Technical Overview

Background & Prior Art

Throughout the 1900s, use of the sun as a source of energy has evolved considerably. Early in the century, the sun was the primary source of interior light for buildings during the day. Eventually, however, the cost, convenience, and performance of electric lamps improved and the sun was displaced as our primary method of lighting building interiors. This, in turn, revolutionized the way we design buildings, particularly commercial buildings, making them minimally dependent on natural daylight. As a result, lighting now represents the single largest consumer of electricity in commercial buildings (see Figure 1).

During and after the oil embargo of the 1970s, renewed interest in using solar energy emerged with advancements in daylighting systems, hot water heaters, photovoltaics, etc. Today, daylighting approaches are designed to overcome earlier shortcomings related to glare, spatial and temporal variability, difficulty of spatial control and excessive illuminance. In doing so, however, they waste a significant portion of the visible light that is available by shading, attenuating, and or diffusing the dominant portion of daylight, i.e., direct sunlight which represents over 80% of the light reaching the earth on a typical day. Further, they do not use the remaining half of energy resident in the solar spectrum (mainly infrared radiation between 0.7 and 1.8 um), often add to building heat gain, require significant architectural modifications, and are not easily reconfigured.

Previous attempts to use sunlight directly for interior lighting via fresnel lenes collectors, reflective light-pipes, and fiber-optic bundles, have been plagued by significant losses in the collection and distribution system, ineffective use of nonvisible solar radiation, and a lack of integration with collocated electric lighting systems required to supplement solar lighting on cloudy days and at night.

Similar deficiencies exist in photovoltaics, solar thermal electric systems, and solar hot water heaters. Figure 2 shows the conversion efficiency of traditional silicon-based solar cells in the ultraviolet and short wavelength visible region of the solar spectrum is low, and the solar energy residing beyond ~1.1 um is essentially wasted. To overcome this and address other economic barriers, one approach has been to develop utility-scale PV and solar thermal concentrators. The rationale being that the cell area and, consequently, the cell cost can be reduced by approximately the same amount as the desired concentration ratio. Unfortunately, this cost-savings is typically offset by the added cost and complexity of the required solar concentrator and tracking system.

In recent years, researchers have also begun developing photobioreactors that use sunlight-induced photosynthesis to sequester carbon to produce biofuels such as hydrogen, using cyanobacteria. Large-scale photobioreactors are already indispensable in the successful commercial production of phototrophic unicellular algae, valued in such markets as aquaculture, pharmaceuticals, animal-feed additives, and health foods. Unfortunately, very little of the incident sunlight is tapped to maximize cyanobacteria growth rates, and only 10% of the energy residing in the visible portion of the spectrum is typically used productively to produce biomass. Terrestrial solar radiation can reach ~2000 $\mu E\ m^2\ s^{-1}$, which easily satisfies the photosynthetic photon flux (PPF) requirements of algae. Indeed, at elevated PPF levels (greater than ~200 $\mu E\ m^2\ s^{-1}$, the kinetic imbalance between the rate of photon excitation and thermally-activated electron transport results in saturation of the photosynthetic rate (Hangata, et al.).[3] In the case of thermophilic and mesophilic cyanobacteria that are ideally-suited for carbon sequestration because of their thermal adaptation to higher temperatures, even a lower PPF level (~60-100 μE mE m^2 s^{-1}) is required to achieve maximum carbon fixation. Thus, most of the lighting energy available from solar irradiance goes unused.

The principal hurdle to the scale up of photobioreactors to achieve a viable commercial-scale production of algae is lighting limitation, both in terms of light delivery and distribution and energy expenditure. For instance, current methods for mass cultivation of marine microalgae include translucent fiberglass cylinders, polyethylene bags, carboys and tanks under artificial lighting, or natural illumination in greenhouses. In these cases, however, at an algal density of 0.45 g/L, for example, light penetrates the suspension only to a depth of 5 cm, leaving a significant percentage of the cells in complete darkness at any given time. As such, microalgal production in these systems seldom exceeds 100 kg DW per year per facility, and maintaining these systems is labor- and space-intensive, and quite unreliable. Moreover, when lighting is provided by artificial lamps (such as fluorescent, high-pressure sodium, or incandescent) in close proximity to the bioreactor vessel, the comparatively poor luminous efficacy and dissipation of heat from the lamps present a constant problem.

Natural bioreactors using traditional raceway cultivators commonly waste 90 to 95% of the incident photosynthetic photon flux at high algal densities along with the remaining solar energy resident in the UV and IR portion of the spectrum. This equates to an overall solar energy utilization factor of 2.5 to 5%, making conventional photobioreactors very difficult to justify from a cost and performance perspective.

The approach first demonstrated in Japan to improve the sunlight utilization efficiency of natural photobioreactors is to collect, transport, and distribute sunlight over a larger surface area, thereby improving the sunlight utilization efficiency by reducing losses caused by saturation. The concept included the use of the earlier-mentioned fresnel-lens sunlight collector and a fiber optic bundle system to transport and distribute the light. Losses in the visible-light collection, transport and distribution system were typically more than 75%, and the 2x-to-3x improvement in sunlight utilization was far outweighed by the added cost ($\$5,000/m^2$ of sunlight collected).

In summary, when used for a single purpose such as lighting, space conditioning, power generation, or the production of biomass, much of the energy resident in sunlight goes unused, and existing collection, distribution, and or energy conversion processes, cannot be justified on a cost and performance basis when compared to alternatives. Further, solar technologies of today are unable to optimize efficiency and affordability by adapting to changing energy end-use needs, sunlight availability, electricity prices, and or ancillary services.

Technical Approach

We suggest that two unique, systems-level strategies are available to solve the key problems discussed above.

Strategy # 1: Better use of the entire solar energy spectrum

First, improvements in the total end-use power displacement efficiency of solar energy may be possible by integrating two or more solar technologies into multi-use hybrid systems that better utilize the entire solar energy spectrum. Figure 3 illustrates one such schematic of this approach. Here, the entire solar spectrum is concentrated by a primary mirror and the visible portion of the solar spectrum separated from the UV and near infrared portions. The two energy streams will be used for different purposes, i.e. lighting and electricity generation or process heat.

