Full spectrum hybrid lighting for commercial buildings

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ABSTRACT

Hybrid lighting is a new approach to lighting that integrates light from natural and electric sources. Hybrid lighting systems collect and distribute the visible portion of sunlight using large-core optical fibers and combine it with electrically-generated light in existing light fixtures. The natural and electric light sources work in unison to light commercial buildings where lighting represents the single largest user of electricity. The infrared (IR) portion of the solar spectrum is used to generate electricity using thermal photovoltaic cells.

Full-spectrum solar energy system targets in commercial buildings are costs under 1.00 $US/W, simple paybacks of between 2 - 5 years, and electrical energy displacement costs under 0.05$US/kWh by 2005 in most parts of the USA. Accordingly, it is expected to more than double the efficiency, affordability, and market penetration of solar energy when compared to other options such as solar electric technologies and conventional daylighting strategies.

Estimates indicate that by the year 2020 widespread use of full-spectrum solar energy systems will lead to: energy savings ranging from 10 x 10^9 kWh to 30 x 10^9 kWh; economic benefits exceeding $5 billion; and reductions in carbon emissions of greater than 5 megatons each year in the United States alone. Worldwide, these impacts will likely increase by an order of magnitude. The U.S. estimate alone equates to approximately 40% of the U.S. Department of Energy's Lighting R&D Portfolio goal for the year 2020.

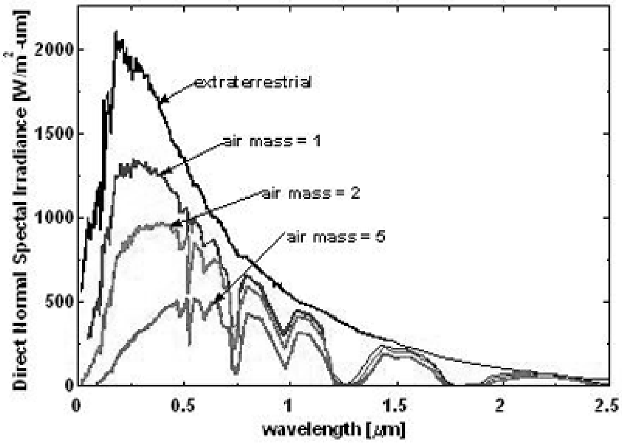
BACKGROUND

Hybrid lighting represents an alternative renewable technology that has the potential to reduce building energy consumption due to lighting. In the U.S. commercial building sector, lighting is the single highest user of energy with current annual lighting energy estimates of about four quadrillion kJ of primary energy. With a domestic energy consumption of that level, hybrid lighting systems could provide significant reductions in demand and energy usage.

By dividing and utilizing different portions of the light spectrum, hybrid lighting has an advantage over other technologies. The first component of the system is a concentrating collector that collects light and focuses it onto a secondary element. The secondary element divides the light into the visible and infrared spectra. The visible spectrum is used directly to light the interior of the building while the infrared radiation is used in either a thermal photovoltaic panel or a solar thermal collector. The use of the infrared radiation for electricity generation or thermal collection is one major advantage of hybrid lighting.

Using sunlight to directly light the building, hybrid lighting overcomes the inefficiencies of secondary lighting systems such as photovoltaics. Photovoltaics use light to generate electricity and the electricity from photovoltaic panels can be used to power interior lighting. Unfortunately commercially available photovoltaics generally operate at an overall efficiency of less than 15 %. Adding up all of the losses and including energy conversions losses,

Figure 1. Extraterrestrial and terrestrial spectrum for various air masses (Iqbal, 1983)



transmission losses, and losses due to electric lighting, the overall PV lighting system efficiency would be less than 5 %. In comparison, a hybrid lighting system will operate with efficiencies in the range of 20-30% (Muhs, 2000a).

The hybrid lighting concept is a technology which effectively uses solar radiation for direct lighting while minimizing additional cooling loads. Hybrid lighting systems use two axis concentrating collectors to maximize collected beam solar energy. Heat load effects are minimized by removing the infrared portion of the solar spectrum and using it for energy generation. The remaining visible light is distributed evenly throughout the space using fiber optic bundles or light tubes.

The Atmosphere

In order to determine the quantity of energy that is available to the system, a thorough understanding of how light is transmitted through the atmosphere is needed. Light leaves the sun and is transmitted through space until it reaches the edge of the earth's atmosphere. At the edge of our atmosphere the energy from the sun has been reduced to the annual average value of 1367 W/m2, the so-called solar constant (Duffie and Beckman, 1991). The solar constant represents the power at the top of the earth's atmosphere integrated over all wavelengths. As the solar radiation is transmitted through the atmosphere, a portion of the energy, ranging from nearly 0 to 80%, is either absorbed or scattered by different components of the atmosphere.

