Luminescent and geometric concentrators for building integrated photovoltaics

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LUMINESCENT AND GEOMETRIC CONCENTRATORS FOR BUILDING INTEGRATED PHOTOVOLTAICS

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ABSTRACT

In developed countries 60% of the electricity consumed is attributable to commercial and public buildings. Even in the UK, the solar energy incident on buildings is more than 7x the electrical energy they consume. This represents a problem (the management of solar heat gain and glare) but also an opportunity that may be taken advantage of using complementary concentrator technologies. We are investigating conventional geometric and luminescent concentrators that may be combined to optimally harvest the direct and diffuse components of sunlight within a double glazed window unit. Initial results suggest that the combined system can achieve power conversion efficiencies approaching 20% under standard AM1.5g illumination at normal incidence.

INTRODUCTION

Energy Consumption in Commercial Buildings and Incident Solar Energy

Many estimates have been made of the potential of building roofs and façades for harvesting the sun's energy for heat and light. Muneer [1] estimates that the solar radiation incident on the surface of UK buildings is more than 7 times the electrical energy they consume. This estimate includes the area of all the facades of the building as well as the roof area. Historically however, photovoltaic (PV) and solar thermal systems have been too unwieldy, inefficient, or unattractive for façade installation, so efforts to harvest solar energy in buildings have until recently focused mainly on roofs, ignoring the significant portion of radiation incident on facades [2, 3].

Recent advances in building integrated photovoltaic and solar thermal technologies have begun to make façade-integrated systems more feasible, and in particular, the potential contribution of windows both to energy efficiency and energy capture and conversion has been the focus of considerable interest. Hill, Pearsall and others [2, 4, 5] modelled the usable roof and façade area of the UK building stock and estimated a potential PV generation capacity of 63 GW in 1995 and 110 GW in 2020. They state this implies an energy production capability of 208 TWh in 1995 and 364 TWh in 2020 comparable to the production of 274 TWh from centralised generators in the UK in 1989 [2]. Commercial buildings represent about 13% of this or 8 GW and 15 GW in 1995 and 2020 respectively. These estimates take into account the effects of shading, building orientation, surface suitability and seasonal variations. Adjustments were made for window areas, on the assumption that the main role of a window, to let light into a building, is incompatible with harvesting the light to generate electricity. With the simplifying assumption that diffuse solar radiation is isotropic, a significant conclusion of their work was that a material percentage of insolation falls on all four walls, not just the south facing wall, throughout the year. This is illustrated in Fig. 1 for the case of a building in Plymouth, UK.

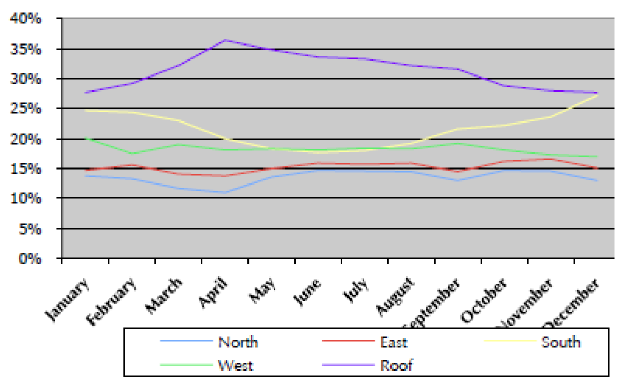

Figure 1. All surfaces of this building in Plymouth receive a significant share of the incident solar radiation at all times of the year. Based on data in reference [5].

Impressive as these figures are they nevertheless understate the case since the following assumptions have been made: (i) window surface area (assumed to be 33% in reference [2]) is ignored in the estimates of available façade area, since solar panels are not typically transparent; (ii) the portion of the incident spectrum which is not convertible to electricity was ignored; and (iii) demand-side impacts were not considered - the ways in which incident solar energy influences the energy consumption of the building, including its effect on heating, cooling and lighting demand. None of these is insignificant and each points to important emerging opportunities for a greater contribution from BIPV to the new energy landscape in the near future. However, we are concerned with the first, so we now turn to the role of windows.

Windows and Energy in Buildings

Given that the average lifetime of a window is 20-50 years, the design and performance of windows can and does have a material impact on future energy consumption of buildings. Arasteh *et al.* [6] estimate that windows are responsible for 35% of the heating and 28% of the cooling energy use in US commercial buildings, representing an annual impact of 1.3 EJ (361 TWh) of primary energy. Of this, they estimate 0.7 EJ could be saved with more energy efficient window technologies including passive blinds, highly insulating low emissivity windows, and dynamic tintable windows whose transmittance changes in response to conditions.

