INFRARED PHOTOVOLTAICS FOR COMBINED SOLAR LIGHTING AND ELECTRICITY FOR BUILDINGS

L. M. Fraas*, W. E. Daniels*, J. Muhs†
*JX Crystals Inc., 1105 12th Ave NW, Issaquah, WA 98027 USA
†Oak Ridge National Laboratory, PO Box 2009, MS-8058, Oak Ridge, TN 32831 USA

ABSTRACT: A concept for indoor illumination using sunlight is described. For this system, a tracking concentrator on the building roof follows the sun and focuses sunlight into a light guide. A system of transparent light guides distributes the sunlight to interior rooms. In this system, a cold mirror splits the solar spectrum into visible light for indoor illumination and infrared radiation which is directed to an array of GaSb infrared sensitive photovoltaic cells which then generate electricity. It is shown that each Watt of visible sunlight displaces two Watts of electricity which otherwise would be used for florescent lighting and air conditioning. The savings from this displaced electricity can then pay back the cost of the concentrator, tracker, and light guides in approximately three years. Meanwhile, the GaSb cell array converts the concentrated infrared energy to electricity with an electric power density of one Watt per square cm. This power density is one hundred times higher than available from a planar silicon cell, thus easily allowing PV electric power production at a capital cost of under $1 per Watt.

Keywords: GaSb – 1: Concentrators – 2: Buildings – 3

1. INTRODUCTION

It is well known that solar energy can be converted to heat or electrical energy and that these forms have value. It is also well known that the sun's light energy can be used directly for illumination. However, the economic value of sunlight is not generally appreciated.

To appreciate the value of sunlight, imagine two alternative solar energy systems. In the first system, solar cells capture sunlight at a desert utility site and convert it to electricity with an efficiency of 10%. Then, the electricity is routed through electrical cables to a building. In the building, the electricity is converted back to light with an efficiency of 20%. For this system, only 2% of the solar energy is delivered as useful illumination energy. For the second system, imagine that the sunlight is captured on the building roof and concentrated and routed with optical cables to overhead lamp fixtures with only 50% transmission loss. The sunlight is used twenty-five times more efficiently in the second system. Since a solar illumination system can displace electricity, the energy in sunlight has more value as light than as electricity.

The value of sunlight has been appreciated qualitatively for centuries through the use of windows and skylights. However, electric lighting is commonly used in buildings even during the day because electric lights have some special and very desirable qualities not available from window lighting. Some of these features are: (1) overhead illumination, (2) illumination well into the interior of the building, (3) adequate illumination levels, (4) constant illumination levels, (5) illumination control (on/off, high/low, portability).

Window lighting does not allow for overhead illumination or illumination well into the interior of the building. Furthermore, the illumination level supplied from a window can vary by orders of magnitude throughout a day. For example, the direct sunbeam entering a window facing east in the morning is much more intense than the diffuse skylight entering the same window in the afternoon.

These problems with window lighting are rectified by the concept shown in figure 1, in which direct light from the sun is collected by a tracking concentrator and focused into a light guide for distribution into overhead lighting fixtures in the building interior (ref. 1). One can install light guides in a manner analogous to installing a fire-extinguishing sprinkler system or an electrical conduit distribution system.

Referring to figure 1, note that the concentrated solar radiation is incident on a beam splitter where the visible sunlight is reflected into the light guides and the infrared portion is transmitted through to a solar photovoltaic (PV) array where it is converted to electricity.

A consortium headed by Dr. Jeff Muhs from Oak Ridge National Laboratory (ORNL) and Prof. Byard Wood from the University of Nevada is now developing this concept for indoor illumination using concentrated and piped sunlight. JX Crystals is developing the IR sensitive photovoltaic array to be used in this application. The consortium is funded by the US Department of Energy.

