the main problems of designing a practical hybrid solar luminaire in their presentation to the Solar Energy: Power to Choose conference.

> Fluctuations in the intensity of collected solar light, due to changing cloud coverage or solar collector movement, requires rapid compensation by electric lamps to maintain a constant room illumination. If the spatial intensity distribution of a hybrid luminaire’s electric lamp does not closely match the

> spatial intensity distribution of the luminaire's fiber optic end-emitted solar illuminant, then the shift between artificial and solar light will be noticeable to the occupant and is highly undesirable (Earl, Muhs 1).

Additionally, conforming to established design practices and modular sizes were a key development goal for many hybrid and passive solar lighting systems. Initial design attempts undertaken at the Oak Ridge National Laboratory began by adapting conventional troffer style fixtures to distribute light transmitted into them via optical fiber. Although several manufacturers produce a variety of fixtures, each suited to a specific application or design objective, two main approaches are used to distribute collected sunlight emitted from an optical fiber. The first pairs each optical fiber with a light-dispersing lens element designed to diffuse incoming light, while the second design uses light-dispersing cylindrical rods similar to linear fluorescent lamps.

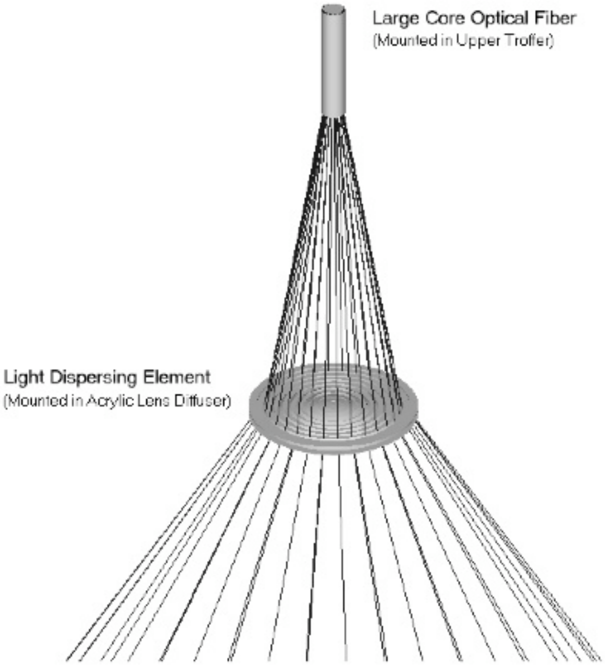
1.6.1 Fixtures Using Light Dispersing Lenses

Sunlight traveling within an optical fiber is unidirectional, meaning that all collected light is transmitted linearly through the fiber by reflecting from side to side down the axis and finally being emitted nearly straight out the end. Due to the unidirectional nature of light within an optical fiber the simplest method for illuminating a space positions each fiber behind an optical element designed to diffuse the light in a uniform pattern across the working plane, similar to the design of a typical accent or downlight intended to direct available light into a concentrated pattern. This method is also the most efficient as all emitted light is focused directly at the work surface or target object and very little light loss occurs within the optical element. Using quality materials such as purified silica glass or highly transparent PMMA to minimize transmission losses within the optical element as well as properly locating and effectively aiming the fixture can easily maintain end-emitted light utilization efficiencies in excess of ninety percent (Earl, Muhs 3).

Despite its efficiency, the design does not allow for simple integration of electric lamps or seamless mixing with artificial light sources as improving the uniformity of sunlight dispersed from the fixture requires increasing the number of optical elements, as a result reducing the optical efficiency of the fixture and increasing cost (Earl, Muhs 4). As with traditional fixtures, different lighting applications require different luminaire designs to achieve the desired effects.

Because the fixture design lends itself to applications using focused direct light, luminaires containing light dispersing lenses are typically intended to emulate traditional accent, spot, or downlight luminaires. Though several manufacturers currently sell systems that use remotely located electric lamps to transmit light via fiber optic cables to fixtures, incorporating this technology into a solar lighting system using independent optical fibers is complex and cost prohibitive. No practical or efficient means of blending the two light streams has yet been developed, making fixtures using light dispersing elements ideal for passive systems but currently impractical for hybrid solar luminaires.

Figure 1.15 Optical Fiber and Light Dispersing Element Configuration



Copyright 2001. ASME (Earl, Muhs 3)

Parans manufactures a passive solar luminaire, shown in Figure 1.16, which is very similar to a conventional accent fixture using an incandescent or MR-16 halogen lamp. This style of fixture disperses end-emitted light from an optical fiber routed through the center of fixture's base through a round lens designed to create a tight circular distribution pattern on the target object or working plane (Parans 20). For passive solar ambient lighting applications Parans has developed a rectangular luminaire containing a series of light dispersing elements mounted in an acrylic panel. Optical fibers from roof mounted collectors are routed into the back of the fixture and connected to each light dispersing element, which are designed to project most of the end-emitted light directly onto the work plane but will refract some light upward for indirect illumination, see Figure 1.17. A range of sizes are available, each containing progressively greater numbers of light dispersing elements and optical fibers, depending on the light levels desired and the size of the area to be illuminated (Parans 23).

Figure 1.16 Parans 'L3' Passive Solar Luminaire Using Light Dispersing Element

Copyright 2008. Parans Solar Lighting AB (Parans 20)

Figure 1.17 Parans 'L1' Passive Solar Luminaire Using Light Four Dispersing Elements

Copyright 2008. Parans Solar Lighting AB (Parans 23)

1.6.2 Fixtures Using Light Dispersing Cylindrical Rods

Designs and installations using conventional troffer-style light fixtures are well understood in the construction industry and such products have become ubiquitous among fixture manufacturers. For this reason the team developing a hybrid solar lighting system at the Oak Ridge National Laboratory began evaluating several two-by-four fixtures with the goal of modifying a standard parabolic troffer to distribute sunlight from an optical fiber as well as the original electric lamps. “A major step toward the realization of using fiber optic transported solar light for internal lighting purposes involves the development of a hybrid luminaire to seamlessly balance lamp and fiber optic transported solar illuminants” (Earl, Muhs 1).

Matching the distribution pattern produced by linear fluorescent lamps necessitated the development of a cylindrical light-dispersing element capable of distributing the end-emitted light from an optical fiber evenly across a four-foot long cylinder similar in diameter to a T8 lamp. Initially the ORNL team sand blasted one half of an acrylic rod and coated the other with reflective foil to disperse light from a butt-coupled optical fiber out one side of the rod. However, this design was very inefficient and did not evenly distribute light along its length so the team sought outside help (Earl, Muhs 3). A new product developed by 3M, the Side-Emitting Rod seen in Figure 1.18 was manufactured with precision-cut grooves along one side intended to release light entering one end of the rod with even intensity across the entire length. The rod also included a mirror at the far end to reflect any light that was not distributed in its initial pass (Earl, Thomas 2-3).

Figure 1.18 3M Side-Emitting Rod

Copyright 2003. ASME (Earl, Thomas 2)

Two Side-Emitting Rods were placed in a conventional two-by-four parabolic troffer with four T8 fluorescent lamps. The rods were positioned between the two pairs of electric lamps as shown in Figure 1.19, with the goal of distributing end-emitted sunlight as uniformly as possible and matching the distribution pattern of natural light to that of the artificial sources. An optical fiber was butt-connected to each of the two 3M cylindrical dispersing rods. After testing it was discovered that the distribution patterns from the natural and artificial light sources were not identical, though much closer than achieved using the original dispersing rod (Earl, Muhs 3; Earl, Thomas 4). The fixture maintained its high efficiency with respect to utilization of available electric light, which was a design goal, and showed improved distribution efficacy at sixty percent of total fiber optic end-emitted sunlight using the dispersing cylinders (Earl, Thomas 4). D. D. Earl and R. R. Thomas summarize the results of their hybrid solar fixture design in a report presented at the 2003 International Solar Energy Conference.

> Obviously, the current luminaire efficiency is significantly lower than desired. However, it is suspected that a significant portion of the fiber optic light (≈20%) was lost due to coupling losses. Since this experiment was conducted, an improved method for coupling large core optical fibers has been developed with

coupling losses as low as 3%. Given these improvements, the efficiency of the 3M side-emitting rod, within the hybrid luminaire, could potentially approach 75%. Such an increase, if confirmed, would make this technique a viable candidate for use with the Hybrid Solar Lighting System (Earl, Thomas 4).

Figure 1.19 Hybrid Troffer Fixture Developed at ORNL Using 3M Side Emitting Rods

Copyright 2003. ASME (Earl, Thomas 3)

CHAPTER 2 - Application of Fiber Optic Daylighting Systems

2.1 Potential Candidates for Solar Lighting Systems

In his presentation for the American Solar Energy Society's Solar2000 Conference Jeff Muhs stated that, "Passive distribution and use of the visible portion of solar energy is the preferred use of solar energy when nonrenewable energy displacement, cost-effectiveness, and lighting quality are the primary deployment driver." To date, market penetration of passive and hybrid solar lighting systems has been limited by the high cost of first generation designs and a relative lack of knowledge about the technology. For a new product to be commercially viable it must generate payback periods of no longer than ten to fifteen years. Many owners and facility managers are hesitant to commit to a single building or system for extended periods of time and prefer shorter paybacks in the five to ten year range. The applicability and economic viability of solar lighting systems with respect to a given project depends on the building's location, the number of floors and the goals of the lighting design, a sentiment conveyed by the Federal Energy Management Program's report on hybrid solar lighting:

> The first commercial use for HSL [Hybrid Solar Lighting] will most likely be on the upper two floors of facilities having the following characteristics: (1) Sunbelt location in areas where daytime electricity prices are highest; (2) occupied every day, including weekends; and (3) in lighting applications where lighting quality is important and less-efficient electric lamps are currently used (Hybrid Solar Lighting).

2.1.1 Applicable Occupancies

An ideal initial market for current generation solar lighting systems are retail stores that rely heavily on direct accent light fixtures using extremely inefficient incandescent lamps due their high color rendering indices. In these retail occupancies displacement of incandescent spot lighting during times of adequate sunlight will significantly reduce lighting power requirements and heat gain from electric lamps, consequently reducing mechanical equipment loads in addition to positive impacts on sales and less tangible worker productivity and job satisfaction benefits. A system designed for commercial buildings, specifically retail occupancies, will likely be the first economically viable market for hybrid solar technology as lighting accounts for the largest percentage of electrical consumption in these occupancies (Hybrid Solar Lighting). "For this application, a system price of $4000 (installed) has been identified as necessary to produce energy savings of 50-million kWh/year by 2012" (Hybrid Solar Lighting). These energy savings estimates are based on early applications and a projection of 5,000 installed hybrid solar lighting systems by 2011 if the targeted single collector system price is achieved.

Wal-Mart, Staples and other smaller retail chains are conducting trial installations of hybrid solar systems and have noted customer and worker satisfaction benefits in addition to increases in sales similar to those documented in stores with skylights. The combination of lowered utility bills, reduced mechanical loads, increased sales and improved worker productivity generates the quickest payback periods in the retail market sector and provides owners with economic as well as social incentives to try new 'green' technologies. For more information on these studies refer to the *Effects of Light on Occupant Productivity* section of this paper (Hybrid Solar Lighting; Lapsa, Maxey, et al. 12).