The path of radiation through the atmosphere directly impacts the amount of radiation received on the ground. The radiation path is represented by a value of air mass, the amount of atmosphere the radiation must travel through to get to the surface of the earth. An air mass of one is defined as the atmosphere the radiation must travel through to get to the equator when the sun is directly over the equator. In general, the higher the location's latitude, the higher the air mass with larger values of air mass leading to smaller amounts of terrestrial radiation (see Figure 1).

Ultraviolet (UV), visible, and infrared (IR) are the three general radiation regions of the solar spectrum. The majority of the energy of the solar spectrum is transmitted at wavelengths between 0.3 µm and 2.4 µm. The visible portion of the spectrum includes wavelengths from 0.38µm - 0.78_µm. The wavelengths of the UV portion of the spectrum are less than 0.38µm, while the IR portion of the spectrum has wavelengths greater than 0.78 µm. Hybrid lighting systems are designed to operate by utilizing the visible and near infrared portions of the spectrum that contain a large percentage of the sun's transmitted energy.

As radiation is transmitted through the atmosphere certain regions of the spectrum, depending on wavelength, will be scattered, absorbed, or transmitted. The attenuation can be attributed to dry air molecules, water vapor, and aerosols. While all elements of dry air scatter radiation regardless of wavelength, absorption is wavelength dependent. Ozone, oxygen, water vapor, and carbon dioxide are some of the best absorbers of radiation in our atmosphere. At wavelengths greater than 2.5 µm, CO2 and water vapor absorb most of the energy from the sun; less than 5% of the total spectral energy at or above this wavelength reaches the Earth's surface (Duffie and Beckman, 1991).

Aerosols, tiny particles suspended in the atmosphere such as dirt, pollen, or soot, scatter incoming spectral radiation. The amount of aerosols in the atmosphere, or turbidity, is heavily dependent upon geographic location and weather conditions. Typically the turbidity of the atmosphere is greater over land than water and the turbidity is reduced in drier climates and seasons. Another major impact on the turbidity of the atmosphere is air pollution from power generation and home heating (Iqbal, 1983).

Air mass, aerosols, water vapor, carbon dioxide, and ozone concentrations all affect the amount of radiation that passes through the atmosphere. Computer models

Figure 2.

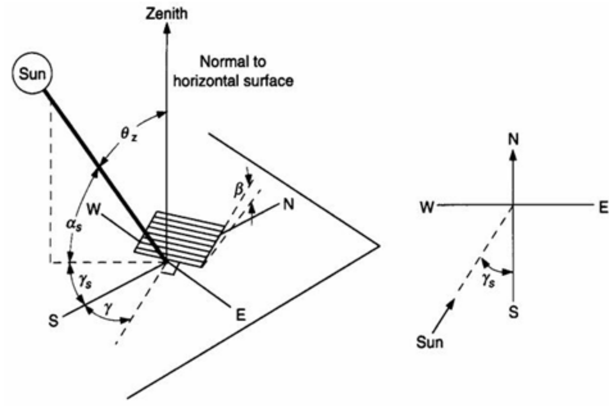


Figure 2. Zenith angle ϑ_z, *solar altitude angle* α_s, *slope* β, *surface azimuth angle* γ *and solar azimuth angle* γ_s *for a tilted surface (Duffie and Beckman, 1991)*

have been created to simulate the attenuation of the solar spectrum due to the atmosphere. Models such as LOWTRAN (Berk *et al*, 1989), MODTRAN (Kneizys *et al*, 1980), and SMARTS2 (Gueymard, 1995) simulate atmospheric transmittance and scattering based on user-defined inputs of the atmosphere composition. Combining an atmospheric model with an annual simulation of the hybrid lighting system would improve the accuracy and flexibility of the system model.

Beam and Diffuse Radiation

The operation of the hybrid lighting system depends on how the atmosphere scatters and absorbs the incoming radiation. The concentrating collector used with these systems gathers only the un-scattered and unabsorbed beam radiation, which is approximately 80% of the total radiation we receive from the sun (Muhs, 2000b). Although the diffuse radiation is useful for other solar applications like thermal heating, it is of no use to the concentrating collector used in hybrid lighting systems.

Since the diffuse radiation is of no use it is very important to gather as much of the beam radiation as possible. The solar collection of beam radiation is maximized by tracking the sun's movement through the sky. The sun moves across the sky from east to west and reaches its highest point in the sky at noon solar time[1]. The solar azimuth angle is defined as 0 degrees when the sun is directly south, -90 degrees when the sun is directly east, and 90 degrees when the sun is pointing west (all values for the northern hemisphere). The height of the sun in the sky is defined by the zenith angle, which is the angle between the perpendicular to the surface horizontal, and the sun (see Figure 2).