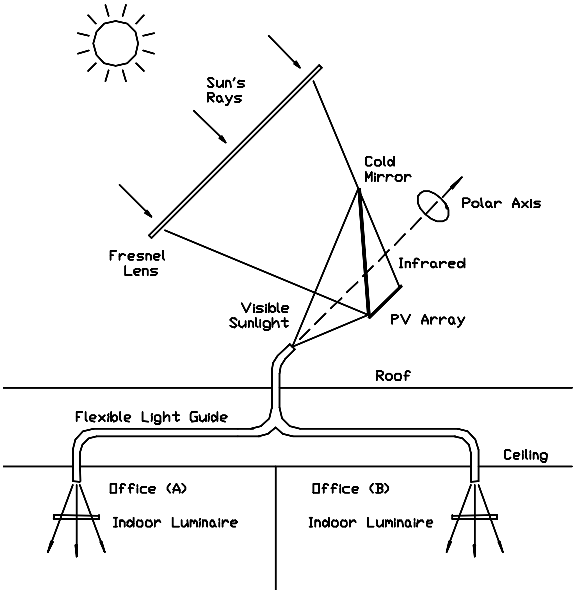

Figure 1: Concept for concentrated and piped lighting for indoor illumination, with infrared energy directed to a panel of infrared-sensitive PV cells.

The consortium refers to the concentrated and piped solar lighting concept as “hybrid lighting” because the indoor luminaire will include both provision for solar lighting and fluorescent lighting with controls to accommodate night time or cloud cover lighting requirements. When the infrared PV array is added, the consortium refers to this system as a “full-spectrum solar energy” system.

In the following section, we first describe this solar lighting concept in more detail. It is shown that each Watt of visible sunlight displaces two Watts of electricity which otherwise would be used for florescent lighting and air conditioning. The savings from this displaced electricity can then payback the cost of the concentrator, tracker, and light guides in approximately three years.

In subsequent sections, the design and fabrication of an infrared sensitive GaSb cell array is described. It is shown that this array converts the free concentrated infrared energy to electricity with an electric power density of one Watt per square cm. This power density is one hundred times higher than that available from a planar silicon cell. Thus PV electric power can be produced economically at under $1 per Watt.

2. CONCENTRATED AND PIPED SUNLIGHT: CONCEPT AND ECONOMICS

The ORNL system for concentrated and piped sunlight replaces the Fresnel lens in Figure 1 with a dish mirror for solar concentration. Figure 2 shows this ORNL rooftop collector in detail. Note that the secondary mirror is a cold mirror with the infrared sensitive PV array located behind it. Figure 3 shows the complete ORNL system concept (2), as it would be mounted on the rooftop of an office building, including hybrid luminaires with controls.

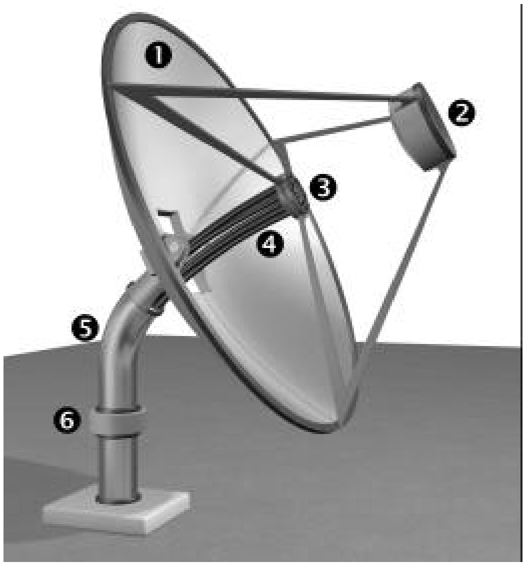

Figure 2: Oak Ridge National Laboratory (ORNL) concept for a rooftop dish mirror solar concentrator, with ❶1.8 meter diameter primary mirror ❷Secondary optical element (cold mirror and concentrating PV cell array) ❸Fiber mount ❹Large-core optical fibers ❺Angled stand with altitude tracking mechanism, and ❻ Azimuth tracking mechanism.

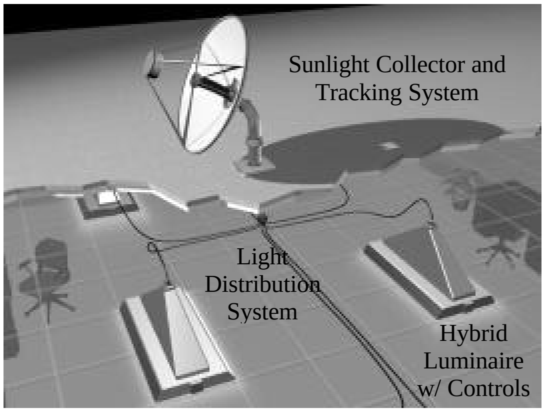

Figure 3: ORNL’s system concept, with close-up showing visible light focal point to fiber optic light pipes, feeding into the light distribution system.