This strategy takes advantage of the fact that new GaSB IR-TPV very efficiently convert concentrated energy residing in the near-IR solar spectrum between 0.7 and 1.8 um at a conversion efficiency of ~23%. Similarly, analyses show that the visible portion of sunlight is inherently more efficient when used directly for lighting. The luminous efficacy of direct sunlight around 100 lm/W depending on the sun's orientation relative to the earth, atmospheric conditions, etc. Interestingly, the luminous efficacy of filtered sunlight (180 - 200 lm/W) far exceeds existing electric lamps (15 - 90 lm/W). Unlike most comparisons with nonrenewable alternatives, the luminous efficacy of filtered sunlight is more than double its only competition (electric lamps), see Figure 4. Therein lies the primary motivation for using filtered sunlight for lighting purposes in buildings and photobioreactors while using the remaining IR energy for electricity generation.

Figure 5 illustrates one design concept that takes advantage of the above strategy for both applications. Numeric references to individual components are as follows: 1) 1.6 m diameter primary mirror fabricated using formed glass and a second surface reflective coating capable of concentrating 2 m^2 of sunlight, 2) 25 cm diameter secondary optical element consisting of a faceted, high temperature glass substrate sectioned into 12 or more surfaces each of which is shaped to reflect visible light onto large-core optical fibers using a sputtered UV cold mirror coating having a spectral response, as shown in Figure 6. It also includes a nonimaging optic concentrator that uniformly distributes IR radiation onto a IR-TPV with an accompanying self-power cooling fan, as shown in Figure 7, 3) concentric fiber mount assembly, 4) 12 or more large-core optical fibers each 5 to 12 mm in diameter, 5) angled, hollow support structure to reduce the range of motion required for altitude tracking, and 6) conventional azimuth rotational tracking system.

For building applications, the most significant loss factor in the light collection/distribution system is the end-to-end attenuation in large-core optical fibers, see Figure 8. Thus, another strategy is to demonstrate the ability to more efficiently and cost-effectively transport sunlight through new polymer-based large-core optical fibers rather than glass fiber optic bundles. We will suggest a new "hybrid luminaire," illustrated in Figure 9 capable of spatially distributing both fiberoptic-delivered sunlight and electric light in a general lighting application and controlling the relative intensity of each based on sunlight availability using photosensors and dimmable electronic ballasts. Thus, natural light will be collected at a central location and distributed to multiple luminaires.

In hybrid solar photobioreactors used in CO_2 mitigation, we suggest the use of large-core optical fibers to transport light into growth chambers and once inside, function as a distributed light source (much like fluorescent lamps) to illuminate cyanobacteria. As such, we anticipate the development of new fiber configurations specifically-designed to optimize the sidelighting efficiency of large-core optical fibers, improving upon the cost and performance of fiber optic bundle sidelighting designs developed in the 1980s. We anticipate the development of illumination design configurations in a lab-scale photobioreactor that: a) takes advantage of improved sidelighting, b) increases the surface area illuminated, c) drastically reduces photosynthetic saturation, d) demonstrates the ability to achieve much higher volumetric carbon fixation rates, e) filters unwanted UV and IR radiation from the bioreactor, f) minimizes heat delivery, and e) increases the overall sunlight utilization efficiency and cost-effectiveness when compared to earlier photobioreactors.

Strategy #2: Better understand and adapt to changing end-use needs

The second strategy we suggest is to make the above system adaptive, that is, able to respond to time-varying factors affecting its overall efficiency. As one or more of the system variables change, "intelligent" solar energy systems must adapt in real-time and continually optimize solar energy utilization. For example, as lights are turned on and off or dimmed inside of buildings because of changing occupant needs or more visible light is available over and beyond what is needed for illuminating a certain region of a building or photobioreactor, the adaptive system must redirect more visible light to other areas requiring illumination or possibly an alternative solar cell ideally-suited for energy conversion in the visible portion of the spectrum, see Figure 10. The ultimate goal is the continual optimization of solar energy use on a real-time basis.

As illustrated in Figure 11, this approach will require the development of a systems-level analytical model linking information about solar technologies, electric industry restructuring, application-specific end-use needs, and available solar energy to find the optimum real-time energy utilization. It will also require the development of adaptive control system strategies capable of defining and implementing communication methodologies and protocols between interdependent system elements, making decisions on a real-time basis, and controlling adaptive system elements electrically, optically, and or mechanically.

Anticipated Outcomes

Anticipated Outcome in Commercial Buildings

In FY 1999, the ORNL completed an initial optical design and performance analysis on the hypothetical system illustrated in Figure 13. Based on this design scenario, optical losses in the sunlight collection/distribution system were estimated from vendor data and discussions with subject matter experts. The results of this evaluation suggest that light collection and delivery losses in the proposed lighting system will be approximately 50% (see Figure 14) for a single-story application and an additional 15% for second-story applications. These loss factors take into account losses attributed to the primary mirror, secondary UV cold mirror, large-core optical fibers (including bends), luminaires, and preliminary estimates for debris build-up and aging of the various optical components. The single largest contributor of loss is the large-core optical fibers. Figure 8 graphs the attenuation of the fibers as a function of incident angle. Note that attenuation is strongly dependent in incident angle. Optical analyses of the proposed design scenario indicates light will enters the fibers at an average incident angle of well under 10 degrees, as shown in Figure 15. This represents one of several advantages of the proposed system when compared to earlier fresnel-based designs. Further, the fibers are solid-filled rather than a fiber optic bundle. As such, packing fraction losses are eliminated. Also, the luminaire efficacy of fiber-based systems is anticipated to be much better than traditional lamp/luminaire combinations (85% -vs-70%) because the directional nature of delivered sunlight emerging from the fibers makes it much more easy to control than light from traditional lamps.

Relative to the electrical energy displacement efficiency of the system, Figure 16 summarizes the projected performance during peak use periods per 1000 W/m^2 of incoming solar flux. Note that the total electrical energy displacement efficiency is very close to 100%. In other words, 1000 W of collected sunlight displaces nearly an equal amount of electricity. At first glance, this might seem unreasonable. However, included in the performance summary are the following considerations: 1) the sunlight is filtered, the visible portion (~490 W) used for displacing much less efficient electric light (see Figure 4) and the near-IR radiation (~400 W) used to generate electricity using ideally-sited IR-TPVs, 2) the luminous efficacy of the displaced electric light (63 lm/W) includes the luminous efficacy of the lamp/ballast (~90 lm/W) and the luminaire efficacy (70%); and 3) the elimination of excess heat generated by electric lights in sunbelt regions, which reduces subsequent HVAC loads by ~ 15%.