While the foregoing approaches reduce cooling, heating and lighting energy consumption, they do not provide energy capture or conversion capability. Technologies which can do this in a window include semi-transparent dye sensitized solar cells such as the 30 cm x 30 cm glass-integrated module developed by Hinsch *et al.* [7]. However, these have achieved efficiencies of only 4.2% in outdoor conditions and their lifetime is significantly shorter than silicon cells.

Low conversion efficiencies (leading to a requirement for large façade or roof areas), the high cost of traditional materials, and the loss of most of the incident energy in the form of heat are among the reasons for the limited adoption of building integrated PV**.** Most approaches to addressing these limitations have attempted to incorporate concentrating devices in windows or window blinds to enhance conversion efficiency and reduce cost, and thermal systems to capture and utilise the heat energy. The systems described in the literature however do not incorporate tracking so concentration is limited to < 10x.

Indeed, it is generally assumed that cost effective deployment of 3rd generation [8] conventional high solar concentration systems based on large parabolic mirrors or arrays of Fresnel lenses to focus solar irradiation onto high efficiency multi-junction or quantum well solar cells for conversion to electricity can only be achieved in open areas with a high degree of direct insolation. However, as a result of the recent advances in the manufacturing of low cost lenses, such solar concentrators have become a viable option for small and light modules that can be incorporated into buildings. These building integrated solar concentrators (BISCs) can take advantage of the transparency of small plastic concentrators and be incorporated into double glazed window elements in order to provide environmentally friendly electricity. Furthermore these solar tracking transparent BISCs can be considered as highly effective “solar blinds” since, like the alternative technologies discussed previously, they also shield the interior from direct sunlight, which is converted to electricity, thereby protecting the building from excessive heating and reducing the need for expensive air-conditioning.

THE BISC VENETIAN BLIND

The modules resemble Venetian blinds as shown in Fig. 2, which eliminate the direct component of sunlight, but also provide a view through the window. In addition they transmit a significant fraction of the diffuse sunlight, which has been scattered in the atmosphere and is incident over a wide range of angles, for glare-free natural interior illumination, even when the sun faces the window. This eliminates the need for interior lights when the blind is working (see Fig.2a).

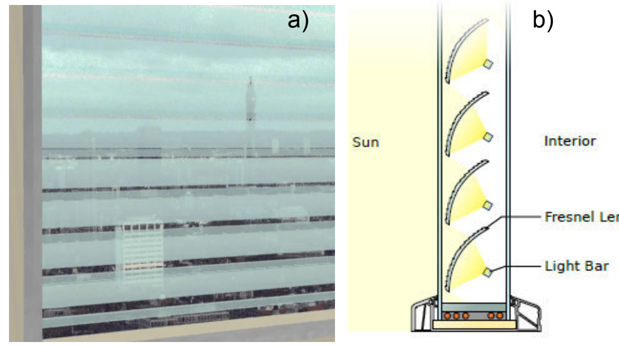

Figure 2. (a) Impression of a BISC Venetian blind. (b) Schematic of a possible design for the BISC blind.

A schematic of a possible design for the BISC blind is shown in Fig. 2b. It consists of an array of plastic, linear Fresnel lenses which focus stripes of light onto light-bars (discussed below) which serve as waveguiding secondary concentrators that couple the light to high efficiency solar cells at the ends of the light-bars. A 1.5 axis tracking system rotates the Fresnel lenses to follow the elevation of the sun and also moves the lenses towards and away from the light-bars so as to keep the sunlight focused on them as the angle of incidence of the direct beam varies throughout the day. The high efficiency solar cells can be water cooled to also supply a component of the hot water requirement of the building.

Mazzer *et al.* [9] predicted the average electricity generated by 1 m^2 of the solar blind over a year as a function of building shape and orientation for London and San Francisco. With two walls entirely clad with solar blinds it is estimated that the blind could reduce the electricity consumed for artificial lighting and cooling in a typical commercial building in the US by 50%, and provide enough on-site generation for 50% of the remaining needs of the building – for example, to run office equipment and refrigeration. A PV cell efficiency of 30% and an optical efficiency of 80% for the light-bar were assumed.