Dr. Jeff Muhs at ORNL has previously pointed out that lighting is the single largest specific energy end-use in commercial buildings and that buildings represent the largest energy end-use sector in the United States (3). These statements can be quantified. Conservative estimates by an independent evaluator (4) under a DOE contract indicate that by the year 2020 in the United States alone, widespread use of full-spectrum solar energy systems will lead to:

- Energy savings of over 30 billion kWh (>0.3 Quads)
- Economic benefits exceeding $5 billion; and
- Reduction in carbon emissions of greater than 5 MtC

Worldwide, these impacts will likely increase by an order of magnitude.

The high economic value of solar lighting results from the fact that there are more lumens per Watt in filtered sunlight than in fluorescent lighting. On the following page, Table I (extracted from a DOE study) shows how the energy in the sun’s spectrum is used in a full-spectrum hybrid lighting system. Table I divides the sun’s spectrum into its visible and infrared parts, as represented visually in figure 4. The sun’s energy of approximately 970 Watts per square meter includes approximately 490 W/m^2 of visible energy (wavelengths < 0.7 microns) and 480 W/m^2 of infrared energy. In the solar lighting scheme, the sun’s visible energy displaces 930 Watts of electrical energy for lighting and cooling. In addition, the sun’s infrared energy is converted into 70 Watts of electric energy.

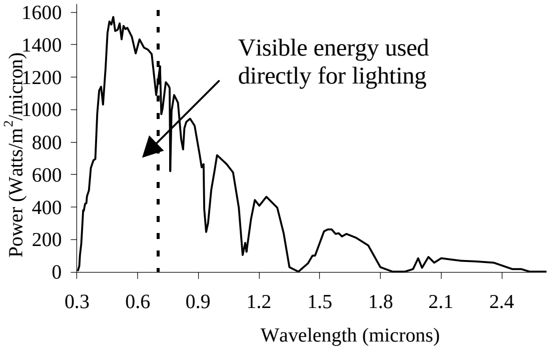

Figure 4: The solar spectrum at Air Mass 1.5. The dashed line at 0.7 microns divides the spectrum into its visible and infrared parts.

Table I: Energy displacement for the hybrid lighting system. The sun's visible energy of 490 W/m^2 can displace 930 Watts of electrical energy, and the sun's infrared energy of 480 W/m^2 can generate 70 Watts of electric energy using PV cells. The total grid-provided electrical energy displaced = 930 + 70 = 1 kW/m^2.

490 Watts	**Visible solar energy / m^2**
x 200 lm/W	luminous efficiency of filtered sunlight
= 98,000 lm	available visible light
x 0.5	passive distribution losses
= 50,000 lm	distributed light
÷ 63 lm/W = 800 W	efficiency of electric lamp/ ballast/luminaire
+ 130 W	cooling load credit
= 930 Watts	electrical energy displaced / m^2

480 Watts	**Infrared solar energy / m^2**
- 10% = 432 W	collection losses
x 18% = 78 W	IR energy conversion efficiency
x 90%	DC/AC conversion efficiency
= 70 Watts	electrical energy generated / m^2

As Table I shows, there are more lumens per Watt in filtered sunlight (200 lm/W) than in fluorescent lights (62 lm/W), so the 490 W of filtered sunlight can displace approximately 800 W of electricity otherwise used for lighting. Also, since less heat is dissipated in the building, there is an additional credit of 130 W because of a reduced air conditioning load. Hence, 490 W of filtered sunlight can displace 800+130=930 W of electricity. In other words, 1 Watt of sunlight can displace almost 2 Watts of electricity. Table I also shows that the 480 W per square meter in the infrared can be used. Using a GaSb cell array, approximately 70 W of useful electric power can be generated bringing the total number of Watts displaced or produced with 1 square meter of sunlight up to approximately 1 kW.

The DOE has also sponsored a study of the potential cost of a full-spectrum hybrid lighting system. Their analysis for the future potential cost for this system assuming a 2.5 m^2 mirror collector is summarized in table II. By reference to table I, a 2.5 m^2 system should displace and produce 2.5 kW. Referring to table II, the sum of the component, installation, and maintenance cost for this system is projected to be $2100, or 84 cents per Watt.