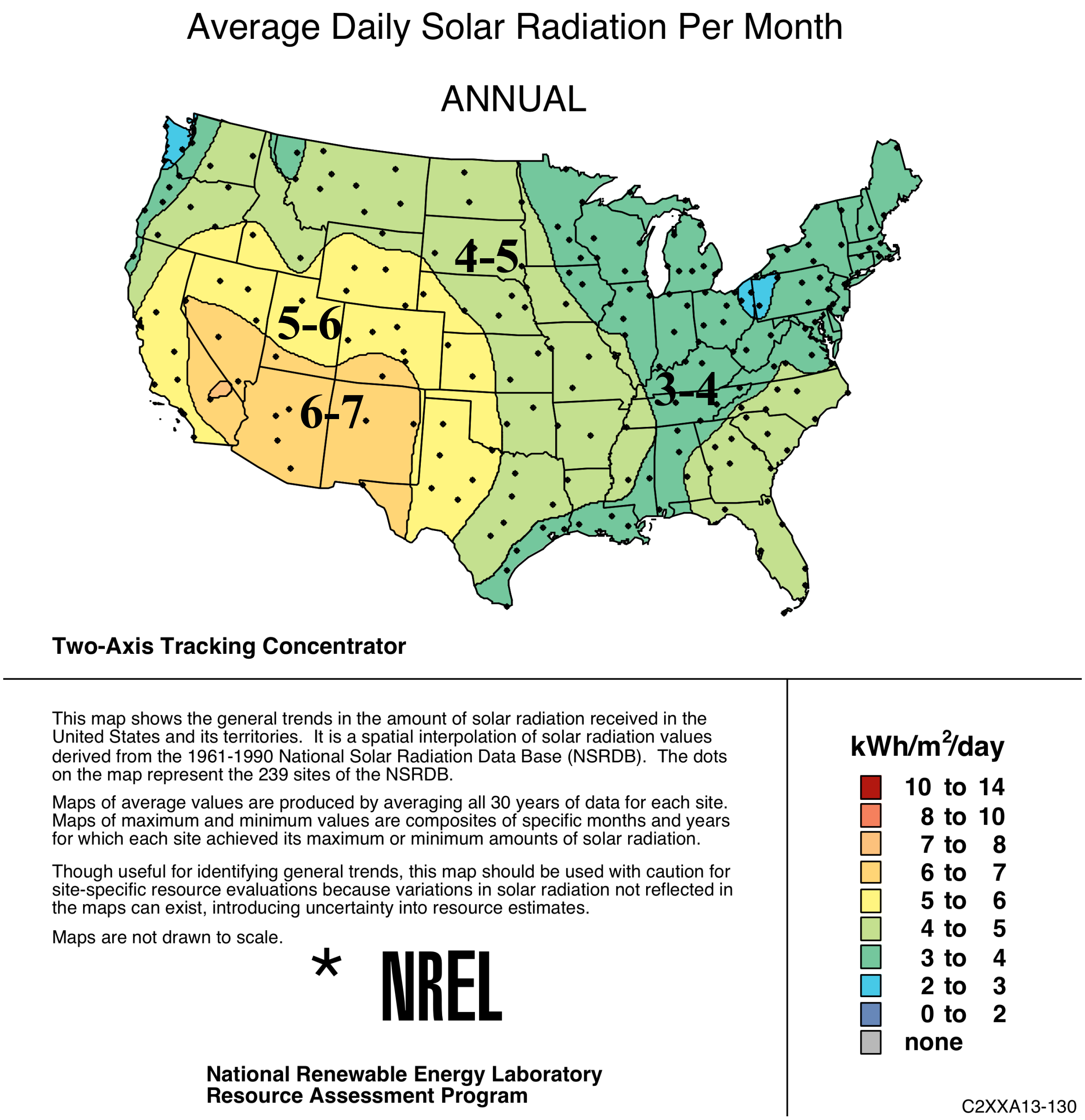
Hybrid or passive solar lighting is particularly advantageous in commercial, educational and federal buildings that meet the previously mentioned location and occupancy criteria. Office buildings, classrooms, training facilities at military bases and industrial processing buildings such as postal service sorting facilities are attractive applications for solar systems as lighting loads constitute the largest percentage of power bills in these occupancies, lighting quality is highly important to tenants and the majority of use occurs during daytime hours. Office, educational and governmental facilities are also the most likely occupancies to produce tangible benefits to the owner from occupant comfort and productivity improvements associated with greater indoor environmental quality. Owners and facility managers of these building types are usually more interested in the life-cycle cost of a structure and are more likely to accept longer payback periods, sometimes as high as fifteen to twenty years, compared to commercial owners or developers seeking a more immediate return on investment. (Hybrid Solar Lighting; Maxey, et al. 10-2).

2.1.2 Applicable Geographic Locations

In addition to occupied hours and space usage, the availability of clear skies and plentiful direct sunlight is a crucial factor in determining the applicability and cost effectiveness of a solar lighting system. A greater intensity of available direct sunlight corresponds to higher supported lighting levels within the space or fewer solar collectors needed to achieve equivalent light levels. Solar lighting installations located in highly sunlit portions of the country are most likely to displace electric lighting frequently enough to maximize system potential, shortening the payback period associated with a hybrid or passive solar system (Maxey, et al. 12).

In order to produce consistently useful light levels and reasonable hours of operation a facility considering a passive or hybrid solar system should be located in regions that receive at least 4-kilowatt-hours of equivalent electrical energy per-square-meter of earth per-day ($kWh/m^2/day$), though locations that receive less average light intensity may benefit from solar systems if clear sky conditions and weather patterns correspond favorably to the intended occupancy schedule. Areas that receive at least 4-$kWh/m^2/day$ are considered to be in the 'Sunbelt' region, an area that encompasses about 24 states. The 'High-Sun' region is defined as locations that receive more than 6-kWh/m^2/day, an area that covers portions of 10 states including: California, Texas, Colorado, Oklahoma, Nevada, New Mexico and nearly all of Hawaii. The figure below, created by the National Renewable Energy Laboratory, shows average daily solar radiation values measured from 1960 to 1990 across the United States. Passive or hybrid solar lighting systems may not be feasible in regions shown in dark green or blue, illustrating the broad range of potentially viable locations for installation.

Figure 2.1 Average Daily Solar Radiation in the United States



This map shows the general trends in the amount of solar radiation received in the United States and its territories. It is a spatial interpolation of solar radiation values derived from the 1961-1990 National Solar Radiation Data Base (NSRDB). The dots on the map represent the 239 sites of the NSRDB.

Maps of average values are produced by averaging all 30 years of data for each site. Maps of maximum and minimum values are composites of specific months and years for which each site achieved its maximum or minimum amounts of solar radiation.

Though useful for identifying general trends, this map should be used with caution for site-specific resource evaluations because variations in solar radiation not reflected in the maps can exist, introducing uncertainty into resource estimates.

Maps are not drawn to scale.

National Renewable Energy Laboratory
Resource Assessment Program

April 2009. <http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/atlas/serve.cgi>

2.2 Design Baseline and Comparison of Alternatives

Once the desired lighting design criteria are established for a given space, determining the ideal system requires a comparison of available solutions. Although many lighting quality issues are relevant when considering a lighting system, available light utilization efficiency and system cost are the two criteria most often used when comparing options. Owners considering passive or hybrid solar lighting systems are typically interested in reducing energy consumption and operating cost compared to simple electric lighting systems. For this reason system comparisons are usually made in terms of cost per-kilowatt-hour of displaced electric lighting, which can be combined with projected utility rates to determine the payback period associated with improvements beyond the simplest conventional lighting system. Three systems are considered in this section as alternatives to the use of passive or hybrid solar daylighting with the goal of reducing energy consumption: advanced electric lighting, conventional topside daylighting systems and solar energy systems such as photovoltaic panels.

2.2.1 Baseline Hybrid Solar System

Estimating cost and determining payback periods for a potential solar lighting system requires specific information about installed systems, anticipated operational hours, lamp type and quantity of electric lights required to illuminate the same area. Lighting schemes including passive solar lighting systems are difficult to design and price as specific fixtures and collectors required to achieve the desired lighting goals are not always associated with an electric counterpart. Different manufacturers have developed proprietary design standards and components are not interchangeable, therefore the economic viability of a passive system depends on a detailed case-by-case analysis of the solar design and proposed electric lighting.

Hybrid solar systems are more conventional in application as fixture locations and quantities are determined using only the electric lamp output. Hybrid fixtures are designed to blend natural and artificial light sources together, meaning that in an ideal application electric lamp output is displaced during times when direct sunlight is available while light levels within the space remain consistent. Although many hybrid light fixtures are also proprietary, they are based on common modular fixtures and fluorescent lamps capable of being modeled with standard lighting design practices and software.

The hybrid solar lighting system developed at the Oak Ridge National Laboratory and manufactured by Sunlight Direct is used as a baseline of cost comparison against other potentially applicable lighting strategies for a comparable space. The baseline system assumes the installation of one parabolic reflecting collector supplying twelve two-by-four-foot hybrid fixtures equipped with linear fluorescent lamps, representing a typical lighting installation for a 900-square-foot floor area (Muhs(b) 8). During the initial product offering installed system cost was approximately $24,000, which “is less than half of the early cost projections for the technology” (Lapsa, Maxey, et. al 11). As individual components are improved, parts become designed for manufacturability, materials evolve and production is scaled up to commercial levels prices will continue to decrease dramatically. According to Lapsa, Maxey and others in their report for *Energy Engineering,* “Sunlight Direct has a development plan that aggressively targets the commercialization cost goal of $3 per square foot of illuminated space.” By reducing cost to the target range hybrid solar systems for commercial buildings will be comparable in cost to conventional lighting designs and could potentially produce two to three year payback periods using utility bill savings in expensive energy markets (Hybrid Solar Lighting; Lapsa, Maxey, et al. 11). Figure 2.2 is taken from a *CADDET Energy Efficiency Newsletter* article written in 2000 by Jeff Muhs. The figure is divided into three sunlight availability regions and shows estimated installed hybrid solar system costs in cents-per-kilowatt-hour of displaced electricity as well as the associated payback periods anticipated for different hours of building use.

Figure 2.2 Hybrid Solar Lighting System Cost By Region

Region	Building use scenario	Cost/kWh displaced		Years to payback at 12.5 ¢/kWh	
		Current	Projected	Current	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

Copyright 2000. CADDET Energy Efficiency Newsletter (Muhs(b) 8)

2.2.2 Advanced Electric Lighting Systems

Advanced electric lighting systems using high efficiency light sources and occupancy responsive controls are the current industry design standard. "For hybrid lighting to gain widespread acceptance, it must displace a significant amount of inexpensive electrically generated light. Continued advancements in lamp efficacy (~15% over the past decade) and lighting controls will continue to increase their efficiency and reduce the time electric lights are in use" (Muhs(a) 6). The luminous efficiency of filtered visible sunlight is currently about 180 to 200-lumens-per-watt (lm/W) of electrical input, compared to approximately 15 to 90-lm/W from common electric lamps (Muhs(b) 9). At nearly double the typical efficacy of electric lamps, passive solar daylighting represents a means to improve the quality of indoor light while reducing power consumption.

Hybrid solar lighting systems compliment advanced electric lighting systems by reducing the electric light required during times of adequate sunlight. Furthermore, hybrid solar systems rely on advanced lighting controls, dimming ballasts and efficient lamps during times of inadequate sunlight. Because most fiber optic lighting applications require installation of hybrid fixtures or separate electric lighting with advanced photocell dimming controls to maintain illumination levels during periods of inadequate sunlight, a side-by-side comparison of the two options is not fully appropriate as both are used in combination. However, the additive cost of an installed hybrid solar lighting system in combination with conventional fixtures is estimated at ¢5 to ¢12/kWh of displaced electricity, which can be less than the cost of operating electric lights (Muhs(b) 8). According to the Department of Energy's *Electric Power Annual 2006* commercial projects were billed at an average rate of ¢9.46/kWh, demonstrating the potential for savings using solar systems in regions with sufficient sunlight and average utility rates. In a deregulated energy market using time-of-day billing rates at peak demand periods, prices of ¢10 to ¢15/kWh are not unusual, further justifying use of daylight harvest to shave peak power consumption (Muhs(b) 8).

2.2.3 Conventional Topside Daylighting Systems

Though a plethora of products exist to bring natural light into buildings, conventional skylights are considered to be the most cost-effective method of increasing sunlit area within a space using a topside system. The quantity of useful light entering a space is dependent on the type and configuration of the skylight, but in all cases the intensity of light transmitted varies significantly and must be attenuated to mitigate glare and solar heat gain. Control of direct sunlight is typically achieved using baffles, shades or motorized louvers but these methods complicate the design and significantly reduce the utilization efficiency of captured sunlight. To further control glare and heat gain skylight applications are typically intended to approximate lighting levels created by electric lights when the total exterior illuminance is 3,000-footcandles, significantly less than the approximately 11,500-footcandles created by direct sunlight at sea-level on a clear day (Muhs(a) 3). Because of this design practice interior light levels above the approximation are not used to further reduce electric lighting levels and conserve power, writing off up to thirty percent of incoming sunlight as 'excess illumination' (Muhs(a) 8).

Skylights are not easily relocated to adapt to changes in space usage or furniture locations, making precise location of skylights for specific tasks difficult, complicating the lighting design and control scheme while shrinking the range of potential application. Designers often provide even general illumination to create a lighting design flexible to various space uses, but achieving uniform light levels with a conventional topside system requires a series of smaller skylights distributed across the space. Skylights suffer from maintenance issues and water intrusion problems due to the damaging effects of sunlight and large area of roof penetrations required. This problem is compounded if a large floor area is to be illuminated with topside systems as the size of individual skylights is reduced but the number and perimeter of roof penetrations required increases (Muhs(b) 9). Jeff Muhs summarizes the comparison in his article for *CADDET Energy Efficiency Newsletter*, "Once all factors are considered, the simple payback (typically >10 years) and energy end-use efficiency of even the best topside daylighting systems is considerably worse than projected hybrid lighting systems" (Muhs(a) 8).

2.2.4 Photovoltaic Power Generation

One answer to the cost issues associated with harnessing sunlight has been to develop utility-scale power generation from photovoltaic arrays and solar thermal collectors. However, the cost savings related with quantities of scale is usually offset by the added complexity of the tracking and transmission systems. Losses accumulated during conversion of sunlight into direct electric current, further conversion into alternating current and transmission to end uses severely limits the process efficiency of solar conversion extending associated payback periods (Muhs(a)

2). Unacceptable payback for most applications has limited the market penetration of large-scale solar conversion technologies to regions with favorable climate and relatively high electricity rates.