The electricity demand over 24-hour periods at Imperial College London was monitored and found be almost identical in winter, spring and summer [10]. The demand profile, with a peak approximately double the night-time base load, is typical of public, educational and commercial buildings. Solar PV systems are ideally suited to meet these requirements as they provide power at the time of peak demand that occurs between 11am and 5pm [10].

HARVESTING DIFFUSE INSOLATION

It has long been recognized that in much of Europe over half the insolation is diffuse [11]. Recent calculations [12], using standard NREL insolation software BIRD to provide the daily and yearly solar insolation with appropriate parameters for aerosol absorption and humidity taken from a NASA database, suggest that the figure is closer to 60% in, for example, London (see Fig. 3).

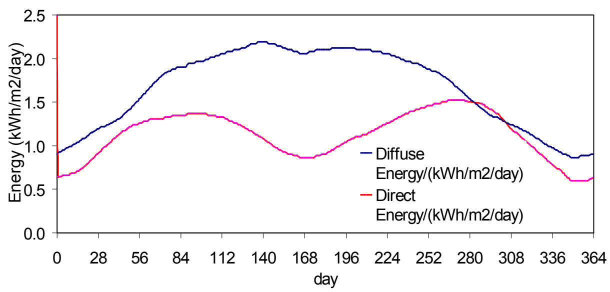

Figure 3. Direct and diffuse insolation on a vertical south facing façade in London [12]

The highest building integrated photovoltaic power generation density will therefore be achieved by making optimal use of both the diffuse and direct components of sunlight.

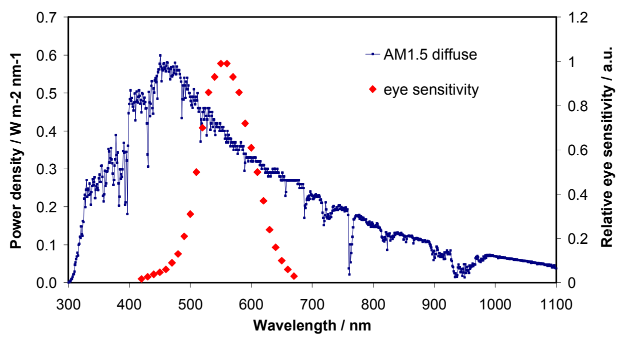

Figure 4. Relative sensitivity of the human eye and diffuse solar spectrum estimated by the difference between AM1.5g and AM1.5d.

The conventional BISCs described above only harvest the direct sunlight and we have therefore studied a “transparent” luminescent solar concentrator (LSC) which can be added to the window glass to harvest the significant short wavelength fraction (< 450nm) of the diffuse sunlight to which the eye is insensitive. This is illustrated in Fig. 4 in which the diffuse spectrum is estimated by the difference between the standard global (AM1.5g) and direct (AM1.5d) spectra. It can be seen that this estimate of the diffuse spectrum peaks below 500 nm rendering the sky blue.

THE “TRANSPARENT” LSC

The LSC, as illustrated in Fig. 5 generally consists of a transparent plate doped with luminescent centers that first absorb the incident sunlight and then re-emit it, usually isotropically, at longer wavelengths such that a significant fraction is trapped by total internal reflection and waveguided to the edges where it can be converted by solar cells with system power conversion efficiencies in the range of 5-10% [13-15].

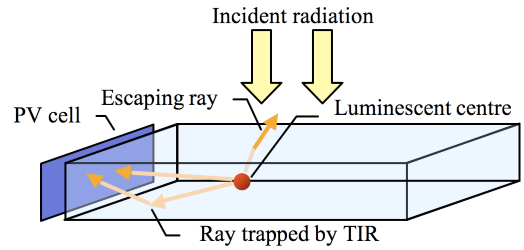

Figure 5. Schematic of a conventional LSC

LSCs are particularly suited to diffuse radiation because the luminescent efficiency of most luminescent materials is highest at short wavelengths, and, in addition they accept light at all angles of incidence with the absorption increasing with angle. The diffuse sunlight will see a significantly thicker absorber as it is incident over a very wide angular range. The direct sunlight impinging on the LSC within its absorption range (e.g. < 450nm) will see the minimum thickness of absorber and a significant fraction will be transmitted to the conventional BISC if the LSC is integrated within the front pane of a double glazing unit. The “transparent” LSC could also be integrated into the back pane where the solar irradiation will be lower due to multiple Fresnel reflections at all the interfaces. But, since this arrangement has the advantage of not absorbing any of the direct light that could be utilized in the tracking BISC solar blind, which operates at a higher system efficiency of around 20%, this configuration is preferred here.