Based on this design scenario and an associated analysis of cost values for each component, a systems-level cost and performance analysis was completed. The current installed system cost for a single-story application is estimated to be ~$3,200 in commercial quantities, see Figure 17, assumes a 2-m^2 collector, illuminating approximately 12 hybrid luminaires, covering close to 1000 ft^2 of floor space. This translates into peak performance of ~ $1.64/Wp.

When considering the cost and performance of various energy-efficiency approaches, it is often convenient to display them in terms of cost per kilowatt-hour (kWh) displaced. In the case of the current analysis, this method is dependent on several factors, including the regional availability of sunlight, building use scenarios, and the price of displaced electrical energy. Table 1 provides the resultant cost of hybrid lighting in terms of cents per kilowatt hour (¢/kWh) of displaced electricity in different regions of the United States over a 18-year lifetime under differing building end-use scenarios (365, 300, and 250 days per year) and differing levels of sunlight availability (9, 7, and 5.5 kWh/m^2/day as per a two-axis tracking flat-plate collector 4. It also assumes that 20% of the energy is not direct sunlight and only 80% of the direct sunlight available is used to displace electric light. The remainder of the sunlight will likely not be used in initial systems lacking adaptive controls because occupants do not always need lighting and insufficient color matching between natural and electric illuminants may occur in the early morning and late evening.

The average cost of electricity during the day, during peak demand periods when sunlight is available, is projected by the American Solar Energy Society to be between 10 - 15 ¢/kWh in a deregulated marketplace within this decade (ref). Based on PG&E time-of-day rates in 1999, these projections are already becoming a reality. Using an average value of 12.5 ¢/kWh for the cost of displaced electricity when using sunlight to displace electric lights, the estimated current and projected simple payback in years is also provided in Table 1. Similar to cost-reductions in other solar technologies, the projected simple payback is based on a 50% reduction in system cost once the system is readily available in high volume quantities.

Anticipated Outcome in Hybrid Solar Photobioreactors

Based on the design illustrated in Figure 13, the optical losses in the sunlight collection/distribution system described above were recalculated for the hybrid solar photobioreactor. The results of this evaluation suggest that light collection and delivery losses in the proposed solar lighting system will be approximately 40% as compared to 50% for the top story of a commercial building. This is due to the fact that once inside the bioreactor, light losses along its length are desirable. Losses cause fibers to emit light (glow like a linear fluorescent lamp). The estimated photon flux rate that is effectively used to achieve maximum photosynthetic efficiency is therefore 1200 $\mu E\ m^2\ s^{-1}$.

For mesophilic cyanobacteria whose preferred photosynthetic flux rate is 60 $\mu E\ m^2\ s^{-1}$, early estimates suggest that approximately 15 large-core fibers 5 mm in diameter, 6 m in length, and spaced 20 cm apart will deliver adequate lighting to achieve the desired spatial redistribution of 1 m^2 of direct sunlight into ~ 20 m^2 of vertically-stacked enclosed cyanobacteria growth area, i.e. $(0.60)(2000\ \mu E\ m^2\ s^{-1})\ /\ 20\ m^2 = 60\ \mu Es^{-1}$. Figure 18 illustrates an example of how this hypothetical sidelighting configuration could be used to illuminate cyanobacteria surfaces spaced 15 cm apart.

An optimization of the required size/configuration of a hypothetical hybrid solar photobioreactor based on the above design is beyond the scope of this discussion. However, we anticipate the size of the solar collector will likely be significantly larger than those designed for building applications because the space being illuminated is directly below the collector/receiver, minimal lateral light transport is required, and the overall spatial illumination requirements are conducive to such an arrangement. For the sake of comparative analyses, we assume that when in full production late this decade, the overall cost of the light delivery and power generation system will remain at ~\$1,000/ m^2 of collected sunlight (see Table 1 - \$2,100.00 system cost for a 2 m^2 system) though the proportional component cost will shift.

Based on the calculations provided in Table 2, the proposed system applied to a 500 MW facility will provide 889,000 metric tons of sequestered CO_2, 505,000 metric tons of biomass and 647,000 metric tons of regenerated O_2 per year, and require 10.2 MW of power to operate the system, as illustrated in Figure 18.

Assuming a plant lifetime of 30 years and the previous example parameters, we first estimated an 8.8% auxiliary load for electric lighting, pumping, and dewatering at an average cost of \$0.035 per kW-hr, a labor cost of \$1 per ton (mostly for hauling the dry biomass) and a comparable production price of a similar sized ESP (scaled by a factor of five (5) for the solar collectors), yields a maximum cost of \$15-\$16 per ton of CO_2 removed. The breakdown costs, per unit ton of CO_2 removed assuming no cost of capital, are \$4.50 capital cost, \$10 for operating costs, and \$1-\$2 for associated operating labor.

However, if no auxiliary lighting is used (as is the case in this proposal), the potential long term cost drops to only \$5-\$8 per ton including only \$1.50 per ton for power consumption because of the high level of self-generated (photovoltaic) power. Finally, while these numbers are only estimates, they are consistent with prior assumptions. The calculations for cost also do not include any potential revenue from the sale or use of the biomass, which would further reduce overall costs.

In addition, an operational photobioreactor will require power to run the auxiliary systems, including the harvesting and nutrient delivery systems. The use of photovoltaics will supply more than a quarter of the energy required to run all systems during the day when the loads are greatest.

Technology Comparisons

Comparisons with previous solar lighting systems

Compared to earlier light collection systems developed by Himawara Corp. for solar lighting applications in buildings and photobioreactors, the proposed hybrid collector design provides several advantages:

1. Fewer, easily assembled, system components integrated into a smaller, less costly, and more compact design configuration;
2. Improved IR heat removal and management;
3. Improved optical fiber placement and articulation (bundled and pivoted about a radial axis);
4. A longer optical path for light and lower entrance angles for visible light entering large-core optical fibers. This results in much lower overall transmission losses in the accompanying light delivery system (see Figure 8); and
5. Centrally concentrated IR radiation, allowing for convenient implementation of IR-TPVs.