In some areas small-scale photovoltaic arrays are incorporated into whole building peak power shaving and intermediate daytime load reduction strategies as the operating cost savings generated produce acceptable returns on these investments. Though photovoltaic cell production has improved conversion efficiencies to about fourteen percent of total incident solar energy, once transmission and conversion back into electric light have been accounted for the total process efficiency is reduced to between one and five percent (What is the Energy; Muhs(a) 2). Ironically, much of the solar power generated on site is converted back into light by electric systems. Electric lighting represents a substantial percentage of power consumption in commercial buildings, many of which are primarily used during daytime hours and stand to benefit more from utilizing collected sunlight directly. Collecting and channeling direct sunlight into the building for lighting, thus forgoing the added complexity of converting sunlight into power, improves end-use efficiency of incident solar energy to between twenty and thirty percent (Muhs(a) 2).

Inefficient utilization of generated power for electric lighting is compounded by the high cost of installing and maintaining a small-scale photovoltaic system. The complexity of materials and required conversion equipment causes solar cells to typically cost between \$3 and \$5/Watt of power generated at peak performance. Compared to the projected cost of \$1.64/Watt of electric light displaced at peak efficiency, a solar daylighting system represents a more economically viable means of reducing peak power consumption for most building types (Muhs(b) 9).

CHAPTER 3 - Designing with Daylight

Prior to the 1940's daylight was the primary source of illumination in commercial buildings, with electric lighting systems designed to supplement natural sunlight. Myriad advancements in lamp and fixture design precipitated a relatively quick transition toward present design standards where artificial lighting systems provide all or most of necessary lighting levels (Edwards, Torcellini 2). "In a world newly concerned about carbon emissions, global warming, and sustainable design, the planned use of natural light in non-residential buildings has become an important strategy to improve energy efficiency by minimizing lighting, heating, and cooling loads" (Oyvind, et al. 1-1). This renewed concern has catalyzed a resurgence in daylighting popularity, leading to a variety of innovations in design practices and control strategies, more effectively incorporating daylight into lighting designs while mitigating the potential problems associated with direct sunlight. With the goal of increasing the market penetration of solar lighting technologies, thus improving indoor environmental quality and reducing energy usage, the Solar Heating and Cooling Programme of the International Energy Agency compiled a reference book summarizing the current state of technology and design regarding daylighting. Daylight in Buildings: A Sourcebook On Daylighting Systems And Components contains the IEA's literature review and analysis of daylighting design considerations, effective design criteria, and the strengths and weaknesses of current daylighting technologies.

3.1 Effective Daylighting Design Criteria

To evaluate the effectiveness of a daylighting strategy design objectives must be clearly defined. "An objective evaluation of an innovative system requires definition of performance parameters. In addition, the evaluation depends on defining baseline conditions against which the performance should be compared" (Oyvind, et al. 3-2). A major issue in the evaluation of daylighting effectiveness is that most performance parameters are developed around static electric lighting systems and therefore aren't directly applicable. For this reason the baseline design models which the International Energy Agency recommends as points of comparison are first: a conventional window, with or without glazing, and standard shading such as venetian or roller blinds; or second: clear, unobstructed glass (Oyvind, et al. 3-3). Significant emphasis is placed on providing 'useable' daylight, a term employed frequently in analysis due to the high potential for excessive illuminance levels, glare, non-uniform light distribution, and thermal discomfort.

The International Energy Agency created a task force to address the general lack of understanding surrounding advanced daylighting strategies, the inadequacy of current tools to assist designers, and the minimal evidence of daylighting's advantages available to owners and designers alike. The task force established performance parameters that can "characterize a daylighting system within the context of a specific building application and can be used to determine whether a system should be used to achieve the design objectives" (Oyvind, et al. 3-1).

The key functions identified for daylighting technologies are: (1) Increase usable daylight for climates with predominantly overcast skies, (2) Increase usable daylight for very sunny climates where control of direct sun is required, (3) Increase usable daylight for windows that are blocked by exterior obstructions and therefore have a restricted view of the sky, and (4) Transport usable daylight to windowless spaces (Oyvind, et al. 3-1).

3.2 Daylighting Design Considerations

The major limitations of daylighting typically extend from the harsh nature of direct sunlight and the variability of sun position, light intensity and sky conditions. Effectively controlling incoming sunlight and incorporating it into an electric lighting strategy is crucial to creating high quality lighting. Passive and hybrid solar lighting systems are unique in their ability to channel sunlight through optical fibers, removing the light's thermal component, before distributing it in a controlled pattern similar to conventional electric fixtures. Typical issues that must be accounted for in a successful daylighting strategy are: illuminance, distribution, glare, direction, apparent brightness, color and thermal comfort.

3.2.1 Illuminance

In the United States, the Illuminating Engineering Society (IES) publishes recommended design illuminance levels at the work plane based on task, occupant age, background reflectance, visual acuteness and accuracy required. These recommendations are tailored to minimize electric lighting loads and are not designed to account for the intensity of sunlight. In daylighting applications, light levels two or more times the IES recommendation are often acceptable to workers provided glare, relative brightness and thermal comfort considerations are adequately accounted for.

> For some countries, an absolute illuminance level is used in a systematic evaluation. For other countries, particularly those that are dominated by cloudy sky conditions, the *daylight factor*, or the ratio between the illuminance measured indoors at a reference point (e.g. work plane) and the outdoor global illuminance on an unobstructed, horizontal surface, is used as a measure of light quantity. Because of the variability of daylight available from the sun and sky, daylighting systems are evaluated based on the quantity of illumination provided at a task

over time. For office work that involves both paper-based and computer-based tasks, the larger the number of hours per year that a system is able to meet but not grossly exceed the design illuminance level, the more successful the design (Oyvind, et al. 3-4).

3.2.2 Distribution

Distribution of light within the space is critical to occupant comfort and productivity. Forcing the eye to adapt too quickly to varied light intensities is not only distracting and stressful but potentially damaging. IES recommends minimizing variations in illuminance levels throughout the space and has created guidelines to assist in evaluating relative brightness. Illuminance variation across the immediate task should be kept to a minimum in order to avoid distracting occupants and causing visual fatigue (Rea 10-5). Variation between the task plane and the background can draw attention to the task, improving worker concentration. Accenting the work areas is particularly applicable in task lighting applications but should be limited between 1.5 and 3 times the background illuminance level to minimize visual fatigue (Rea 10-5). Issues of light distribution are particularly important in daylighting applications because recommended design intensities for electric light have been progressively lowered to minimize power consumption, further expanding the gap between natural sunlight and efficient artificial lighting. Integrating daylighting into the lighting strategy from the beginning of the design process is essential to creating an environment that effectively limits the intensity of sunlight allowed into the space while providing uniform and controllable light distribution (Rea 8-22, 10-5).

3.2.3 Glare

Non-uniform light distribution is typically associated with another major problem in daylighting design: glare. Glare is categorized by discomfort glare, disability glare, and overhead glare though discomfort and disability are the two most frequently encountered (Rea 10-5). Discomfort glare is the most common of the three though its’ physiological causes are not well understood. “Discomfort glare is a sensation of annoyance caused by high or non-uniform distributions of brightness in the field of view” (Oyvind, et al. 3-6). Occurrence of glare is usually just distracting and irritating but if sustained for long periods discomfort glare can cause eyestrain, headaches and other problems. Size, luminance, number of glare sources, and the geometry of sources in relation to the eye and task plane are all key factors in minimizing the potential for discomfort.

The second, more acute form of glare is disability glare, which partially or totally obstructs vision and causes severe discomfort. Disability glare occurs when light scatters within the eye, typically during low light conditions when the contrast of the retinal image is already lessened. Although there are no models to accurately predict incidences of disability glare, experts agree that the size of the area affected, relative brightness, and the composite intensity of all glare sources within the field of view are important factors (Oyvind, et al. 3-6).

Overhead or ‘Reflected’ glare is due to bright reflections of the sun or light source off of polished or glossy surfaces. Though these reflected images may actually assist with tasks such as inspection of paint for defects the benefits of reflected glare are limited and uncommon. Video Display Terminal (VDT) screens are particularly susceptible to reflected glare, complicating lighting design in high VDT use spaces. Reflected glare can be mitigated by providing light from both sides of the task or by specifying fixtures with optical designs intended to minimize reflected lamp images (Rea 10-6).

3.2.4 Direction

In some applications, multi-direction light is needed to accurately visualize three-dimensional objects and surfaces. By increasing the ratio of diffuse to direct light shadowing becomes less distinct, objects appear flatter and the ability to distinguish detail, depth, shape and texture are lessened. Quality lighting designs require a balance of direct and diffuse light to provide sufficient unidirectional light to distinguish three-dimensional detail while limiting glare and maintaining adequate luminance ratios between the task plane and the background.

> There are no standard performance parameters to evaluate the direction and diffusion of light. Direct sunlight is typically directional with sufficient diffuse light from the sky to balance out the contrast of a three-dimensional object. Daylighting systems that rely on sky light will typically produce diffuse omni-directional light. Some daylighting systems using non-imaging optics (e.g., anidolic systems) can redirect diffuse daylight in the same way a light projector

does, so some directional effects appear even in diffuse daylight (Oyvind, et al. 3-7).

3.2.5 Apparent Brightness

The subjective impression of brightness is an important psychological characteristic of lighting design within a space. Occupant perception of the space, "whether the interior *appears* to be dark or bright can be independent of the physical value of illuminance or luminance" (Oyvind, et al. 3-9). Two rooms with identical lamp and fixture layouts, both with equivalent measured light levels, may be perceived by occupants to differ in brightness based on variance in views available out windows, wall and furniture colors, or myriad other factors. Distribution of light within may also affect the human perception of room brightness. In an experiment by Tiller and Veitch, subjects were asked to match brightness levels with dimmer controls for two rooms having the same electric light fixtures but different luminance distributions, one very homogeneous and the other non-uniform. Subjects repeatedly applied five to ten percent less working plane illuminance in the room with non-uniform luminance distribution than the working plane light levels present under uniform distribution (Tiller, Veitch 93).

3.2.6 Color

The sun is a full-spectrum source that has an approximate color temperature of 6000ºK and produces true color rendering acting as a 100 percent baseline for the Color Rendering Index, which is used to compare the apparent quality of colors viewed under artificial lamps (Muhs(a) 3). Although incandescent and halogen lamps are effectively black body radiators and produce a nearly complete visual light spectrum, their use has declined with the push to reduce electrical loads and minimize internal heat gains. Advances in artificial light sources have produced efficient lamps that imitate the color temperature and appearance of sunlight with color rendering indices very near that of natural light. Ceramic metal halide lamps have achieved CRI ratings around 96, and tri-phosphor cool white fluorescent lamps approach CRI values of 89. Blending natural and artificial light effectively has been shown to improve the perception of color and increase occupant satisfaction with lighting, especially when high CRI light sources were used in conjunction with daylight. However, some daylighting systems utilize tinted or coated window glazings which filter certain wavelengths of light and can affect perception of color for objects inside the building and exterior views through the window. Holographic diffractive glazings and prismatic lenses can be used to control and diffuse incoming sunlight but may also cause chromatic dispersion, creating rainbow lighting effects at certain times and potentially affecting interior color rendering (Oyvind, et al. 3-9; Rea 10-4).

3.2.7 Thermal Comfort

Daylighting systems and the use of glass can have dramatic impact on the appearance of a space and the satisfaction of occupants, but they can have an equally great impact on mechanical systems used to condition the space. Uncontrolled direct sunlight is substantially brighter than conventional artificial light sources and carries much more infrared energy thus contributing significant heat to any surface it hits. Uncontrolled direct sunlight and poorly insulated glazing, especially south facing glass, can have a profound impact on heat gain and mechanical loads, making the maintenance of occupant thermal comfort difficult.

> Daylighting systems can affect thermal comfort in a variety of ways. A cold window surface can increase thermal discomfort caused by longwave radiative exchange between the window and occupant in the winter, and a hot window surface can do the same during the summer. Convective downdrafts caused by cold window surfaces and infiltration can also contribute to discomfort. In some cases, direct sun can contribute to greater thermal comfort during the winter (Oyvind, et al. 3-10).

It is critical to manage the direct portion of sunlight used in any lighting application in order to mitigate the dramatic thermal comfort effects of uncontrolled sunlight. Daylighting designs should incorporate baffles or glazing designed to diffuse or attenuate direct sunlight. Occupants can be given shades or louvers to help prevent unwanted glare, over-illumination or solar heat gain. Passive or hybrid solar lighting systems can be used to remove the thermal portion of captured sunlight before bringing it into the building while ensuring adequate control is provided.