To maximize the amount of incident beam radiation, the collector must rotate to match the solar azimuth angle and the slope of the collector should follow the solar zenith angle. In order to track both angles a two axis tracking system must be used.

Concentrating Collectors

Unlike a heliostat, the concentrator and the secondary element are integrated into the same component which tracks the sun. The concentrating collector is composed of a concentrator, a circular concave parabolic mirror, and a secondary element, or receiver, onto which the radiation is focused. The aperture area is the area of the concentrator that can collect sunlight. The geometric concentration ratio is defined as the ratio of the aperture area to the secondary element area. The collector gathers the terrestrial radiation and increases the power density of the light by focusing it onto the smaller area of the secondary element. Typical materials used for the concentrator have a high reflectivity of around 0.95. Reflection losses, losses due to the secondary element obstruction, and the concentration ratio determine the output of a concentrating collector.

Hybrid Lighting Components

The radiation collection system, the light distribution system, the controls, and the luminaries are the four major components of a hybrid lighting system. The collection system is composed of a concentrating solar collector that tracks the sun and gathers solar beam radiation. The radiation is filtered into two types of radiation, the visible and the IR spectrum. The IR portion of the radiation can be harnessed to perform a number of tasks but initially it will be used for electricity generation in a thermal photovoltaic cell. Thermal photovoltaic cells are designed to operate more efficiently over the infrared spectrum then typical photovoltaic cells. The remaining visible portion of the light spectrum is channeled through the light transmission system.

The light transmission system currently used is made of flexible, low cost, large core optical fibers. The visible light is focused into these tubes and the light is transmitted to locations in the building where it is needed. Other tube

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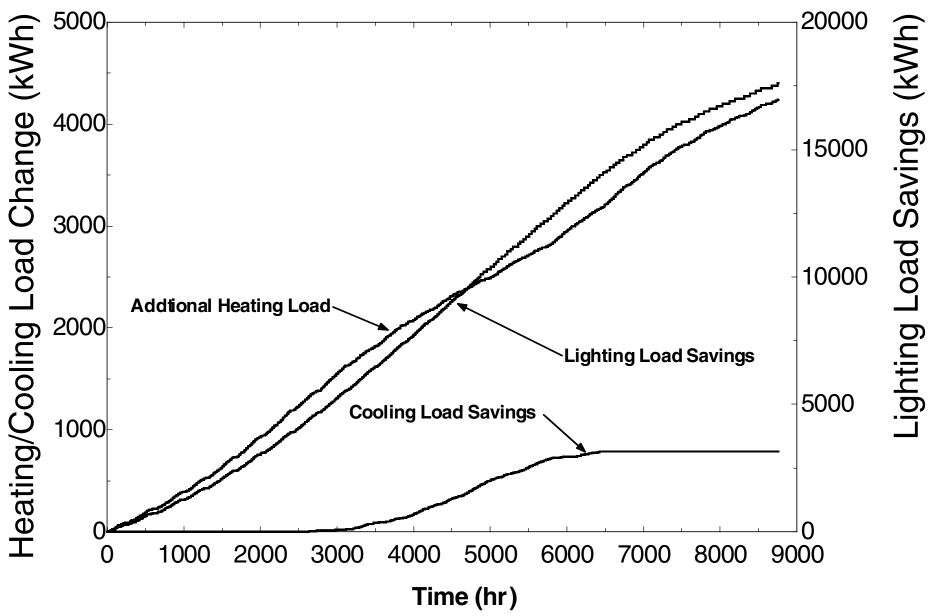
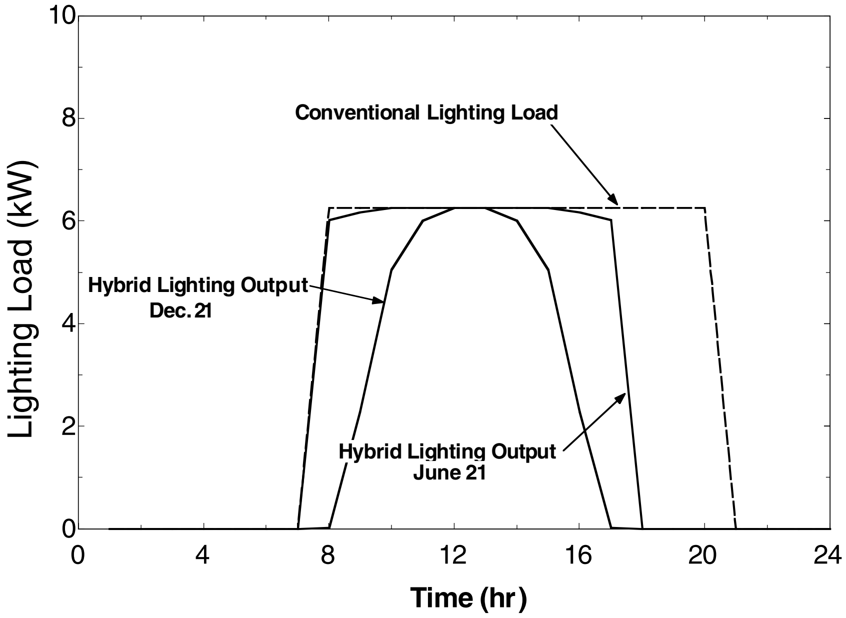
[1] Solar time is the time used for all sun time relationships and can be thought of as noon when the sun is directly overhead (Duffie and Beckman, 1991)