Table 3 compares the projected cost and performance of the proposed system with that of a state-of-the-art commercial system. Accordingly, the anticipated cost per delivered lumen of the proposed system far exceeds its only commercial counterpart.

Comparisons with alternatives in buildings

Alternative # 1: Advanced Electric Lighting

Because hybrid lighting systems require the use of state-of-the-art electric lights when sunlight is not available, their cost is additive. As such it is not fully appropriate to compare them directly. However, in a "head-to-head" comparative analysis, the estimated additive cost of installed hybrid solar lighting systems (a clean energy alternative) in terms of ¢/kwh displaced (5 - 11 cents/kWh) is typically lower than the cost of running electric lighting systems in a deregulated market considering time of day rates (10 - 15 cents/kWh) during peak demand periods on hot, sunny days.

Alternative # 2: Conventional Topside Daylighting

A complete study of all types of topside daylighting is not warranted for the purposes of a comparative analysis with adaptive full-spectrum solar energy systems. We limit this discussion to skylights, generally accepted as the most cost-effective form of conventional topside daylighting. On average, incident sunlight does not enter skylights normal to the horizontal plane. Depending on the type and configuration of skylight, light transmission varies dramatically and is attenuated significantly. This is due to several factors but is predominately determined by the efficiency of the light well and glare control media. The typical transmittance of state-of-the-art tubular, domed skylights varies widely depending on lighting requirements, but for commercial applications is typically well under 50%.

Comparatively speaking, several other factors must also be considered. First, the coefficient of utilization (CU) of a single 1-m^2 tubular skylight will inherently be much lower than a system that distributes light from the same square meter to six or more luminaires. Assuming that the room cavity ratio and other room parameters are identical, the CU of the more distributed hybrid system is significantly better. If the single 1-m^2 skylight were replaced by ~6 much smaller skylights, the two systems CUs would compare equally, yet the cost of the skylights would increase prohibitively.

Skylights are typically not designed based on the maximum amount of light that can be supplied but rather designed to approximate that which is produced by the electric lighting system when the total exterior illuminance is 3000 footcandles. This reduces over-illumination and glare. Because of this, all light produced by skylights beyond this value is typically wasted. As such, preliminary estimates suggest that on average, depending on location, approximately 30% of the total visible light emerging from skylights on a sunny day is excess light not used to displace electric lighting. Conventional skylights are also plagued by problems associated with heat gain and do not harvest non-visible light. Finally, conventional skylights are not easily reconfigured during floor-space renovations common in today's commercial marketplace. Once all factors are considered, the simple payback (typically >8 years) and energy end-use efficiency of even the best topside daylighting systems is considerably worse than projected adaptive, full spectrum solar energy systems.

Alternative #3: Solar Electric Technologies

To date, the United States has invested billions of dollars in systems capable of converting solar energy into electricity. The most relevant examples include solar PV modules and solar thermal technologies. The advantages of these systems are obvious. First, PV modules require no moving parts to convert sunlight into direct-current electricity, and they can be conveniently used for any electrically powered end use. Unfortunately, these advantages come with a steep price in terms of overall efficiency. For example, commercial solid-state semiconductor PV modules typically have a total conversion efficiency of < 15%. Solar thermal systems typically have conversion efficiency somewhat higher (< 25%), depending on system design and complexity. Further, losses attributed to electric power transmission/distribution (~8%) and dc-ac power conversion (10 - 15%) further reduce the overall efficacy of conventional solar technologies. Because of these and other reasons, conventional solar technologies have not displaced significant quantities of nonrenewable energy and are expected to be used in the United States for residential and commercial buildings, peak power shaving, and intermediate daytime load reduction. The PV modules currently sell for between \$3 - \$5/Wp. The projected peak performance of adaptive full spectrum solar energy systems (\$3,200 per 1,940 Wp or \$1.65/Wp) have the immediate potential to more than double the affordability of solar energy when compared to these solar technologies.

If the intended uses of solar technologies are for reductions in energy use in buildings, peak power shaving, and intermediate daytime load reduction as recent U.S. DOE documents suggest[1], we suggest that our approach reflects a more effective way of using solar energy to reduce nonrenewable energy consumption in developed countries like the United States that have a well-established electrical grid.

Comparisons with previous photobioreactors

Calculations based on earlier studies by Hirata et al. and Ohtaguchi et al. indicated that a little more than 1,000,000 m^2 bioreactor surface are would be required to reduce the CO_2 emission of a typical 500 MW coal-fired generation unit by 25% [4,5]. This translates into 257 acres of water surface area for a high-density raceway type reactor. Using the design of Bayless et al., incorporating the novel solar collection technology described herein, the required area decreases to 11.7 acres. In a more practical scenario that considers rooftop collector/receiver packing densities and other factors, the required space would likely increase to 15 acres. An enclosed reactor of this size may be formidable to site and construct, but is certainly manageable compared to siting and operating a 257-acre pond near a power plant, which would create numerous groundwater contamination concerns. Further, an enclosed reactor has a number of options for delivery of the CO_2, including as raw flue gas. Bubbling flue gas through a 257-acre pond would be illegal, as the ground level contamination would be pose extreme health threats to the area. Therefore, a raceway reactor would require CO_2 separation before utilization, eliminating virtually any energy advantage of a bioreactor in CO_2 control.

Compared to previous attempts to develop similar solar-enhanced photobioreactors incorporating fresnel lenses and fiber optic bundles, the anticipated cost per delivered lumen (2.8 cents -vs- 20 cents) also represents a seven-fold improvement in the cost of sunlight utilization not including the added benefit of electrical power generation. Thus, the primary advantages are enhanced sunlight utilization and less power consumption.

Comparisons with non photosynthetic carbon sequestration techniques

Non-photosynthetic carbon sequestration is a significant net energy loss. Separation of CO_2 from the flue gas either requires refrigeration or mechanical action. The sequestration (compression or pumping) of the separated CO_2 also requires significant energy. All totaled, CO_2 sequestration by non-photosynthetic means will require 25-40% of the power generated by a host utility compared to 2-5% for the hybrid solar photobioreactor. That means more fossil fuel will have to be burned to produce the same net power output before sequestration. This also has direct implications on the environment. Because more fuel must be burned to power the sequestration systems, more associated pollutants will be released, including ozone forming NO_x, mercury, PM.2.5 and other particulates. Only a system utilizing solar energy to produce biomass, as described in this proposal, will require minimal power generation to minimize CO_2 emissions and does not produce significant harmful emissions.