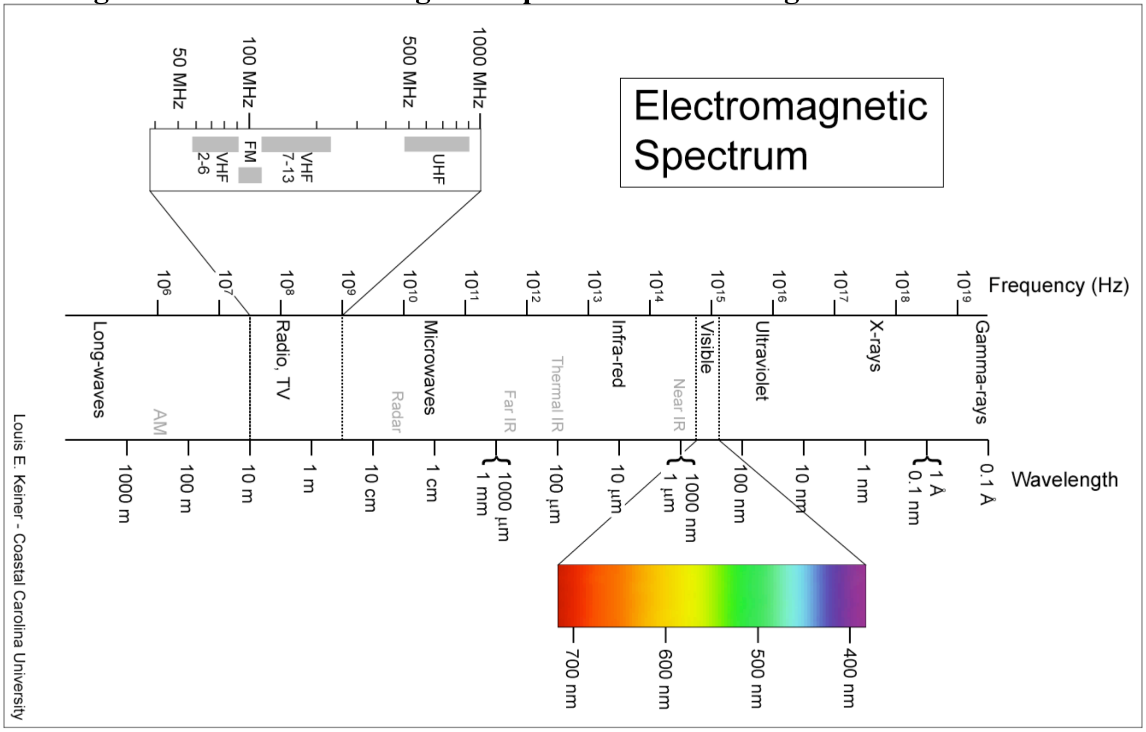
CHAPTER 4 - Properties of Sunlight and the Human Response

With the development of highly efficient electric light sources such as fluorescent, high-pressure sodium and metal halide lamps, natural light has become more novel than necessary in modern building design. Electric lighting's continually increasing efficiency, light quality, reliability, controllability and ease of application have made it an attractive choice for design professionals and largely displaced the more complicated art of effective daylighting. Recent movements toward sustainability, reduced energy consumption and improving the indoor environment have helped generate renewed interest in natural lighting. "However, benefits from daylighting extend beyond architecture and energy. The psychological and physiological aspects of natural light should also be considered" (Edwards, Torcellini 2).

4.1 Properties of Light

Energy transmitted through space in the form of waves is called electromagnetic radiation, which occurs naturally in spectrum of frequencies and wavelengths as shown in Figure 4.1. Light is merely the small visible portion of the much larger electromagnetic spectrum that includes radio waves, infrared, ultraviolet, X rays and gamma rays.

Figure 4.1 The Electromagnetic Spectrum and Enlarged Visible Portion



April 2009. <http://en.wikipedia.org/wiki/File:Electromagnetic-Spectrum.png>

Many medical studies have been conducted to determine the effects of different wavelengths of radiation on humans but this section is limited to those studies that seek to determine the precise psychological and physiological impacts of visible light on people. The results of human trials are difficult to draw simple conclusions from as myriad factors affect the responses of test subjects. Exposing subjects to an isolated wavelength of light can cause different affects than exposure to the same wavelength in combination with other wavelengths, or under different exposure conditions or at different intensities. However, it has been repeatedly proven that different spectra of light have different effects on the human body, that natural light stimulates essential biological functions in the brain and is vital to psychological and physiological health (Liberman 21). In his book Light: Medicine of the Future Dr. Liberman summarized that, "When we speak about health, balance, and physiological regulation, we are referring to the function of the body's major health keepers: the nervous system and the endocrine system. These major control centers of the body are *directly stimulated and regulated by light"* (Liberman 22).

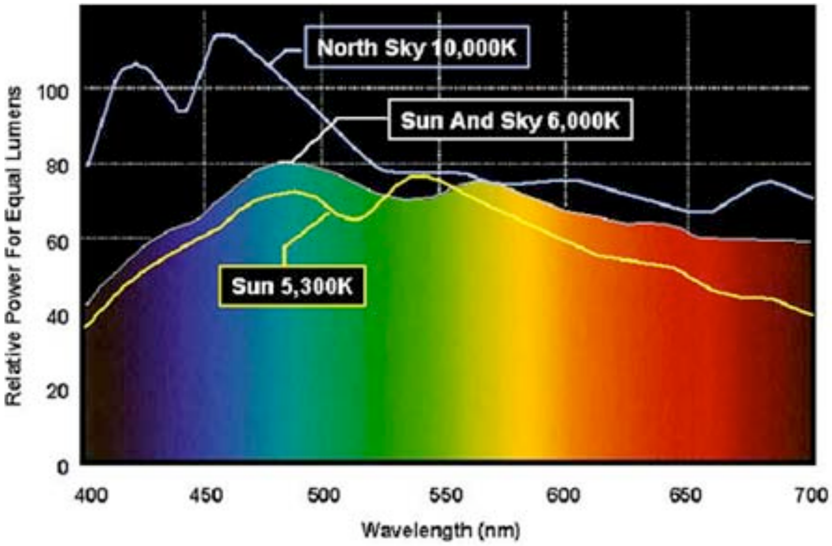
Daylighting has been associated with improved mood, enhanced morale, lower fatigue, and reduced eyestrain. One of the important psychological aspects from daylighting is meeting a need for contact with the outside living environment. The body uses light for metabolic processes and on a cloudy day, or under poor lighting conditions, the inability to perceive the colors from light can affect our mood and energy level. Studies have shown that under a wide variety of conditions a majority people prefer sunlit spaces because daylight consists of a balanced color spectrum, with its energy peaking slightly in the blue-green range (Muneer 147). While conducting research for the Branch Planning and Information Services Division of the Alberta Department of Education, Hathaway et al. concluded:

> The photobiologic action spectra of greatest importance to humans ranges from 290 to 770 nanometers. Skin reddening and vitamin D synthesis occurs in the range of 290 to 315 nanometers. Tanning or pigmentation of the skin and reduction of dental [cavities] occurs in response to band light in the band from 280 to 400 nanometers. Vision is the most sensitive to light in the 500 to 650 nanometer range (yellow-green light). Billirubin degradation occurs in response to

> light in the 400 to 500 nanometer range (blue light)… Full-spectrum fluorescent illumination also provides substantially all of the spectral energy distribution although light levels are much lower than daylight levels. The spectra of incandescent, cool-white fluorescent, and high-pressure sodium vapor light sources appear to fall short of covering the entire photobiologic action spectra of importance to human beings (Hathaway, et al. 11).

Most electric light sources lack the complete spectral distribution necessary to stimulate all the biological functions of the human body. ‘Cool White’ fluorescent lamps are concentrated in the yellow to red end of the visible spectrum. Incandescent lamps are also concentrated in the orange to red region of the spectrum. High output fluorescent lamps produce light concentrated in the yellow to green region of the visible spectrum as they are designed for maximum luminous flux and the human eye is most sensitive in this region. Full-Spectrum fluorescent lighting most closely simulates natural light because it has wavelengths in the blue portion of the spectrum between 400 and 500-nm (Edwards, Torcellini 3). To compare these electric sources to natural light Figures 4.2-4.5 show spectral distribution curves released by General Electric’s Lighting division illustrating the wavelengths of light emitted from incandescent, cool-white fluorescent, warm-white fluorescent, and the ‘Reveal’ full-spectrum fluorescent lamps manufactured by GE.

Figure 4.2 Spectral Distribution Curve of Daylight



Copyright 2009. General Electric Lighting Company <http://www.gelighting.com/na/business_lighting/education_resources/learn_about_light/distribution_curves.htm>.

Figure 4.3 Spectral Distribution Curves of Incandescent Lamps

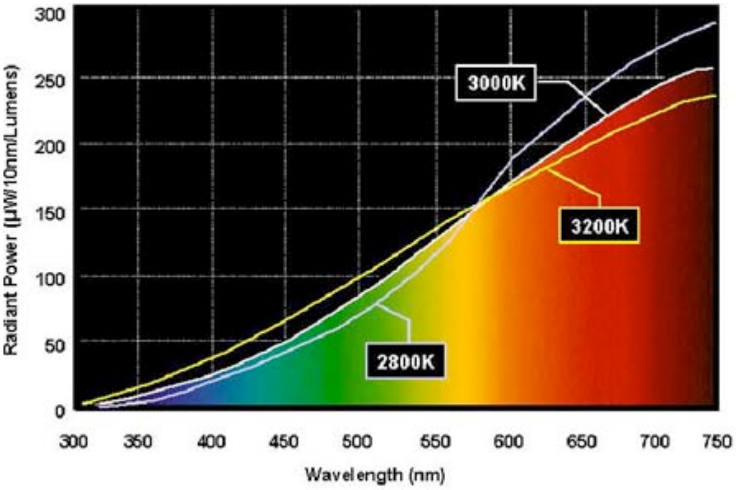


Figure 4.4 Spectral Distribution Curves of Cool and Warm-White Fluorescent Lamps

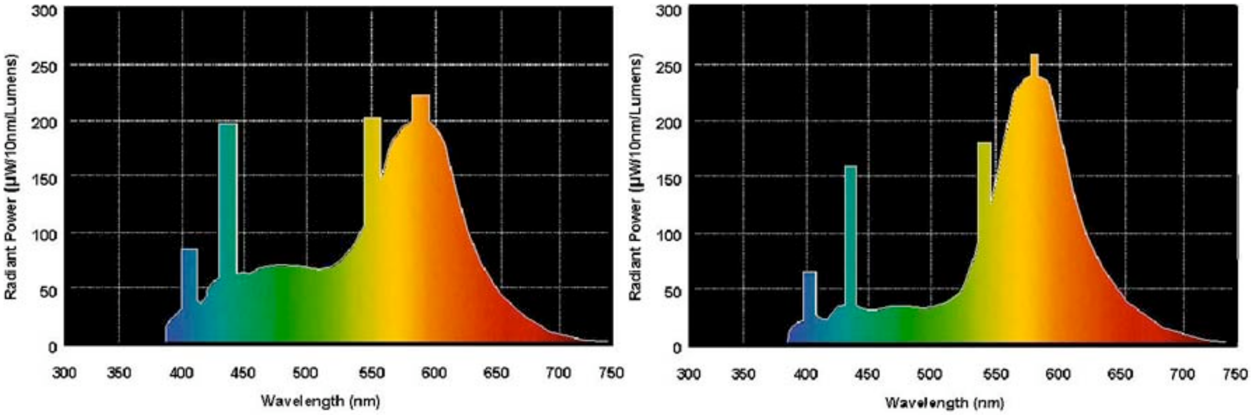
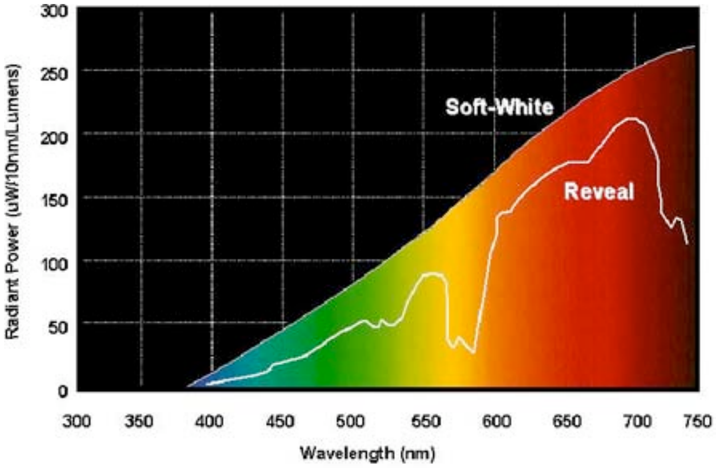


Figure 4.5 Spectral Distribution Curve of GE Reveal Full-Spectrum Fluorescent Lamp



Copyright 2009. General Electric Lighting Company
<http://www.gelighting.com/na/business_lighting/education_resources/learn_about_light/distribution_curves.htm>.