Table II: System-level cost for a 2.5 m^2 mirror collector and complete hybrid lighting system. This will displace 2.5 kW of electricity, for a cost of $0.84 per Watt.

Component	**Projected Cost**
Collector / Tracker	$800
Primary Mirror	200
Secondary Optical Element	100
Structural Support	200
Tracking System	200
Assembly	100
Concentrating PV Cells	$100
Optical Fiber (70m @ $10/M)	$250
Hybrid Luminaire (add-on cost)	$150
Installation	$200
Total Installed System	$1500
Lifecycle Maintenance	$600
Total Lifecycle System	**$2100**

Independent analysis confirms that from a nonrenewable energy displacement perspective, full-spectrum solar energy systems will likely emerge as the preferred use of solar energy in commercial buildings. These systems will potentially achieve costs under $1.00/W, simple paybacks of between 2 – 5 years and electrical energy displacement costs of well below 5 cents per kWh by 2005 in most parts of the world. 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 day lighting strategies.

3. DESIGN, FABRICATION AND PERFORMANCE FOR THE INFRARED PV ARRAY

The focus of this article is on the infrared sensitive photovoltaic array for the full-spectrum hybrid solar lighting system described above. JX Crystals has designed, fabricated, and measured the performance of an array intended for use in this system.

Referring to figure 2 and table I, The hybrid collector system's apex mounted 'cold mirror' transmits 480 W/m^2 x 2.5 m^2 x 0.9 = 1120 W of concentrated infrared (IR) radiation through to the PV circuit for conversion into electrical energy. An IRPV array circuit mounted in the antenna apex with a high packing density is required along with provision for high IR intensity uniformity. It is also necessary to provide cooling to keep the circuit from overheating in the intense radiation.

Figure 5 shows the design of the IRPV circuit (fabricated at JX Crystals Inc.). This GaSb circuit captures more of the infrared than traditional silicon solar cells. In this application, a GaSb cell will capture infrared energy over the wavelength band from 0.7 microns to 1.8 microns while the traditional silicon cell will only capture wavelengths over the smaller band between 0.7 microns and 1.1 microns. As is shown in figure 5, a cell array is mounted in shingle fashion on metal pads on a thin dielectric applied to a metal substrate. The bottom of each cell is soldered to the top bus bar of the previously placed cell in that row. The rows are backside wired in series completing the IRPV circuit with 81+% active area density.

The light directing cone is used in this application to mount the IRPV receiver behind the apex mirror while its highly reflective inner surface shapes the incoming IR intensity distribution. This is necessary because, with the cells connected in series, maximum electrical power output at any illumination intensity is achieved when all cells receive equal convertible infrared energy.

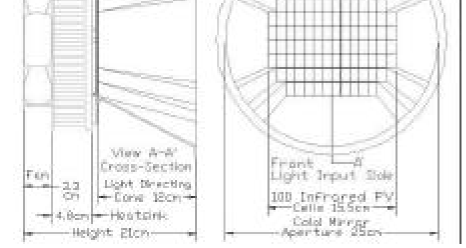

Figure 5: Conceptual mounting of Infrared PhotoVoltaic (IRPV) circuit for combined light and power system.

With the infrared energy beam larger in diameter within the window than the active cell pattern width, the cone reflective surface, acting as Non-Imaging-Optics, shape configures the impinging energy pattern. Thus, what would have been infrared over spill outside the active area is reflected back in with this reflected intensity tapering off inward from the outer edge of the active area, thereby raising the corner cell's illumination levels up to the level of the center cells. The receiver circuit substrate is mounted directly on an array heat sink with an integral cooling-fan. Given a 2.5 m^2 solar collector mirror, this 100-cell array should produce approximately 2.5 x 70 = 175 Watts of electric power. The active area of this cell array is approximately 180 cm^2. The cooling fan will require approximately 5 W. While we have designed and built this shingle PV array with shaping mirror and cooling fan using GaSb IR sensitive cells, our patent application on this receiver design notes that traditional cell types can also be used, including silicon cells.