Comparisons with utility-scale PV facilities

Compared to a utility-scale PV system of the same size that generates ~5 MW (peak) at a cost of $3-5 /Wp, the proposed system will remove carbon from approximately 125 MW (peak) fossil-based generated power using a net load of 10 MW. The estimated cost of proposed photobioreactor system is $3,300 as shown in Table 4. Considering the size of the facility (54,000 m^2), this equates to an approximate two-fold improvement in cost, i.e. [($3,300/$m^2$ x 54,000 m^2) / (125 MW - 10 MW)] = $1.54 / Wp of cleaned fossil-based power produced. As such, separation and use of different portions of the solar spectrum for different purposes improves the overall cost and performance of solar energy used at power plants. In addition to this advantage, biomass has inherent value beyond that of carbon sequestration. It can be used as a feedstock, agricultural supplement, food supplement, or in pharmacological uses. Third, coal must remain a viable fuel to maintain fuel diversity. Without coal, the long term (20+ years) price of electrical power will escalate at a dangerous rate, especially with regards to national economic growth. This system provides a critical component in the portfolio of carbon management techniques that will allow coal to remain viable (note, not favorable, just viable.)

Finally, it should be noted that preliminary estimates show that hybrid solar photosynthetic CO_2 control system could potentially sequester CO_2 at a cost of $5-8 per ton, which exceeds DOE's target of \$10 per ton. The key is the low cost of the power source to sequester CO_2, namely solar power. The capital cost of the bioreactor facility then is the major cost, at about \$4-6 per ton of CO_2 sequestered over a thirty-year period. Clearly, better utilization of solar energy has a substantial economic gain that is realized in this application.

Benefits

Crosscutting both end-use scenarios, hybrid lighting and adaptive, full-spectrum solar energy systems provide a new and realistic opportunity for solar energy to provide wide ranging energy, environmental, and economic benefits as follows:

Benefits in the buildings sector

In FY 1999, two EERE Offices (OPT and BTS) tasked an independent consulting firm (Antares Engineers and Economists) to conduct a preliminary technical assessment and market analysis on a more narrowly defined precursor to full-spectrum solar energy systems called hybrid lighting systems. Essentially, their analysis focused only on the lighting component in commercial buildings. Aside from the cost and performance of hybrid lighting systems, several other factors, illustrated in Figure 20, were considered prior to determining the overall market penetration values of this technology. Using off-the-shelf components and widely accepted building industry cost estimating guides, Antares developed conceptual-level, installed cost and lighting system operating costs models using constant 1999 dollars. Their estimates were based on comparing conceptual-level designs of: a) a first-generation hybrid lighting system, b) the most energy-efficient conventional daylighting strategy available (tubular skylights), and c) state-of-the-art electric lighting systems.

Unlike most metrics, the focus of the analysis was performed on an emerging technology for which no commercially available products exist. Fortunately, most of the components were commercially available elsewhere. Antares assessed the energy-savings potential based on two scenarios. First, they assumed no major improvements were achieved other than that which can be achieved through relatively low-risk, applied engineering and manufacturing automation enhancements. In the second, they assumed significant cost/performance improvements of approximately 50% were achieved similar to those observed in other solar technologies during their early years of development and commercialization.

Antares concluded that hybrid lighting was more cost-effective than the most efficient traditional topside daylighting system commercially available and provided more flexibility within the context of current buildings designs and construction practices. Further, it concluded that hybrid lighting also competed favorably with other solar technologies. For a more detailed discussion of competitive advantages in each case, see Section 1.5.

Antares determined that the overall buildings market for hybrid lighting was quite large and estimated an initial market entry in new commercial office buildings and schools beginning in the 2003/2004 timeframe assuming a national-scale R&D effort was initiated in FY 2000. Antares estimates indicated a slow market penetration initially with a growing market base in outyears. By 2020, they projected 1.12 million units sold per year with an installed base of 7.42 million units by 2020. Considering all other types of commercial and institutional buildings, Antares estimated that the potential energy displacement capacity of hybrid lighting could exceed 0.3 Quads, reductions in carbon emissions could exceed over 5 MtC, and economic benefits totaling \$5 billion (\$2 billion in energy savings and \$3 billion in new product economic stimulus) could be realized. Antares did not attempt to quantify or factor in the additional benefits associated with student/worker health and productivity gains when occupying daylit buildings.

Since their initial analysis in the summer of 1999, continuing design improvements have been made to the hybrid solar collector. This includes the inclusion of IR-TPVs and improved collection/distribution optics. The Antares analysts have reviewed these design changes, determined they will positively affect the cost and performance of full-spectrum solar energy systems by ~15%, and subsequently anticipate a further broadening of the commercial building market, making their initial estimates mentioned above somewhat more conservative.

Benefits in the bioenergy sector

EIA estimated nearly 942 million tons of coal were used to produce electricity (U.S. Coal Supply and Demand: 1999 Review by F. L. Freme and B. D. Hong U.S. Energy Information Administration) taking an average carbon content of 75% and accounting for the molecular weight of carbon transformed to CO_2, assuming 5% LOI (that is unburned carbon in the fly ash), we have about 2.4 billion tons of CO_2 emitted from coal fired generation. Soon, we will have about 0.5 billion tons from gas and fuel oil. But just taking coal into consideration and assuming that only 20% of generation capacity utilizes photobioreactor in 2020 and that only 25% of the CO_2 is removed where implemented, 123 million tons CO_2 (or 40 MtC) will be sequestered. This is easily doable considering that more than 40% of capacity is 300 miles or more from an ocean where ocean sequestration isn't a viable option. Economic benefits are estimated to be well over $10 billion annually by 2020.