4.2 Effects of Light Exposure on the Human Body

To understand the effects of different light sources on the human body is necessary to understand how the body functions with respect to light. Light's affect on the human body falls into two categories: those modifying individual endocrine, hormone, and metabolic state by light reaching the retina and those resulting from light on the skin.

4.2.1 Light Entering the Human Eye

While performing experiments with different spectra of light on small animals and later humans, Hollowich and Dieckhues found that photoelectric energy influences the functioning of the pituitary gland which controls the hormonal system and by extension our coping mechanisms, emotional and stress relations. To better determine how light incident on the eye affects humans it is necessary to understand the neurological connections between the eye and the brain.

The human eye is a light-sensing system with a pupil and a photoreceptive medium called the retina. The retina contains two types of photoreceptors: rods and cones. Cones, which see 'photopic' lumens or bright light, are responsible for day vision. Rods, which see 'scotopic' lumens or dim light, are used primarily for night vision.

> For many years scientists did not believe that such effects occurred in humans at the illuminances typically used indoors. Researchers thought that illuminances of at least 2000 lux were necessary to have any photobiological effect. Recently it has been shown that this is not true, depending upon the time of day that the light is administered (Boyce par. 18).

> Light reaching the retina of the eye is converted into electrical signals that are transmitted by the optic nerve. Most of these signals end up in the visual cortex of the brain and produce our sense of vision. However, some of the nerve fibers split off from the optic nerve soon after leaving the eye and send signals to the suprachiasmatic nucleus, which is the area of the brain where the main clock for the human body resides (Boyce par. 13).

Light falling on the retina and being transmitted to the hypothalamus controls the human 'Circadian rhythm' that is responsible for synchronizing our internal clock to the normal twenty-four hour day/night cycle (Boyce par. 14). The effects of light on Circadian rhythms can be studied using physiological variables such as daily patterns of core body temperature, levels of melatonin, urine production, cortex activity and alertness (Boyce par. 10). A part of the hypothalamus called the suprachiasmatic nucleus receives signals about light and dark from the retina where special photoreceptor cells relay signals to the pineal gland, which is responsible for the production melatonin. During exposure to natural light the pineal gland suppresses melatonin production precipitating low melatonin levels that correspond to an alert state of consciousness, while high melatonin levels cause drowsiness (Circadian Rhythm). Melatonin levels in the body significantly influences a person's activity and energy levels in addition to less severe effects on mood, mental agility and reproductive processes. Melatonin production is closely followed by cortisol secretion from the adrenal cortex, which affects the breaking down of carbohydrates, protein and fat, as well as the development of white blood cells, nervous system activity and the regulation of blood pressure (Bryan 204).

4.2.2 Light Incident on the Skin

Early in the twentieth century it was discovered that rickets, a common calcium deficiency ailment leading to weak and deformed bones, could be cured by exposing patients to direct sunlight. Vitamin D is not really a vitamin, as it is not an essential dietary factor, but a prohormone produced photochemically in the skin from 7-dehydrocholesterol (Hollick 203). Vitamin D deficiency can cause death, immobilization or pelvic deformities that prevent normal childbirth (Neer 415). Independent studies by Neer in 1975 and later Hollick in 1980 concluded that ultraviolet radiation from sunlight in the region of 290 to 315-nm triggers the development of vitamin D in the skin. Liberman summarized the findings of these early studies as they relate to clinical treatment of rickets:

> Although the reason of sunlight's effectiveness was not immediately understood, it was later discovered that sunlight striking the skin initiated a series of reactions in the body leading to the production of vitamin D, a necessary ingredient for the absorption of calcium and other minerals from the diet. If

> vitamin D is absent, the body will not absorb the amount of calcium required for normal growth and development of the bones. This deficiency leads to the condition called rickets in children and osteomalacia in adults, which is characterized by a weak, porous, and malformed skeleton. It is known that both the development and maintenance of healthy bones is dependent upon the body's ability to absorb calcium and phosphorus (Liberman 70).

4.2.3 Seasonal Affective Disorder

Seasonal Affective Disorder, or SAD, is one of the best understood and most thoroughly studied medical conditions directly impacted by exposure to sunlight. "SAD is an emotional disorder characterized by drastic mood swings, lowered energy and depression that occur about the same time each year, arriving in the winter and vanishing in the spring" (Liberman 121). Originally called winter depression, SAD was thought to be a natural occurrence during the usually dark and cold months of the year. The effects of this disorder are so common and have been observed for so long that SAD was thought to be a normal seasonal occurrence and was not studied in depth until recently. Clinical studies have revealed the true nature of this affliction and explained why it is so prevalent, especially in far northern or southern regions of the globe. Dr. Liberman discusses the variable of latitude:

> The farther north people live, the more likely they are to experience winter depression. For example, while SAD affects only 8.9% of the residents of Sarasota, Florida, more than 30% of those living in Nashua, New Hampshire are affected. Although this condition is seen primarily in adults between the ages of 20 and 40, children have also been found to suffer from this affliction. For them, the irritability, fatigue, and sadness are frequently accompanied by a decline in concentration and school performance (Liberman 124).

It is believed that SAD is caused primarily by abnormally high melatonin levels in the blood due to the shortened sunlit hours of winter months. Although the exact physiological mechanism that causes the condition is unknown, bright light treatment has proven to be the medicine of choice for treatment of SAD. Exposing patients to bright light via the eyes reduces melatonin levels in the blood and has significant antidepressant effects for eighty percent of people treated (Liberman 124).

4.3 Effects of Light on Occupant Productivity

From an owner's perspective design and construction of a building is an exercise in estimation and quantification of building construction, operation and maintenance costs. Consideration is given to the satisfaction of the building's end users but the increased first cost associated with improvements to indoor environmental quality beyond code minimums often limits the extent to which an owner will invest. Attempting to quantify the benefits of an improved indoor environment to both workers and owners has been the driving force behind many studies on the subject of occupant productivity.

> The improved health of building occupants benefits employers and building owners because of improved performance… The effects of natural light on building occupants should be an important consideration for building design because studies have shown the strong influence light has on people in many different environments" (Edwards, Torcellini 38).

Although the health effects of natural light on the human body are becoming better understood, quantifying daylighting's influence on student performance has been the subject of much research. The following sections cover several studies into the less tangible benefits of daylighting on occupants in different types of facilities. As the most common public buildings educational, office, retail and healthcare facilities are discussed to provide further justification of the extra cost and effort required to implement effective daylighting strategies.

4.3.1 Educational Lighting

Both students and teachers can benefit from daylighting in classrooms. Many studies have been conducted to better understand the impacts of properly incorporating daylight into classrooms without creating the negative consequences associated with direct sunlight such as glare, thermal discomfort and distracting exterior views. Well designed daylighting schemes have proven to reduce utility costs, decrease student and teacher absenteeism, increase academic performance, improve student concentration and health, reduce stress factors, and even mitigate the effects of Attention Deficit Hyperactivity Disorder (Edwards, Torcellini 17).

A study of five Canadian public schools compared attendance rates, student performance and student health in classrooms lit with high-pressure sodium and conventional fluorescent lamps to those illuminated by full-spectrum fluorescent lighting with an ultra-violet component. Students were found to attend approximately 3.2 additional days of school per year when provided full-spectrum lighting (Hathaway, et al. 28). During the same study Hathaway discovered students receiving ultra-violet light, at levels less than half that of sunlight, had an average of 0.79 fewer decayed teeth than those in a control group under standard fluorescent lighting. Some students actually saw reversal of previously existing tooth decay (Hathaway, et al. 23-4). Furthermore, students grew faster and gained more body weight while in classrooms illuminated by full-spectrum lighting (Hathaway, et al. 30).

In Seattle, Washington and Fort Collins, Colorado end-of-year test scores by students in classrooms with the most daylight were compared to those in the least sunlit. Students in classrooms with high levels of daylight had 7 to 18 percent higher test scores than those in poorly-daylit rooms. During the same study, in San Juan Capistrano, California scores on spring and fall term exams were compared. Students with the highest levels of daylighting in class progressed 20 percent faster in math and 26 percent faster in reading than those with the least daylight over a one year period (Heschong(b) vii). Similar results were observed in Canadian public schools when results from the *Canadian Test of Basic Skills* were analyzed. Students under full-spectrum lighting progressed 4 to 20 percent faster than those in classrooms illuminated by standard fluorescent lamps, and 22 to 40 percent faster than those in classrooms illuminated by high-pressure sodium light fixtures (Hathaway, et al. 30-3).

At the request of the California Energy Commission, the Public Interest Energy Research (PIER) program conducted studies of over 450 elementary school classrooms with a variety of widow configurations, daylighting strategies and equipped with differing levels of lighting control. "Our studies of the classrooms showed that windows and the resulting lighting quality in classrooms are very much a key issue in learning, and can have both positive and negative impacts on student performance" (Heschong(b) 109). Teachers surveyed consistently preferred more daylight and better views from the classroom. Data collected from the study clearly demonstrates that glare, direct sunlight and lack of window controls negatively impacts learning.

"Direct sun penetration into classrooms, especially through un-shaded east or south facing windows, is associated with negative student performance, likely causing both glare and thermal discomfort" (Heschong(b) 109). Teachers provided with blinds or other methods of controlling glare and sun penetration were not always correlated with improved student achievement but student performance in classrooms without daylighting control was negatively impacted.

4.3.2 Office Lighting

Occupants in offices with full-spectrum fluorescent lights or well-designed daylighting systems report an increase in work satisfaction and general well being. Specific benefits include better health, reduced stress, improved focus, reduced absenteeism and increased productivity (Edwards, Torcellini 9). There is great difficulty quantifying benefits specifically attributable to daylighting, as it is difficult to isolate variables and determine precise impacts of indoor environmental quality improvements. However, even the most marginal increases in productivity and satisfaction can be greatly multiplied as they apply to every worker in the building over its entire life. Considering that employee payroll constitutes about 95 percent of the life cycle cost of a typical office building, even costly daylighting improvements can generate quick paybacks if tied to modest increases in worker productivity and retention. Daylighting benefits to office workers are substantial enough that many European countries require desks located within 27 feet of a window and some Scandinavian countries require the windows be operable (Franta, Anstead par. 5).

Lockheed Martin, VeriFone, West Bend Mutual Insurance, Pennsylvania Power and Light and the Reno Post Office reported increased worker productivity when improved lighting and other indoor quality conditions were implemented in their respective offices. However, these studies were often done internally without consideration for isolating variables and the metrics used to gauge worker productivity were often poorly defined (Edwards, Torcellini 9). A study by the Heschong Mahone Group, Inc. produced for the California Energy Commission attempted to isolate occupant comfort variables at a call center, through statistical regression analysis, and correlate those variables to changes in employee productivity and performance on several mental and visual acuity tests. One test administered during the study asked workers to memorize and recall a string of numbers written backwards, this test is commonly used as a measure of mental function and attention span. By increasing the portion of general lighting provided by daylight from 1 to 20 footcandles, a 13 percent improvement in performance was documented. “A logged function was found to have the best fit, implying the greatest increase in performance at the lowest levels of daylight illumination and a diminishing positive effect at increasingly higher daylight illumination levels” (Heschong(c) 153). In addition to this finding the study noted that during analysis of November hourly performance answering customer phone calls the data most closely matched performance predictions if a one-hour time lag was applied between daylight exposures and testing. “This implies that illumination levels can be expected to have diminishing effects as they increase in intensity, and that any effects on human performance are likely to have a physiological component (delayed effect) in addition to a visual component (instantaneous effect)” (Heschong(c) 153).

4.3.3 Retail Lighting

Many retailers have begun to explore the potential of daylighting in the retail environment. Several large retailers have started experimenting with skylights and other methods to bring natural light into their stores, improve the indoor environment, increase sales, attract customers and improve color rendering of products on display. Wal-Mart and Target especially have spent a great deal of time and effort creating prototype stores with varying degrees of natural lighting as internal records indicate that sales increase by up to 20 percent in daylit stores compared to those with only artificial light. However, these numbers are difficult to examine in detail, as retailers don’t typically disclose the records and methods used. Surveys of employees and customers also indicate a strong preference for daylit spaces, so much so that employees in artificially lit portions of stores with skylights requested that they be transferred to departments with natural light (Edwards, Torcellini 28-9). Possible reasons for the human preference to natural light in a retail environment include: improved color rendering, greater depth perception, perception of improved lighting quality, increased variability of lighting and a significant increase in vertical light levels on product shelving (Heschong(a) 54-5).