SIMULATION TECHNIQUES

The Imperial group has developed three independent models to analyze LSCs. The first of these is the Thermodynamic Model, see e.g. references [16, 17], which is based on a detailed-balance approach, relating absorption and luminescence via the brightness theorem. The resulting differential equations are solved numerically according to the boundary conditions while allowing the photon chemical potential and incident and absorbed fluxes to vary in three dimensions.

The main advantages of the Thermodynamic Model are that it is an absolute calculation, can be used to predict luminescence profiles and Stokes’ shifts and to determine the luminescence QY of the dopant species. Its main disadvantage is lack of flexibility, being restricted to rectangular, homogeneous samples and it cannot be adapted for the thin-film devices studied in this project. It is also difficult to avoid computational problems when modeling large area devices. The thermodynamic model has however been extremely useful in providing an absolute standard for calculation of homogeneous concentrators for our two Raytrace Monte Carlo programs developed by Rahul Bose and Daniel Farrell (pvtrace [18]).

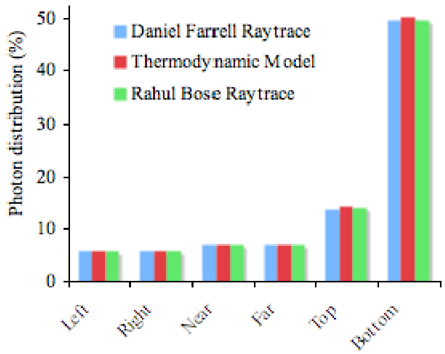

Figure 6. Comparison of predictions of the three models for the total photon fluxes exiting the various faces of a homogeneously doped luminescent plate.

Fig. 6 compares the predictions for all three models for the fluxes exiting the faces of a homogeneous LSC with the same absolute absorption and emission spectra for the dopant species. Very good agreement is observed from all faces and for all three models. The Raytrace models track individual photon paths through the LSC and use Monte Carlo methods to determine the outcome of events such as reflection at surfaces, absorption depth, whether an absorbed photon is emitted, and if so in what direction and at what wavelength it is emitted. Input to the model consists of the absorption and emission spectra of the materials comprising the device together with its configuration, dimensions and illumination source.

A variant of the LSC is the thin film concentrator. It consists of a thin layer of heavily doped material (typically a polymer) on top of a transparent substrate, ideally with matching refractive indices, such that trapped emission travels within the entire substrate without refraction or reflection at the interface. Our previous experimental measurements and computational simulations have shown that for the same dopant absorptivity there no noticeable difference in performance between conventional, homogeneously doped LSCs and thin film LSCs [19]. The increased re-absorption losses in the optically dense active layer of the thin film LSC are balanced by the reduced losses in the transparent substrate. However, for a "transparent" LSC on window glass a thin film LSC offers distinct advantages as dopant stability is not in general compatible with the high temperatures involved in dispersal in glass and coating is a considerably more convenient manufacturing technique.

RESULTS

Simulation of "transparent" LSCs

Simulations have been performed for a window on a vertical, south-facing, wall in London by weighting the diffuse and direct spectra (AM1.5g-AM1.5d and AM1.5d respectively) by the data in Fig. 3. The thickness of the LSC was assumed to be 3mm. The absorption and luminescence data for the UV absorbing dye, Lumogen F Violet 570 was taken from experimental measurements and the dye has a luminescence QY of 95%. A system efficiency of 2% and an energy harvesting yield around 30 kWh m^{-2} year^{-1} in London are predicted for 25cm x 25cm x 0.3cm LSC modules with optimal dye concentration and GaInP cells (bandgap 1.8eV) attached to all four edges. This cell was chosen as we have both external quantum efficiency (EQE) and dark current data. We use the known wavelength dependence of the EQE to determine the short circuit current (J_{SC}) from the photon flux coupled into the cell. We then assume the light IV curve is given by the difference of the J_{SC} and the dark current. A higher bandgap cell would be a better match than GaInP not only in terms of higher EQE and hence higher J_{SC} but also less thermalisation loss and a higher open circuit voltage, V_{OC}. In the III-V system a GaP cell with a bandgap of 2.3eV would be appropriate and could also be grown on Si which would dramatically reduce costs. We estimate that the system efficiency in London would be increased to 3% with a 20% higher EQE and increase in V_{OC} estimated by the ratio of bandgaps.