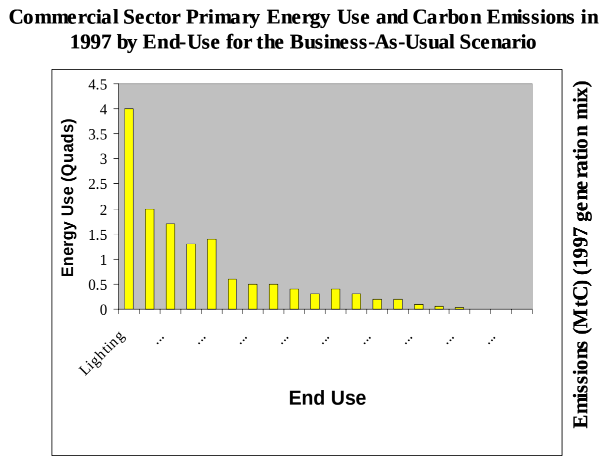


Fig. 1. Commercial building sector primary end-use and carbon emissions in 1997 by end-use.

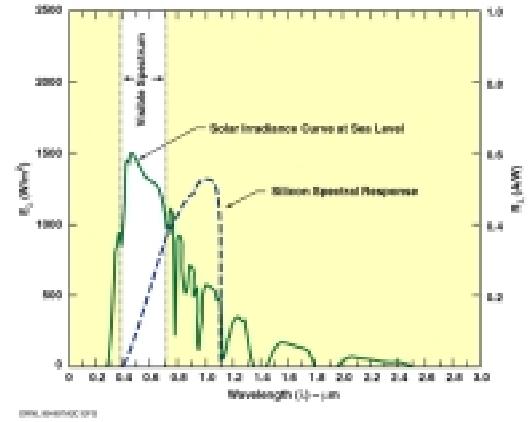


Fig. 2. Approximate spectral radiance of the sun at mean earth-sun separation and associated silicon spectral response.

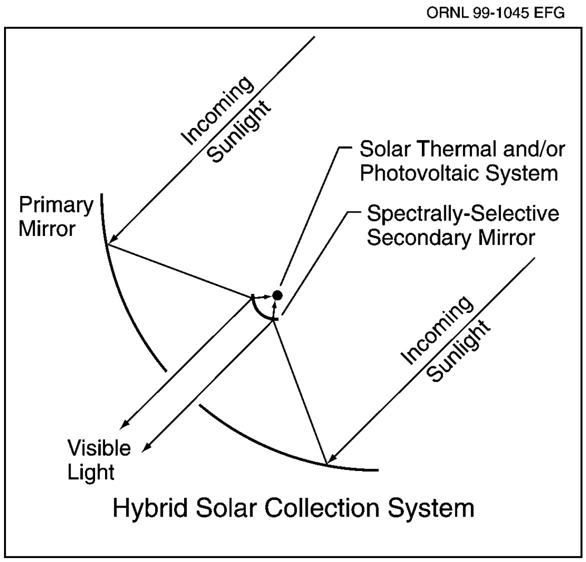


Fig. 3. Schematic representation of hybrid solar concentrator.

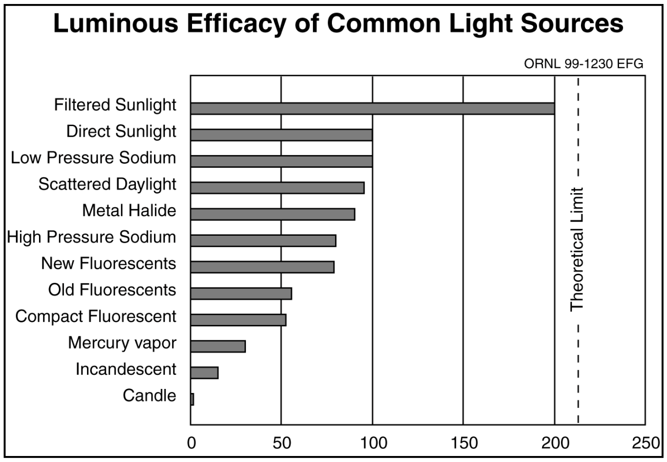


Fig. 4. Luminous efficacy of various light sources.

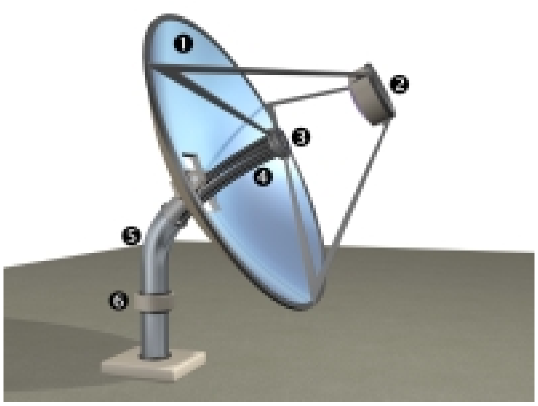


Fig. 5. Preferred hybrid solar concentrator design concept.

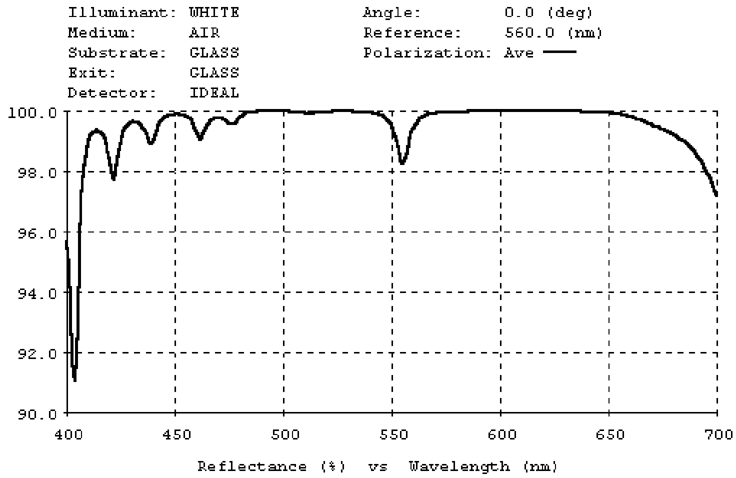


Fig. 6. Spectral response of UV cold mirror.