Attempting to expand upon previous studies and isolate variables that influence customer behavior in retail environments the Heschong Mahone Group, Inc. conducted a study of 73 retail stores in California, 24 of which had some type of daylighting. Using statistical analysis to isolate the numerous variables inherent in any comparison between different buildings the study tested a variety of store sizes, configurations, ages and daylighting schemes. “This study represents evidence that a major retailer is experiencing higher sales in daylit stores compared to similar non-daylit stores” (Heschong(a) 49). The report concluded that the retailer experienced, on average, a 6 percent increase in sales along with a 2 percent increase in volume of transactions in daylit facilities compared to similar stores without daylight, “with a maximum effect found in the most favorable stores of about a 40% increase in sales” (Heschong(a) 49). “Daylight was found to have as much explanatory power in predicting sales as other more traditional measures of retail potential, such as parking area, number of local competitors, and neighborhood demographics” (Heschong(a) 49). Furthermore, the study found that increased hours of useful daylight played a more prominent role in predicting customer behavior than the percentage of lighting provided by the sun. In addition to customer preference toward daylit areas and sales increases employee satisfaction with the work environment improved noticeably.

> Employees of the daylit stores reported slightly higher satisfaction with the lighting quality conditions overall than those in the non-daylit stores. Most strikingly, they perceived the daylit stores to have more uniform lighting than the non-daylit stores, even though direct measurements showed the daylight stores to have much greater variation in both horizontal and vertical illuminance levels (Heschong(a) 49).

4.3.4 Healthcare Lighting

“The goal of the healing environment is to provide non-institutional surroundings and a sense of calmness for patients, staff, and visitors. Natural light is one of many ideas used to create these environments” (Edwards, Torcellini 35). Many studies have been done on the subject of patient recovery with the objective of creating an optimal healing environment. One conclusion that has become widely accepted is the correlation between quality natural lighting, pastoral views and improved patient morale and recovery time. By improving patients’ indoor environment and light quality their mental well-being improves and the likelihood of complicating factors decreases, increasing recovery rates. Daylighting can lower a treatment or assisted living facility's operating costs by improving patient recovery and reducing the quantity of services and medication administered. Regulations on windows in hospitals have been created in the United States, some requiring a window in rooms where patients stay for 23 hours or more and others stipulating the minimum window area needed in rooms with patient beds (Edwards, Torcellini 33-5).

CHAPTER 5 - Electrical Consumption in the United States

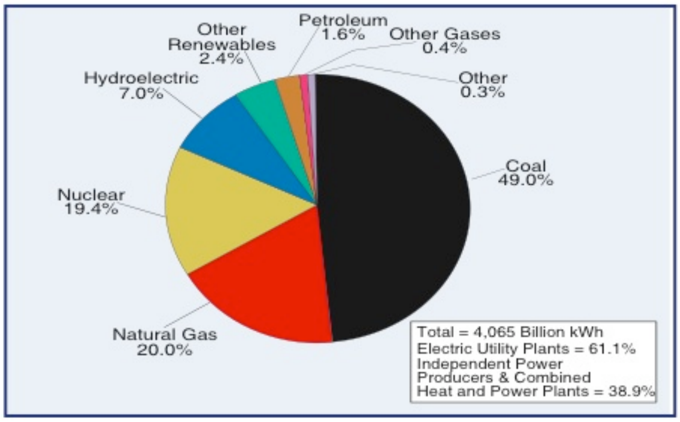
Although scientific and allegorical evidence of the health and satisfaction benefits associated with natural light continues to grow, the bottom line will inevitably be the economic impact of a technology. A creative natural or artificial lighting design must do more than create an exceptional indoor environment, it must also produce tangible benefits to the owner that are at least perceived to offset the additional system cost. Occupant health and satisfaction improvements can translate into significant savings and additional productivity but these effects are difficult to accurately quantify. The primary financial justification for a solar lighting system comes from its ability to displace electric lighting and reduce the operating cost of a facility. This chapter provides statistical information about the total power consumption of various building types in the United States in order to quantify the enormous amount of power currently used for lighting and illustrate the potential for passive and hybrid solar systems to displace substantial amounts of electrical load. Finally, a discussion of industry programs created to foster social incentives encouraging design of efficient, high-quality structures is included to demonstrate the swell of institutional, social and governmental support for environmental design practices.

5.1 Electrical Consumption in the United States

According to the Department of Energy's *Electric Power Annual 2006*, as of January 2007 the United States had 986-gigawatts of total net summer electrical power generating capacity. Coal, natural gas and nuclear energy are the three primary fuel sources for electrical generation in the United States, accounting for 49.0, 20.0 and 19.4 percent of annual net power respectively, as shown in Figure 5.1. Power plants, especially coal-fire plants, are inherently inefficient in their conversion of fuel to electricity, losing much of the fuel's energy in the form of heat. Further losses are incurred during the conversion and transmission of power from source to sub-station to end-users, exacerbating the already inefficient use of natural resources.

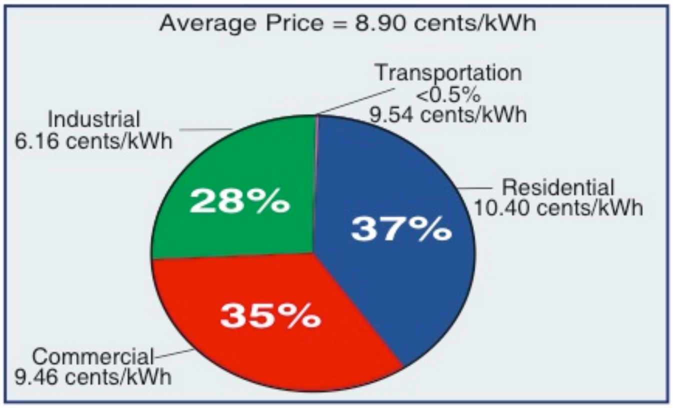
Hydroelectric and other renewable energy sources account for only 9.4 percent of total net summer generating capacity; underscoring U.S. reliance on limited fossil fuel supplies. The relative lack of renewable energy infrastructure also illustrates the directly proportional relationship between pollutant emissions and energy generation, further highlighting the potential for reducing pollution by improving efficiency and minimizing consumption. Of the total power consumed annually, residential buildings account for the largest portion with 37 percent, next largest are commercial buildings using 35 percent and finally industrial buildings with 28 percent of total consumption as shown in Figure 5.2.

Figure 5.1 Electrical Power Generation by Fuel Source in 2006



U.S. Department of Energy. *Electric Power Annual, 2006*

Figure 5.2 Percentage of Electrical Power Consumption by Market Sector in 2006



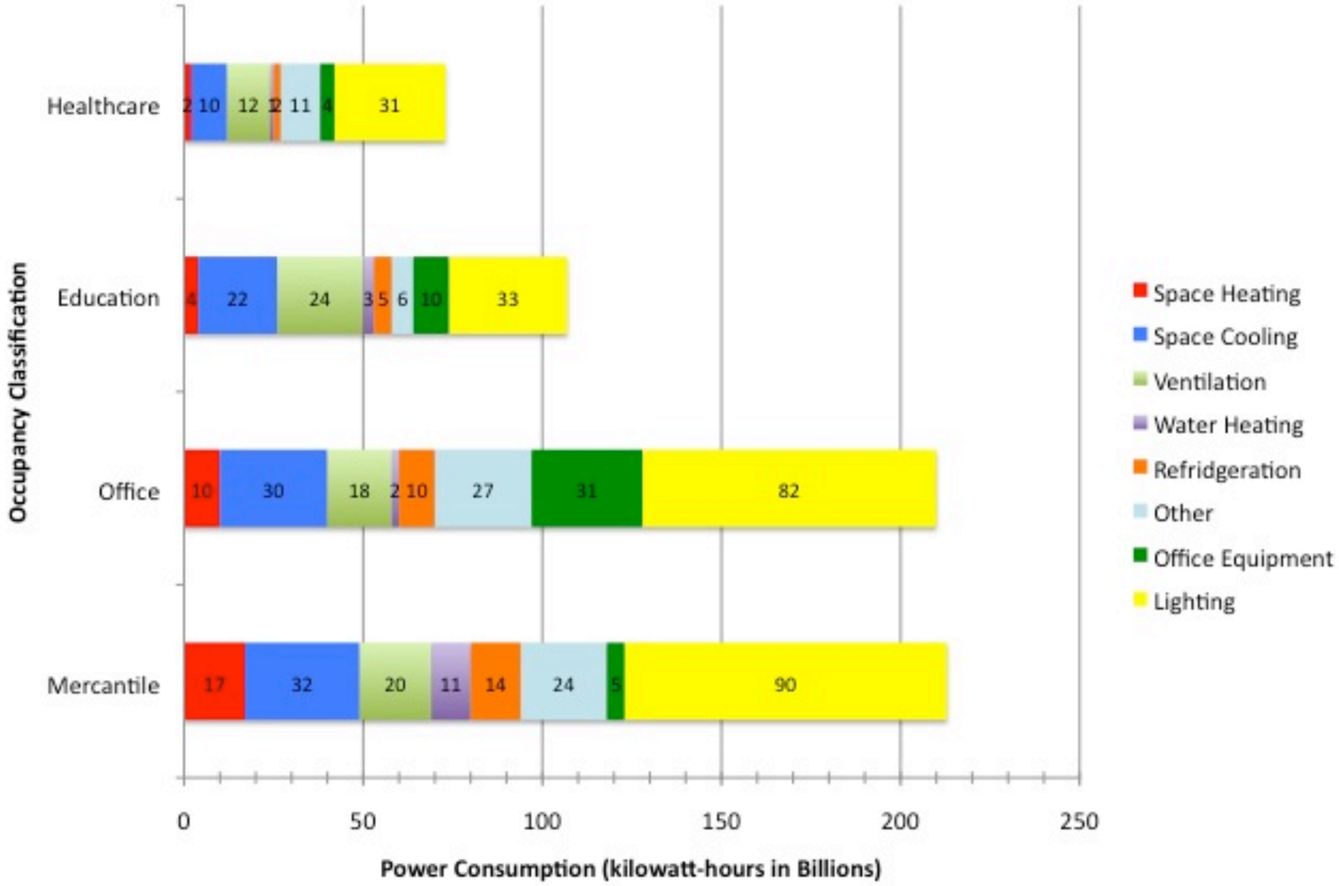
U.S. Department of Energy. *Electric Power Annual, 2006*

5.2 Occupancy Classification and Electrical End Uses

Analysis of energy consumption must begin with a closer look at how occupancy classification affects a structure's power usage and the quantity of electricity needed for different end-uses. Generally speaking, the majority of power buildings consume is used by mechanical equipment for refrigeration, space heating and cooling, conditioning of ventilation air and heating of water. The second largest electrical end-use is typically electric lighting. Analysis of these statistics demonstrates the potential for energy savings through building design improvements intended to minimize power required for operation and maintaining occupant comfort. Daylighting has the potential to displace a large percentage of electricity used to operate artificial lights during the day. If properly designed, daylighting also has the potential to reduce mechanical equipment load by eliminating the heat gain created by electric light sources. Many daylighting systems suffer from thermal comfort issues do the high infrared component of sunlight, but fiber optic lighting systems only transmit visible light and prevent solar heat gain while still illuminating the space with natural light. Fiber optic cables also increase the portion of the building that can be effectively illuminated with sunlight without altering the building footprint. Although daylight harvesting is not applicable or effective in every building type or geographic region, any meaningful reduction in electricity usage will be translated into pollution reductions.

To quantify the potential electrical load reductions for each market sector and determine the occupancies most able to capitalize on free solar energy the following statistics show the percentage of power consumed by different building types and various end-uses within these structures. For fiscal year 2003, the U.S. Department of Energy compiled electrical usage statistics by market sector and concluded that mercantile occupancies, composed of retail stores and malls, represented the largest consumer of electricity followed by office buildings, educational and healthcare facilities. Total reported power consumption by end-use within these occupancy classifications are shown in Figure 5.3 to graphically illustrate the findings of the *2003 Commercial Buildings Energy Consumption Survey*.

Figure 5.3 2003 Building Electrical Consumption per End-Use by Occupancy Type



During fiscal year 2003 mercantile structures consumed 215-billion-kilowatt-hours (kWh) of electricity. Of this 215-billion-kWh, 43.7 percent was used by mechanical equipment for space conditioning, ventilation, water heating and refrigeration. Within these mercantile structures 90-billion-kWh of electricity was used for electric lighting, representing 41.9 percent of total consumption.

Office buildings comprised the second largest market sector in terms of total electrical consumption, accounting for 211-billion-kWh of power usage. Mechanical equipment utilized 33.2 percent of total power consumed and electric lighting used 82-billion-kWh, or 38.9 percent of the total.

Educational facilities consumed 109-billion-kWh of electrical power. Of this 109-billion-kWh, 48.6 percent was used by mechanical equipment and 30.3 percent for electric lighting, representing the smallest percentage of total power consumption for lighting end use found in common occupancy classifications.