The beauty of this hybrid lighting and PV approach is in the high power density now available to the IRPV array at the focus of the solar energy**.** Thus PV electric power can now be produced economically. Referring to table II, we believe that this PV array can be made in high volume production for $100. Given an array output of 175 W, this corresponds to electric power production at 100/175 = 57¢ per Watt. Fifty cents per Watt has been a dream of the solar cell community for 25 years. This cost target is now achievable because the solar lighting pays the balance of system cost and the PV electric power is produced at approximately 1 W/cm^2 rather than the 0.01 W/cm^2 associated with the traditional planar solar array.

We have now fabricated our first GaSb IRPV array designed for this application. Figure 6 shows a photograph of this array and figure 7 shows an illuminated current vs. voltage curve for this array, taken with a photographic flash test system.

As can be seen, this array performs as expected. In the next phase of this work, we plan to incorporate the reflecting cone and cooling fan and deliver this array to the consortium for actual system tests.

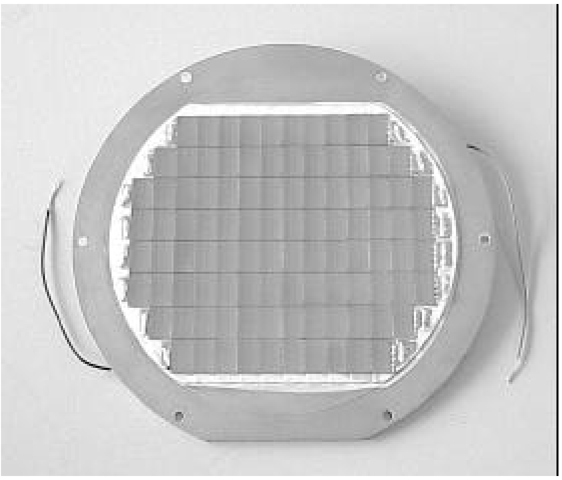

Figure 6: The first IR-sensitive PV cell array for a hybrid lighting system. JX Crystals fabricated this 100 cell array, using GaSb cells. Total active area is 180 cm^2.

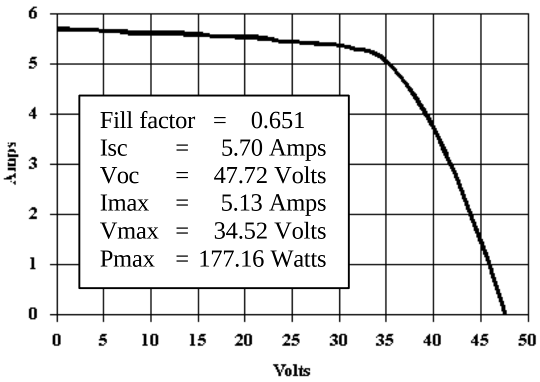

Figure 7: Current vs. voltage flashtest of the 100 cell array, showing power output of 177 Watts.

4. CONCLUSIONS

A concept for indoor illumination using sunlight has been described. For this system, a tracking concentrator on the building roof follows the sun and focuses sunlight into a light guide. A system of transparent light-guides distributes the sunlight to interior rooms. In this system, a cold mirror splits the solar spectrum into visible light for indoor illumination and infrared radiation which is directed to an array of GaSb infrared sensitive photovoltaic cells which then generate electricity. It is shown that each Watt of visible sunlight displaces two Watts of electricity which otherwise would be used for florescent lighting and air conditioning. The savings from this displaced electricity can then pay back the cost of the concentrator, tracker, and light guides in approximately three years. Meanwhile, the GaSb cell array converts the concentrated infrared energy into electricity with an electric power density of 1 Watt per square centimeter (177 W/180 cm^2). This power density is 100 times higher than available from a planar silicon cell, easily allowing PV electric power production at under $1 per Watt invested. A GaSb cell array has now been fabricated and its performance has been demonstrated.

REFERENCES

[1] L.M. Fraas, W.R. Pyle, and P.R. Ryason, "Concentrated and Piped Sunlight for Indoor Illumination", Applied Optics, Vol. 22, p. 578 (1983).

[2] J. Muhs, "Design and Analysis of Hybrid Solar Lighting and Full-Spectrum Solar Energy Systems", American Solar Energy Society SOLAR2000 Conference, Paper Number 33, June 16-21, 2000.

[3] J. Muhs, "Hybrid Solar Lighting Doubles the Efficiency and Affordability of Solar Energy in Commercial Buildings", CADDET-Energy Efficiency Newsletter, No. 4, pp. 6-9 (2000).

[4] web site: ornl.gov/hybrid lighting.