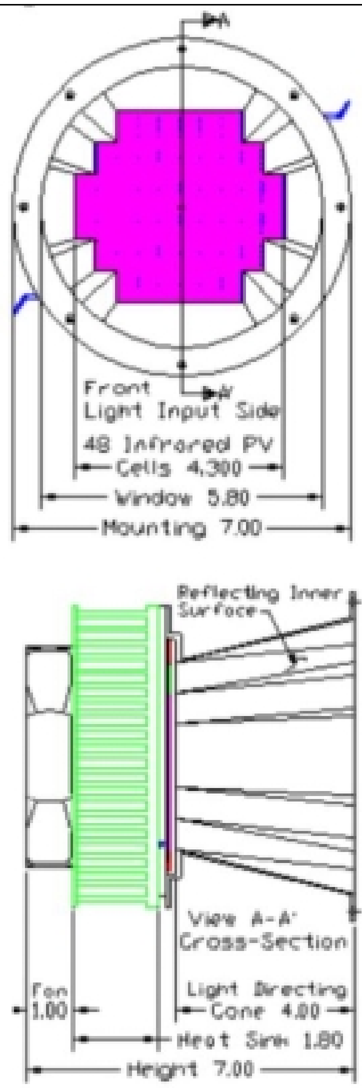
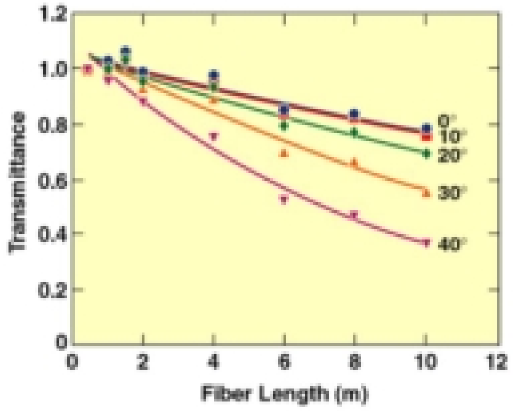


Fig. 7. Schematic of IR-TPV with accompanying cooling fan.



Transmittance as a function of fiber length for various angles of incident flux relative to that of a 0.5 meter fiber. The source spectrum is that of a 2600 K incandescent lamp (12.7 mm fiber).

*Data provided by LRC/RPI

ORNL 2000-920C EFG

Fig. 8.

Fig. 9. Conceptual representation of hybrid luminaire

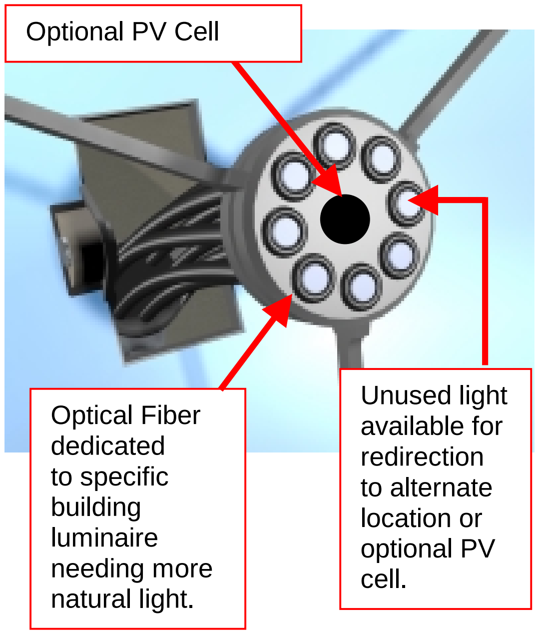


Fig. 10. End-face of large-core optical fibers used in hybrid solar concentrator illustrating light redirection options.

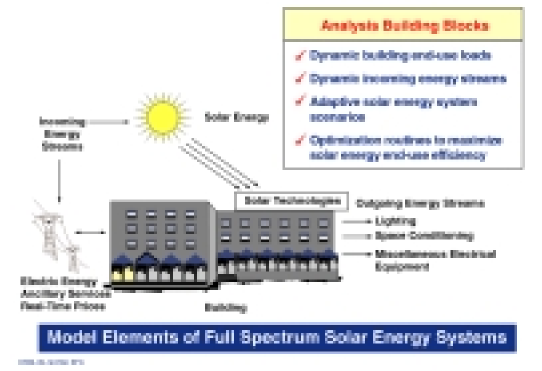


Fig. 11. Systems-level dynamic building analysis model.

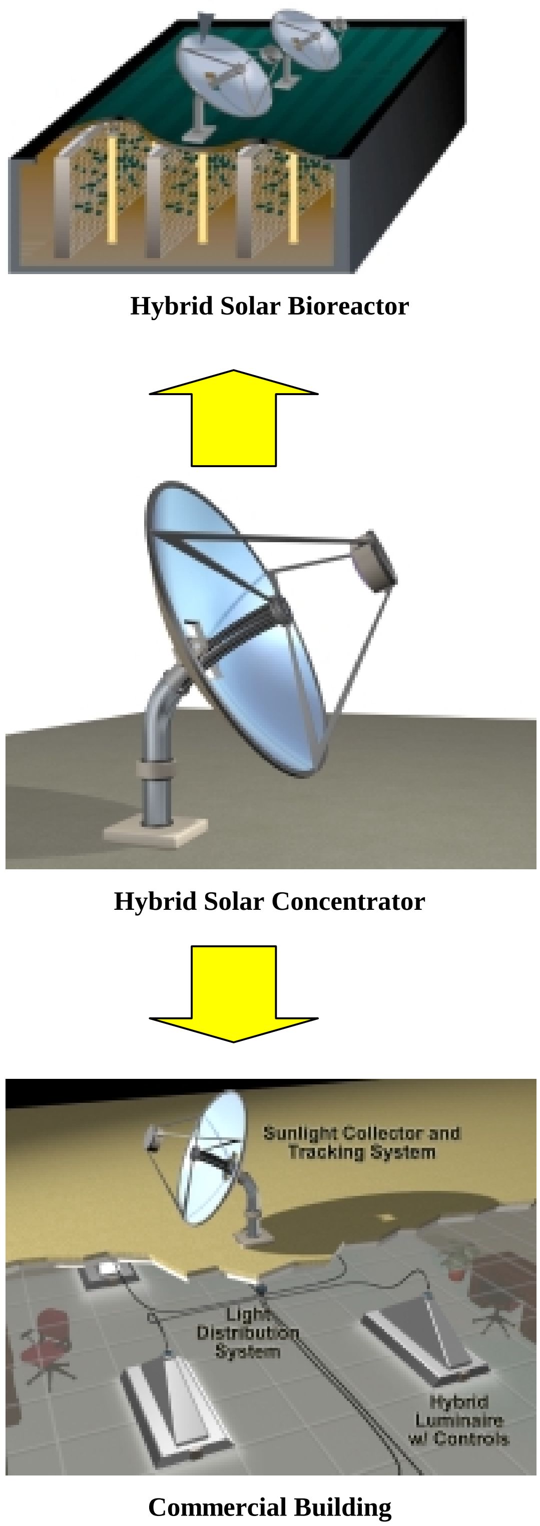


Fig. 12. Hybrid Solar concentrator and associated applications.