materials that are being investigated are fiber optic bundles and hollow core reflective light pipes.

Control systems will have to be created to allow for electrical lighting when adequate solar radiation is not available. The electrical and natural light sources will have to be controlled to provide adequate lighting on cloudy days when there is not enough sunlight. The hybrid lighting systems will have a combination of electrical and natural light sources in each lamp unit. Each luminaire will need to be able to produce a uniform source of light using electrical light, natural light, or both.

Hybrid Lighting Model

The hybrid lighting system will be modeled using TRNSYS (Klein *et al*, 2000). Inside TRNSYS, the lighting system will be separated into components. Each component will be modeled using the appropriate physical relationships. The program can simulate the annual energy savings gained through the hybrid lighting system. Economic models and system parameters can also be integrated into the TRNSYS simulation to determine the cost effectiveness of different hybrid lighting systems in various locations.

The current model components include a weather generator, radiation processors, a secondary element, a distribution system, a thermal photovoltaic cell, and a building component. The weather generator creates hourly weather data based upon monthly average values of solar radiation, dry bulb temperature, humidity ratio, and wind speed. If available, measured weather data can be used. Using the hourly weather data the radiation processor can simulate a two axis tracking system and calculate the available hourly beam solar radiation. The secondary element divides the solar spectrum into visible and infrared portions. The distribution system simulates the losses as the light enters the light tubes and as it is transmitted throughout the building. The thermal photovoltaic cell component calculates the electrical output from the cell using an average efficiency. The building component contains schedules for lighting, heating, cooling, and occupancy loads. Based on a 2500 m2 floor area, and typical office schedules, the building component calculates the baseline heating and cooling loads. A windowless building is being used for preliminary simulations to determine the maximum potential of the hybrid lighting system.

The model outputs the cooling load savings, lighting load savings, heating load loss, and electricity produced by the thermal photovoltaic cell. The simulation can be run over a time period ranging from one hour to one year. Results are presented as either instantaneous or integrated values.

An interface has been created using TRNSED. The TRNSED interface allows the user to modify different input and output parameters of the system to suit their particular needs without having to interface with the underlying FORTRAN code.

A sample annual simulation was performed using the TRNSYS model. The simulation was performed using a building located in Reno, NV, USA, containing 10 hybrid lighting systems each with the following parameters:

- Concentrator reflectance = 0.90
- Concentrator area = 4.0 m2
- Light tube reflectance = 0.9
- Light tube length = 100.0 m
- Light tube extinction coefficient =.009 1/m
- Thermal photovoltaic cell efficiency = 0.2
- Building illuminance = 200 Lux
- Building lamp efficacy = 80 Lm/W

The first plot shows the cooling load savings, additional heating load, and lighting load savings integrated over the year. The second plot shows the daily lighting load and the output of the hybrid lighting system for June 21 and December 21.

Economics

The U.S. Department of Energy predicts that in 20 years lighting will still be the most significant source of energy usage in commercial buildings (U.S. Department of Energy, 2000). Lighting in commercial buildings consumes approximately 4 quadrillion kJ of primary energy. Future predictions indicate that efficiency savings expected in the future will be outweighed by growth resulting in overall demand growth over the next 20 years (U.S. Department of Energy, 2000). Hybrid lighting systems provide a solution to reduce our demand and consumption of primary energy sources by a significant amount.

Scientists at Oak Ridge National Laboratory have estimated a single system cost to be $3200. This would include a 2 m2 collector and 12 luminaries creating an illuminated area of about 90 m2. Current system payback times are estimated at between 5 and 12 years based on peak load performance. Projected payback times are between 2 and 5 years assuming a 50% reduction in capital expenses. (Muhs, 2000a)

Future studies

Future improvements in the hybrid lighting model will focus on using an external atmospheric model such as Smarts2, improving the accuracy of the component models, and integrating the building model into the user interface.

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