Healthcare facilities in the United States consumed 73-billion kWh of electricity in 2003. Mechanical equipment accounted for 37.0 percent of total power consumption, and electric lighting used 42.5 percent. Healthcare buildings require very high lighting levels and quality of light due to the sensitive nature of medical treatment and high visual acuity required in lab, operation, triage and patient care spaces. With 42.5 percent of total electrical consumption used by electric lighting, healthcare facilities present the greatest potential for power use reductions through improved lighting efficiency and daylighting strategies designed to minimize electric lighting loads when sunlight is available.

In any building type occupied during daytime hours there is potential to displace electric lighting with harvested sunlight. Obviously, the more power a market sector uses for lighting and the greater the percentage of occupied hours that occur during the day, the more beneficial a solar lighting system will be. If only a portion of the electric lighting load was replaced by natural sunlight, the United States could potentially reduce daytime power consumption by billions of kilowatt-hours therefore decreasing peak power generation and associated pollution accordingly.

5.3 Industry Programs to Reduce Electrical Consumption

The Energy Information Administration estimated in 2008 that the total impact of U.S. buildings on local resources account for 40 percent of primary energy, 72 percent of electricity, 39 percent of carbon dioxide emissions, and approximately 16 percent of potable water consumption (2003 Commercial Buildings; Estimated Use of Water). The Department of Energy's *Electrical Power Annual 2006* states that, "After a prolonged period of steadily falling prices in real terms, electricity prices began to increase in 2000." Total retail sales of electricity to end-users during fiscal year 2006 was $326 billion at an average price of ¢8.9/kWh, representing a cost increase of 9.3 percent in just one year (Electrical Power Annual 2006).

Price increases are placing pressure on consumers and companies to decrease energy consumption and improve resource efficiency. The most meaningful impact of rising energy prices is the shortening of payback periods associated with advanced building systems designed to reduce power consumption, increase efficiency and improve indoor quality. In addition to the financial benefits, social incentives are emerging for companies to be perceived as ‘green,’ guiding marketing and recruiting strategies while reinforcing the more direct operational advantages of high quality buildings.

Several industry driven organizations have been created to share best design practices and encourage integrated energy efficient design, especially in newly constructed buildings. Two organizations have done a particularly exceptional job of fostering cooperation between all relevant parties, governmental and private, and have compiled comprehensive design guides outlining numerous ideas for green design and construction. These organizations are the United States Green Building Council, who produces the Leadership in Energy and Environmental Design (LEED) Rating Systems and the Sustainable Buildings Industry Council, who conceptualized and helped create the Whole Building Design Guide.

5.3.1 Leadership in Energy and Environmental Design

> The Leadership in Energy and Environmental Design Green Building Rating System™ encourages and accelerates global adoption of sustainable green building and development practices through the creation and implementation of universally understood and accepted tools and performance criteria (LEED Rating Systems).

The United States Green Building Council began development of the LEED Green Building Rating System in 1994 to define ‘green building’ by establishing a common standard of reference, promote consumer awareness of green building benefits, stimulate competition in environmental design, recognize leadership in greed design, and to promote integrated whole-building design practices. The first iteration of LEED for New Construction was released in 1998 as a pilot version of the program and has since evolved and expanded to better meet the needs of construction projects in different market sectors. LEED has evolved through volunteer consensus-based committees of architects, engineers, construction managers, landscape designers, government officials, facilities managers and others who modify criteria to better meet the goals of the LEED program and expand its applicability to all project types.

> LEED gives building owners and operators the tools they need to have an immediate and measurable impact on their buildings' performance. LEED promotes a whole-building approach to sustainability by recognizing performance in five key areas of human and environmental health: sustainable site development, water savings, energy efficiency, materials selection and indoor environmental quality (LEED Rating Systems).

The rating systems are points-based, defining credits under each of the five key areas of human and environmental health listed above. Each credit is assigned certain criteria that building designers must demonstrate compliance with to obtain the given number of points associated with that credit. The project team must first decide which rating system is most applicable to the planned building. Green Building Rating Systems have been created for new construction, existing buildings, commercial interiors, core and shell, schools, retail, healthcare, homes and neighborhood development. Most projects are registered under LEED for New Construction and Major Renovations Rating System (LEED NC). After selecting rating system the project team must choose which credits are feasible to pursue and begin design and credit compliance documentation. All newly registered projects must obtain a few points under Energy and Atmosphere Credit 1: Optimize Energy Performance. LEED certification is divided into four levels, each progressively more difficult to achieve, requiring compliance with increasing numbers of the 69 possible credit points. Under version 2.2 of LEED NC a project must obtain a minimum of 26 credit points to become LEED Certified, 33 credits point to obtain LEED Silver, 39 points for LEED Gold and 52 points for Platinum Certification (LEED Rating Systems).

5.3.1.1 LEED NC v2.2, Indoor Environmental Quality Credit 8.1: Daylight and Views

This credit is intended to advance occupant comfort and productivity by establishing a connection with the outdoors through incorporation of natural light and views into regularly occupied spaces. Three potential compliance paths are given, to obtain the one point associated with this credit the project team must demonstrate compliance with one.

The first compliance path requires installation of sufficient exterior windows to achieve a minimum "glazing factor" of 2 percent in 75 percent of regularly occupied spaces. The glazing factor is calculated based on square footage of window glass and room size using a formula provided in the LEED NC v2.2 Reference Guide.

The remaining two compliance paths are achievable through use of fiber optic daylighting systems in conjunction with effective window placement and sizing. Increasing thermal loads on mechanical equipment is a major concern of daylighting applications and the use of fiber optic and hybrid solar systems can help mitigate these concerns while increasing sunlight levels and improving lighting quality throughout the space. The second compliance path requires the use of a computer simulation to demonstrate that a minimum daylight illumination level of 25 footcandles has been achieved for 75 percent of regularly occupied spaces, measured at a work plane 30 inches above the floor. The third compliance path requires the same daylight illumination level of 25 footcandles for 75 percent of spaces but allows the design team to manually demonstrate achievement of the desired daylight levels by physically measuring illuminance levels on a 10-foot grid throughout the space and recording results across the entire floor plan.

5.3.1.2 LEED NC v2.2, Energy and Atmosphere Prerequisite 2: Minimum Energy Performance

Use of fiber optic and hybrid solar daylighting systems can help lower electrical loads associated with electric lighting as part of a comprehensive strategy to minimize utility energy consumption. To obtain any credits in the Energy and Atmosphere category the project team must demonstrate compliance with all three prerequisites. Prerequisite 2: Minimum Energy Performance requires the project team to demonstrate compliance with the mandatory provisions and prescriptive requirements of ASHRAE 90.1-2004. The ASHRAE standard sets performance requirements for the building's shell and establishes maximum allowable power densities for installed equipment and lighting systems. The design team must use Section 90.1 power densities to establish an energy model reflecting the known equipment and intended occupancy of the structure. The model is used as a baseline case against which the proposed building design is compared and the design team must demonstrate that the building consumes less energy than the baseline ASHRAE 90.1 power densities.

5.3.1.3 LEED NC v2.2, Energy and Atmosphere Credits 1: Optimize Energy Performance

The baseline energy model created in the Energy and Atmosphere Prerequisite 2 is used as a comparison for this credit with one point achieved for a 10.5 percent reduction and a maximum of 10 points for reducing usage by 42. As of June 26th, 2007 all New Construction projects must attempt to achieve at least two EA Credit 1 points. The design team must also demonstrate compliance with Appendix G and all the mandatory provisions of ASHRAE 90.1-2004 as well as include all the energy costs associated with the building project. Four compliance paths are offered and demonstrating achievement of less stringent provisions of ASHRAE 90.1 and the Advanced Buildings Core Performance Guide. Incorporating fiber optic or hybrid solar daylighting systems into the project has the potential to greatly reduce electric lighting loads, even deep within the space. An effective daylighting strategy including hybrid solar fixtures could provide sufficient lighting during clear weather with little to no power consumption, and effective dimming control can maintain levels with significantly reduced electrical use.

5.3.2 The Whole Building Design Guide

The Sustainable Buildings Industry Council, founded in 1980 as the Passive Solar Industries Council, has since expanded in scope to serve as a resource for designers and builders of the latest in sustainable building technology (Our Organization).

> In the 1990s the PSIC's scope expanded to include the other major aspects of sustainable design and construction including optimizing site potential, minimizing energy use, using renewable energy sources, conserving and protecting water, using environmentally preferable products, enhancing indoor environmental quality, and optimizing operations and maintenance practices (Our Organization).

The Sustainable Buildings Industry Council has worked with the General Services Administration, the Department of Defense, the Environmental Protection Agency and the Department of Energy to coordinate public policy relating to construction practices and requirements for future government buildings. In 1997 the SBIC conceptualized the Whole Building Design Guide, intended to provide a free online resource for those in the construction industry interested in improving the quality and functionality of structures through integrated and cost effective sustainable design practices. The Guide is organized in three main sections: Design Guidance, Project Management, and Operations and Maintenance. The Design Guide compiles design techniques and technologies relevant to improving occupant comfort, reducing energy consumption, minimizing water usage, increasing functionality and occupant productivity. Private industry companies, federal agencies, non-profit groups and educational institutions all contribute to improve the content of the design guide (About the WBDG).

The National Institute of Building Sciences, originally created by the United States government in 1974, has served as a liaison between the federal government and the private sector on issues related to building design and construction. The Institute was tasked with creating and maintaining a website offering the Whole Building Design Guide free to the public. Through the cooperation of myriad governmental agencies, educational institutions and private groups the Design Guide continues to evolve with the goal of establishing and disseminating environmental design best practices (All About the NIBS).

Although similar to the LEED Ratings Systems the Whole Building Design Guide does not establish minimum criteria or award points for achieving requirements, it is simply intended as a resource for those interested in incorporating sustainable products and practices into current projects.

5.3 Conclusions

Over time building standards and engineering practices have trended toward integrated, whole-building design approaches aimed at maximizing system functionality, interoperability, control, occupant responsiveness and indoor environmental quality while continuously lowering allowable power densities. As electricity prices continue to increase and concerns about climate change drive construction to be more sustainable innovative technologies will emerge to further improve efficiency and reduce consumption. Fiber optic daylighting systems represent the most effective method of bringing direct sunlight inside while maintaining the level of control desired by occupants and simultaneously mitigating the variability, glare, intensity, distribution and thermal comfort problems of traditional daylighting strategies. Transmission of sunlight through optical fibers maintains the natural frequencies and wavelengths of visible natural light while attenuating the infrared and ultraviolet components, eliminating the space heat gain and thermal comfort problems encountered in conventional daylighting design. In addition to the many documented occupant comfort, worker productivity and health implications of natural lighting daylight harvesting with a fiber optic system represents the most efficient means of utilizing solar energy to reduce electrical consumption while enhancing indoor lighting quality. This technology expands the range of daylighting further into the building core, allowing designers to improve lighting quality across a greater floor area while displacing larger quantities of electric light without affecting space layout or mechanical loads. Further development is needed to address design issues such as blending artificial and natural sources, removing excess heat from fibers and system components, increasing life cycle as well as establishing standards for design, installation and maintenance. Although passive and hybrid solar lighting systems have been installed overseas, the economic justification for these systems is currently not strong enough for widespread market penetration in the United States. Several trial installation of hybrid solar lighting systems have been conducted in large retail stores with positive energy savings, customer perception, employee satisfaction and sales impacts. However, as products improve, design standards emerge, commercial availability increases and energy prices continue to rise solar lighting systems will become progressively more cost effective and economically viable in a widening range of applications.

References

"About the WBDG." 2009. National Institute of Building Sciences. 23 January 2009. < http://www.wbdg.org/about.php>.

"All About the National Institute of Building Sciences." 2008. National Institute of Building Sciences. 23 January 2009. < http://www.nibs.org/aboutnibs.html>.

Altkorn, R., et al. "Low-loss liquid-core optical fiber for low-refractive-index liquids: fabrication, characterization, and application in Raman spectroscopy." Applied Optics. Vol. 36, No. 34 (1 December 1997): 8997.

"Average Daily Solar Radiation Per Month: Annual." 1990. National Renewable Energy Laboratory: Resource Assessment Program. 3 April 2009. <http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/atlas/serve.cgi>.

Beshears, D. L., Capps, G. P., et al. Tracking Systems Evaluation for the 'Hybrid Lighting System'. Proc. of ISEC 2003: International Solar Energy Conference. American Society of Mechanical Engineers. March 16-18. Kohala Coast, Hawaii.

Boyce, Peter. "Light, Sight, and Photobiology." Lighting Futures. 2.3 (1998): Lighting Research Center of the Rensselaer Polytechnic Institute. 13 September 2008. <http://www.lrc.rpi.edu/programs/Futures/LF-Photobiology/index.asp>.

Bryan, H. Justifying Daylighting in an Era of Extremely Efficient Lighting Technologies. Proc. of 23rd National Passive Solar Conference. American Solar Energy Society. June 1998. 203-8.