Optical Performance Summary for
Preferred Collector Design

System Performance	
Loss Parameter	**Transmission**
Primary Mirror	92%
Secondary Mirror	94%
Collection losses	97%
Fresnel losses	94%
Fiber attenuation (@ 6 meters)	78%
Fresnel losses	94%
Luminaire losses	85%
Total	**50%**

Fig. 13. Visible light collection and delivery loss estimates in proposed solar lighting system.

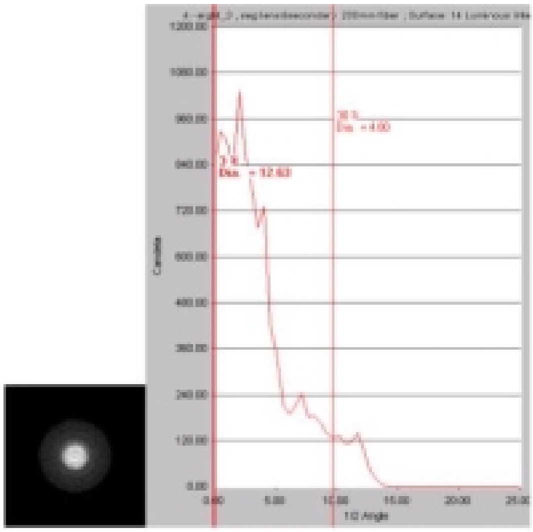


Fig. 14. Results of initial optical analysis showing incident angles of light entering large-core optical fibers.

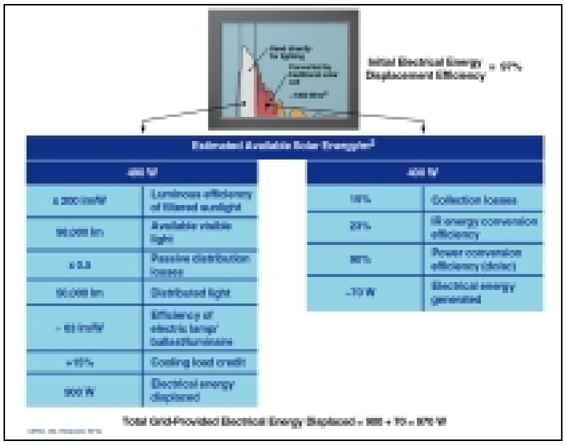


Fig. 15. Summary of full-spectrum solar energy system peak performance @ 1000W/m^2 of incident solar power in commercial building.

	Current (2000)		Projected (2004)	
Component	***Cost***	***Performance***	***Cost***	***Performance***
Collector/Tracker	**$1600**	**Total grid provided electricity displaced** ↓ **(See Table 9 and Figure 23)** ↓	**$800**	**Estimated total grid provided electricity displaced** ↓
Primary Mirror	*400*		*200*	
Secondary Optical Element	*200*		*100*	
Structural Support	*300*		*200*	
Tracking System	*500*		*200*	
Assembly	*200*		*100*	
Concentrating PV Cell	**$200**		**$100**	
Optical Fiber (70m @ $10/M)	**$700**		**$250**	
Hybrid Luminaire (add-on cost)	**$350**		**$150**	
Installation	**$350**		**$200**	
Total Installed System	**$3200**	**2500 Wp**	**$1500**	**2800 Wp**
Lifecycle Maintenance (18 years)	**$1000**		**$600**	
Total Lifecycle System	**$4,000**		**$2,100**	

Fig. 16. Preliminary current and projected component and systems-level cost estimates in single story building environment.

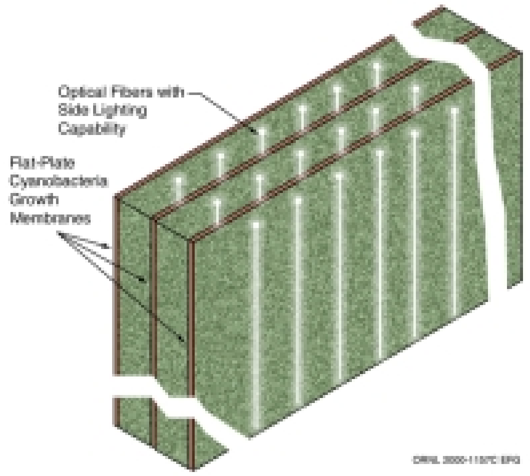


Fig. 17. Hypothetical sidelighting design configuration for hybrid solar photobioreactor.

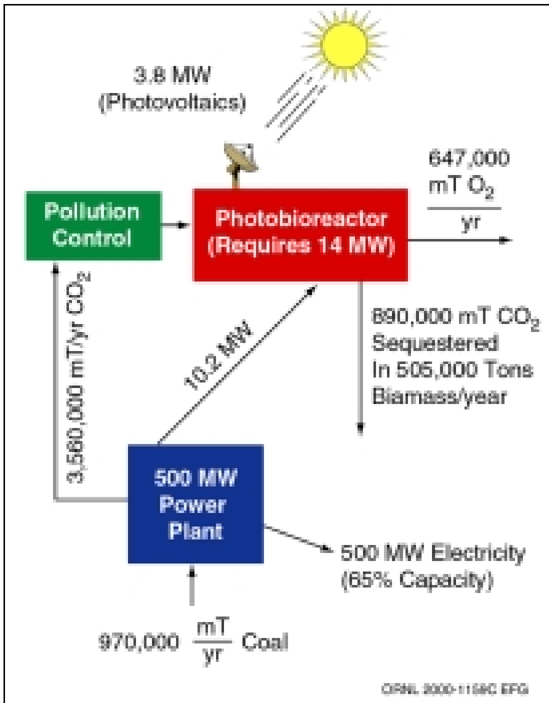


Fig. 18: Summary of input/output performance estimates for a hybrid solar photobioractor used for CO_2 mitigation at a 500 MW power plant.