The Lumogen F Violet 570 dye only absorbs 1.5% of the direct and 8.5% of the diffuse photon fluxes (out to 4000nm). We predict that the power conversion efficiencies of the simulated module with GaP cells under AM1.5 direct and diffuse illumination individually with attached GaP cells would be about 0.8% and 4.5% respectively. The power conversion efficiency under AM1.5g with only around 15% diffuse photons would be 1.32%. A dye with similar properties to Violet 570 but that absorbs out to 490nm would absorb 6% and 25% of the AM1.5 direct and diffuse spectra respectively resulting in power conversion efficiencies of around 3% and 13% for the direct and diffuse components individually and 4.5% for AM1.5g. However, these increases would come at the expense of a window that is more strongly tinted.

Prototype "transparent" LSC

We fabricated a prototype "transparent" LSC by coating a plate of fused quartz glass with a thin film of the Lumogen F Violet 570 fluorescent dye (see Fig. 7). Silicon solar cells (125mm x 3.3mm) with no front contacts from Solaronix were bonded to the four edges of the LSC using Krystalflex PE399 transparent thermosoftening film.

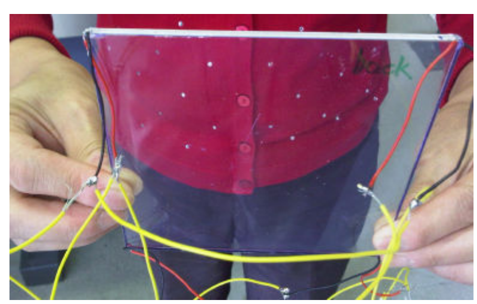

Figure 7. The prototype "transparent" LSC.

With the four cells connected in parallel the power conversion efficiency of this prototype illuminated by a class B solar simulator was found to be only 0.31% but does not represent the ultimate efficiency achievable for this concept. The reasons for the low power conversion efficiency are that the thin-film was not optimally doped, transmitting more than 10% of the incident light even at the absorbance peak, and that the bandgap of the Si solar cells at the edges was not matched to the wavelength of the luminescent light emitted from the edges of the device.

Our simulations (above) suggest that with matched solar cells and optimal doping a power conversion efficiency of over 10% is possible under diffuse light. This figure could be further increased (at least doubled) with an optimal luminescent material that reduces self-absorption losses through a larger Stokes shift or that provides directional emission. A further strategy to increase the efficiency would be to utilize wavelength selective mirrors on the top and bottom surfaces, similar to those we tested in reference [17], that transmit incident light over the wavelength range the luminescent material can absorb but reflect the longer wavelength emitted light.

Developing the light-bar

The light-bars are a key element of the BISC Venetian blind. Their function is to act as secondary concentrators to waveguide the direct light focused by the linear Fresnel lenses to the ends, where it may be converted by high efficiency solar cells. These could be either multi-junction or strain-balanced quantum well solar cells depending on whether a geometric or luminescent design is preferred.

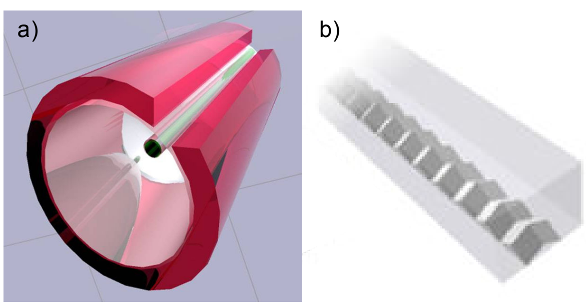

Figure 8. Luminescent a) and geometric b) designs for the light-bar.

We have investigated both approaches using the methodology of testing simple prototypes, to verify the accuracy of the simulation techniques. This then enables optimized designs, which are more difficult to fabricate, to be simulated with confidence. Fig. 8 illustrates the best luminescent and geometric designs to date.

In order to simulate these complex designs the Raytrace model developed by Daniel Farrell was extended to include many different cross sections e.g. rectangular, circular and triangular. The model was then further extended by Carl Poelking to allow addition, subtraction and intersection of the 3D objects via constructive solid geometry. Further development by Karl Gödel added 2D polygons and arbitrary convex objects to the model.