"Circadian Rhythm." Encyclopedia Britannica. 2008. Encyclopedia Britannica Online. 14 September 2008. <http://www.britannica.com/EBchecked/topic/118220/circadian-rhythm>.

Driggers, Ronald G., Ed. Encyclopedia of Optical Engineering: Volume 2. Marcel Dekker: New York, 2003.

Earl, D. D., Muhs, J. D. Preliminary Results on Luminaire Designs for Hybrid Solar Lighting Systems. Proc. of Forum 2001: Solar Energy: The Power to Choose. American Society of Mechanical Engineers. April 21-25. Washington, D.C.

Earl, D. D., Thomas, R. R. Performance of New Hybrid Solar Luminaire Design. Proc. of ISEC 2003: International Solar Energy Conference. American Society of Mechanical Engineers. March 16-18. Kohala Coast, Hawaii.

Franta, G., Anstead, K. "Daylighting Offers Great Opportunities." WDMA Articles. Spring 1994. Window and Door Manufacturers Association. 7 October 2008. <http://www.wdma.com/i4a/pages/index.cfm?pageid=3668>.

"Fresnel Lens." Encyclopedia Britannica. 2008. Encyclopedia Britannica Online. 6 February 2009. <http://www.britannica.com/EBchecked/topic/219816/Fresnel-lens>.

Hathaway, Warren E., et al. Canada. Alberta Department of Education. Planning and Information Services Division. A Study Into the Effects of Types of Light on Children: A Case of Daylight Robbery (IRC Internal Report No. 659). February 1992.

Heschong(a), Lisa. "Daylight and Retail Sales." California Energy Commission. October 2003. 49-55.

Heschong(b), Lisa. "Windows and Classrooms: A Study of Student Performance and the Indoor Environment." California Energy Commission. October 2003. vii-xi; 109-10.

Heschong(c), Lisa. “Windows and Offices: A Study of Office Worker Performance and the Indoor Environment.” California Energy Commission. October 2003. 132-43.

“History of the Himawari System.” 2006. La Forêt Engineering Co., Ltd. 27 January 2009. <http://www.himawari-net.co.jp./e_page-index01.html>.

Holick, Michael F., et al. “Photosynthesis of Previtamin D3 in Human Skin and the Physiologic Consequences.” Science 210.4466 (Oct. 1980): 203–5.

Hollwich, F., Dieckhues, B. “The Effect of Natural and Artificial Light Via the Eye on the Hormonal and Metabolic Balance of Animal and Man.” Ophthalmologica 180.4 (1980): 188-97.

“Hybrid Solar Lighting Illuminates Energy Savings for Government Facilities.” 2007. Department of Energy. Federal Energy Management Program. 4 December 2008. <http://www1.eere.energy.gov/femp/pdfs/tf_hybridsolar.pdf>.

Lapsa, Melissa V., Maxey, Curt L., et al. “Hybrid Solar Lighting Provides Energy Savings and Reduces Waste Heat.” Energy Engineering 104.4 (2007): 7-20.

“LEED for New Construction and Major Renovations: Version 2.2.” 2005. United States Green Building Council. 5 May 2007. <http://www.usgbc.org/ShowFile.aspx?DocumentID=1095>.

“LEED Rating Systems.” 2008. United States Green Building Council. 22 January 2009. <http://www.usgbc.org/DisplayPage.aspx?CMSPageID=222>.

Liberman, Jacob. Light: Medicine of the Future. New Mexico: Bear & Company Publishing, 1990.

Maxey, L. C., Cates, M. R., Jaiswal, S. L. Efficient Optical Couplings for Fiber-Distributed Solar Lighting. Proc. of ISEC 2003: International Solar Energy Conference. American Society of Mechanical Engineers. March 16-18. Kohala Coast, Hawaii.

Muhs(a), Jeff. Design and Analysis of Hybrid Solar Lighting and Full-Spectrum Solar Energy Systems. Proc. of American Solar Energy Society's Solar2000 Conference. American Society of Mechanical Engineers. June 2000. Paper No. 33.

Muhs(b), Jeff. "Hybrid Solar Lighting Doubles the Efficiency and Affordability of Solar Energy in Commercial Buildings." CADDET Energy Efficiency Newsletter No. 4 (2000): 6-9.

Muneer, Tariq, et al. Windows in Buildings: Thermal, Acoustic, Visual and Solar Performance. Oxford: Architectural Press, 2000.

Neer, Robert M. "The Evolutionary Significance of Vitamin D, Skin Pigment, and Ultraviolet Light." American Journal of Physical Anthropology 43.3 (Nov. 1975): 409-16.

"Our Organization: SBICs History." 2008. Sustainable Buildings Industry Council. 29 January 2009. < http://www.sbicouncil.org/displaycommon.cfm?an=1&subarticlenbr=92>.

Oyvind, A., et al. Daylighting in Buildings: A Source Book on Daylighting Systems and Components. California: Lawrence Berkley National Laboratory, 2000.

Parans: Bringing Nature Inside. Goteborg, Sweden: Parans Solar Lighting AB, 2008.

"Products Line-Up." 2006. La Forêt Engineering Co., Ltd. 28 January 2009. <http://www.himawari-net.co.jp./e_page-index01.html>.

Rea, Mark S., Ed. The IESNA Lighting Handbook: Reference and Application, 9th Edition. New York: IESNA, 2000.

"Specifications of the Himawari/Solar Lighting System." 2006. La Forêt Engineering Co., Ltd. 9 May 2009. <http://www.himawari-net.co.jp/e_page-index01.html>.

"Spectral Power Distribution Curves." 2009. General Electric Lighting Company. 13 May 2009. <http://www.gelighting.com/na/business_lighting/education_resources/learn_about_light/distribution_curves.htm>.

Soydan, Y., Engin, T. "Lighting Building Interiors Requiring Lighting at Day Times by Conveying Daylight." Diss. Sakarya University, 2007.

Tariq, et al. Windows in Buildings: Thermal, Acoustic, Visual and Solar Performance. Oxford: Architectural Press, 2000.

"Telescope." Encyclopedia Britannica. 2008. Encyclopedia Britannica Online. 24 February 2009. < http://www.britannica.com/EBchecked/topic/586053/telescope/44229>.

"The Inventor of the HIMIWARI System." 2006. La Forêt Engineering Co., Ltd. 27 January 2009. <http://www.himawari-net.co.jp./e_page24.htm>.

Tiller, D.K., Veitch, J.A. "Perceived Room Brightness: Pilot Study on the Effect of Luminance Distribution." Lighting Research and Technology. 27.2 (1995): 93-101.

United States. Department of Energy. Electric Power Annual, 2006. Washington: GPO, 2006.

---. Department of Energy. Energy Information Administration. 2003 Commercial Buildings Energy Consumption Survey: Energy End-Use Consumption Tables. Washington: GPO, 2008.

---. Department of Energy. Energy Information Administration. 2008 Annual Energy Outlook: With Projections to 2030. Washington: GPO, 2008.

---. U.S. Geological Survey. Estimated Use of Water in the United States in 2000. Washington: GPO, 2000.

“What is the Energy Payback for PV?” December 2004. National Renewable Energy Laboratory. 30 December 2008. <http://www.nrel.gov/docs/fy05osti/37322.pdf>.

Whole Building Design Guide. 2009. National Institute of Building Sciences. 29 January 2009. < http://wbdg.org/design/index.php>.

Appendix A - Glossary of Lighting Terminology

The following is a list of definitions for selected lighting terms taken from the *IESNA Lighting Handbook* (Rea G-1 – G-38).

Ambient Lighting – Lighting throughout an area that produces general illumination.

Azimuth – The angular distance between the vertical plane containing a given line or celestial body and the plane of the meridian.

Baffle – A single opaque or translucent element to shield a source from direct view at certain angles, to absorb or block unwanted light, or to reflect and redirect light.

Ballast – A device used with an electric-discharge lamp to obtain the necessary circuit conditions (voltage, current, and waveform) for starting and operating.

Blackbody – A temperature radiator of uniform temperature whose radiant exitance in all parts of the spectrum is the maximum obtainable from any temperature radiator at the same temperature.

Coefficient of Attenuation – The decrement in flux per unit distance in a given direction within a medium.

Color Rendering – A general expression for the effect of a light source on the color appearance of objects in conscious or subconscious comparison with their color appearance under a reference light source.

Color Rendering Index – Measure appraising a light source for enhancing the appearance of an object or objects by making their colors tend toward people's preferences.

Color Temperature – The absolute temperature of a blackbody radiator having a chromaticity equal to that of the light source.

Daylight Availability – The luminous flux from sun plus sky at a specific location, time, date, and sky conditions.

Direct Lighting – Lighting involving luminaires that distribute 90 to 100% of the emitted light in the general direction of the surface to be illuminated.

Direct Glare – Glare resulting from luminances or insufficiently shielded light sources within the field of view.

Disability Glare – The effect of stray light entering the eye whereby visibility and visual performance are reduced.

Discomfort Glare – Glare that produces discomfort. It does not necessarily interfere with visual performance or visibility.

Downlight – A small direct lighting unit that directs the light downward and can be recessed, surface-mounted, or suspended.

Electromagnetic Spectrum – A continuum of electric and magnetic radiation encompassing all wavelengths.

Fenestration – Any opening or arrangement of openings (normally filled with media for control) for the admission of daylight.

Footcandle – A unit of illuminance equal to 1-lumen/square-foot or 10.76-lux.

General Lighting – Lighting designed to provide a substantially uniform level of illuminance throughout an area, exclusive of any provisions for special local requirements.

Glare – The sensation produced by luminances within the visual field that are sufficiently greater than the luminance to which the eyes are adapted, which causes annoyance, discomfort, or loss in visual performance and visibility.

Illuminance – The areal density of the luminous flux incident at a point on a surface.

Intensity – A shortening of the terms *luminous intensity* and *radiant energy*. Often misused for level illumination or illuminance.

Irradiance – The density of radiant flux (power) incident on a surface.

Lens – A glass or plastic element used in luminaires to change the direction and control the distribution of light rays.

Louver – A series of baffles used to shield a source from view at certain angles, to absorb or block unwanted light, or to reflect or redirect light.

Lumen – SI unit of luminous flux. Radiometrically, it is determined from the radiant power as in *luminous flux*.

Luminaire (Light Fixture) – A complete lighting unit consisting of a lamp or lamps and ballast(s) (when applicable) together with the parts designed to distribute the light, to position and protect the lamps, and to connect the lamps to the power supply.

Luminance – The quotient of the luminous flux at an element of the surface surrounding the point, and propagated in directions defined by an elementary cone containing the given direction, by the product of the solid angle of the cone and the area of the orthogonal projection of the element of the surface on a plane perpendicular to the given direction. The luminous flux can be leaving, passing through, or arriving at the surface.

Luminous Flux – The time rate of flow of radiant energy.

Lux – The SI unit of illuminance. 1-lux is 1-lumen/square-meter.

Photobiology – A branch of biology that deals with the effects of optical radiation on living systems.

Photoelectric Receiver (Photocell) – A device that reacts electrically in a measurable manner in response to incident radiant energy.

Point Source – A source of radiation whose dimensions are sufficiently small, compared with the distance between the source and the irradiated surface, that these dimensions can be neglected in calculations and measurements.

Quality of Lighting – Pertains to the distribution of luminance in a visual environment. The term is used in a positive sense and implies that all luminances contribute favorably to visual performance, visual comfort, ease of seeing, safety, and aesthetics for the specific visual tasks involved.

Radiance – The quotient of the radiant flux leaving, passing through, or arriving at an element of the surface surrounding the point, and propagated in directions defined by an elementary cone containing the given direction, by the product of the solid angle of the cone, and the area of the orthogonal projection of the element of the surface on a plane perpendicular to the given direction.

Radiant Exitance – The density of radiant flux leaving a surface. It is expressed in watts per unit area of the surface.

Radiant Flux – The time rate of flow of radiant energy. It is expressed preferably in watts.

Radiator – An emitter of radiant energy.

Shade – A screen made of opaque or diffusing material that is designed to prevent a light source from being directly visible at normal angles of view.

Spotlight – Any of several different types of luminaires with narrow beam angle designed to illuminate a well-defined area.

Task Lighting – Lighting directed to a specific surface or area that provides illumination for visual tasks.

Total Internal Reflectance – Total reflection of a light ray at a surface of a transmitting medium occurs when the angle of incidence exceeds a certain value whose sine equals $n1/n2$, the ratio of indices of refraction, or when sin $r = 1$, where r equals the angle of reflection.

Transmission – A general term for the process by which incident flux leaves a surface or medium on a side other than the incident side, without change in frequency.

Troffer – A long recessed lighting unit usually installed with the opening flush with the ceiling. The term is derived from 'trough' and 'coffer.'

Workplane – The plane on which a visual task is usually done, and on which the illuminance is specified and measured.