Cylindrical luminescent light-bars

For the light-bar, a cylindrical LSC is advantageous owing to improved waveguiding properties and, in order to reduce the re-absorption losses, a composite LSC with a thin cylindrical luminescent core was suggested [20]. The sunlight is focused on the luminescent core which absorbs and re-emits the light, whereas the outer transparent bar functions as a waveguide with a greatly reduced re-absorption probability. Modelling results showed that if a ray gets absorbed by the dye, the probability that it reaches the edges can be quite high: For the composite cylindrical light-bar depicted in Fig. 8a) the probability of an absorbed photon reaching the ends can be as high as 55%. However, highly luminescent materials can generally only absorb the fraction of the solar spectrum below 650nm thereby limiting optical efficiencies to around 13.5%. This figure could be further dramatically improved with the advent of highly luminescent IR absorbers or broad-band efficient up-conversion.

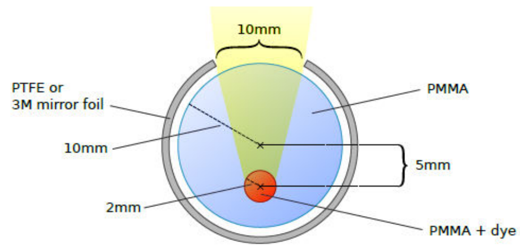

Figure 9. Cross section of the luminescent light-bar.

We have fabricated a prototype composite luminescent light-bar as shown in Fig. 9. It has a length of 47cm and diameter of 2cm with a core doped with Lumogen F Red 305 and was optimized for the 15cm wide linear Fresnel lens we have available that provides a 1cm wide focus.

The simulations for the bare light bar and for the diffuse PTFE mirror coating are well confirmed by our experiments. For the bare light-bar the simulated and experimental optical efficiencies were 2.43±0.24% and 3.48±0.32%. With the PTFE reflector these figures increase to 8.52±0.12% and 8.30±0.97%. From these studies we conclude that with the materials currently available the ambitious target of 80% for the optical efficiency of the light-bar (used in reference [9]) cannot be achieved with a luminescent design at present.

Geometric light-bar

We therefore turned to geometric concentrator designs for the light-bar The rationale behind our geometric design (see Fig. 6b) is to reflect the focused light off mirrored facets such that it is trapped within totally internally reflected modes on the other surfaces. Given the difficulty of finding luminescent materials with ideal properties we have found this approach has significant advantages. The dimensions chosen for this study were a light-bar length of

20cm, width 2.5cm and height 2cm. The PMMA (absorption coefficient $0.3m^{-1}$) light-bar had air-gap specular reflectors (R=97%) covering the vertical surfaces and the remainder of the bottom surface not occupied by the deflection mirrors (for which R=97% was also assumed). The linear Fresnel lens available for this study provided a concentration of 15x but a lens with a tighter focus could be produced providing a concentration of 25x. We therefore studied the effect of focal width and the optical efficiency of the light-bar as a function of the azimuthal angle, ϕ, of incidence (which will vary throughout the day) of the direct beam, for two different focal widths, are compared in Fig. 8. We have also studied the effects of varying the light-bar geometry and the detailed parameters of the deflection mirrors but there is insufficient space to discuss these here.

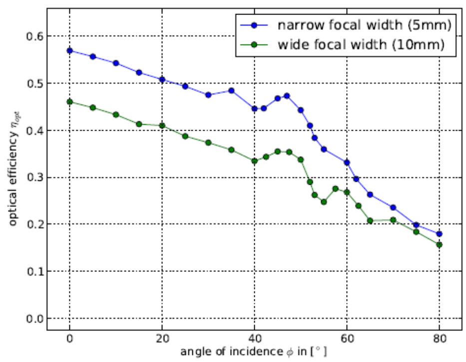

Figure 8. Comparison of the optical efficiency of the light-bar with different focal widths.

CONCLUSIONS

With a module size of 25cm x 25cm incorporating a tinted LSC window glass with GaP cells on all edges, Fresnel lenses providing a concentration of 25x and an optimized light-bar (with a peak optical efficiency of 60% when ϕ=0, at noon for a south facing wall) with water cooled triple junction cells operating at a power conversion efficiency of 36% [21] optically coupled to the ends of the light-bar in the frame, it is expected that the full integrated system would operate at a peak efficiency of 19% under AM1.5g at normal incidence. This is 2 to 3 times the efficiency of current building integrated PV systems based on 2nd generation thin or semitransparent a-Si or CIS cells and this system makes more effective use of the solar spectrum. We predict that in the standard AM1.5g spectrum a tinted LSC window could achieve power conversion efficiencies of 4.5%. However, in the UK or other regions of high diffuse insolation, both the efficiency and the boost to a BISC Venetian blind provided by a tinted LSC window will be higher and it may also find application as a stand-alone component.

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