DEVELOPMENT AND EXPERIMENTAL CHARACTERISATION OF LOW COST FACADE INTEGRATED CONCENTRATOR PHOTOVOLTAICS.

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Summary

For photovoltaics to achieve wide scale implementation as a building facade cladding material their cost must be reduced while maintaining or exceeding present levels of performance. Solar energy concentration can achieve cost reduction. Due to the restrictions inherent to facade mounting for total energy collection not to be significantly curtailed, the maximum level of concentration is limited to the range of 2.5 to 3. The general specification and design for a system that employs non-imaging optical design, a solid transparent refractive element and total internal reflection to give a theoretical concentration of 2.46 are provided. Details of the laboratory fabrication of pre-prototypes are given. Variation in electrical performance with direct solar radiation incidence angle is measured experimentally, using the collimated radiation output from a line-axis solar simulator. This is compared with theoretical predictions of the variation in optical performance with radiation incidence angle determined by ray trace techniques. A finite element model is used to predict the thermal response of the concentrating system and that of a standard non-concentrating system subject to similar applied conditions. Annual performance predictions for both systems are made for systems located in the United Kingdom and in Greece.

Introduction

Photovoltaic systems have been restricted to niche markets. To achieve wide scale adoption, the cost of producing electricity output from such systems must be reduced. This may result from economies of scale concomitant with increased manufacturing production output, improvements in solar conversion efficiency and by the substitution of expensive photovoltaic materials by lower cost concentrating systems. Concentrating solar energy onto a photovoltaic material reduces cell area per unit output and, for certain cell materials and designs, increases photovoltaic conversion efficiency. The cost of the total system is thus reduced per unit of energy delivered.

Orientated correctly and not significantly over-shaded building facades can provide ideal locations for photovoltaic cladding. Concentration is however restricted as such installations are non-tracking to avoid additional initial and maintenance costs and unwanted mechanical complexity. A two-dimensional non-dielectric Compound Parabolic Concentrator (CPC) (1) can concentrate direct solar radiation by a factor of two without tracking. This increases to approximately three for a dielectric CPC. In contrast to previous work using dielectric concentrators which were for standalone photovoltaic applications (2, 3) the work reported herein develops dielectric CPC geometries designed specifically for photovoltaic-clad building facades.

Optical Design

The plane glass covers present to prevent photovoltaic material degradation are reconfigured conceptually as thin low concentration ratio, non-imaging stationery solar energy concentrating devices. A dielectric-field compound parabolic, solar energy concentrating cover collects most direct and some diffuse incident insolation onto a reduced semiconductor material area. To achieve a large cost reduction it is essential that the concentrating cover subsystem incurs marginal additional cost.

In developing the optical design for the concentrating cover the following were considered: the

- panel would be fixed onto vertical facades
- most solar radiation incident on the concentrator aperture should reach the photovoltaic cell
- concentration ratio would be in the range of 2 to 3
- weight of the panel and dimensions should be similar to that of current cladding elements
- additional cost of the concentrating system should be low.

Optical designs using non-imaging optics allow both direct and diffuse insolation to be concentrated. Collecting the total direct insolation and approximately 50% of the diffuse insolation assuming that it has an isotropic angular skywards distribution for a stationary non-refracting system the maximum concentration ratio that can be achieved is 2. Using a solid transparent dielectric-field concentrator fabricated from a glass/acrylic material with a refractive index of approximately 1.5 in which refraction at the aperture to the concentrator occurs, the concentration ratio can be increased to 3 while maintaining acceptance of all of the direct and 50% of the diffuse insolation.

The developed concentrator design (4) was developed by consideration of the solar motion as seen from a south-facing wall in the UK and is based on a truncated asymmetric CPC (5) whose two parabolas have axis 37° apart. For this design the concentration ratio is 2.46 and high levels of optical efficiency are achieved for insolation incident within the angular range between 2°-65° from the perpendicular to the aperture surface.

Refraction in a dielectric-field concentrator enables greater concentration to be achieved with a stationary system while maintaining a wide acceptance angle, thus increasing collected diffuse insolation. The majority of reflections occur within the angle of total internal reflection, metallisation of concentrator walls is avoided and reflection losses are minimised. A solid cover however absorbs some energy, reducing that reaching the absorber. The latter can be minimised by using as the dielectric material "low iron" glass (6) or a material with similar optical properties of low extinction coefficient and high solar transmittance. For a path length of 10mm through a concentrator fabricated from low-iron glass with an extinction coefficient of $4m^{-1}$, only 3.04% of incident insolation is absorbed during transmission. To absorb 10% of the incident insolation the path length would need to increase to 26.3mm. For glass with an extinction coefficient of $32m^{-1}$, a thickness of 3.3mm will absorb 10% during transmission. For a 9 mm wide photovoltaic strip placed at the exit aperture of the designed concentrator a concentrator depth of only 15.9 mm is required. A schematic diagram illustrating the scale and design of the system is presented in figure 1.

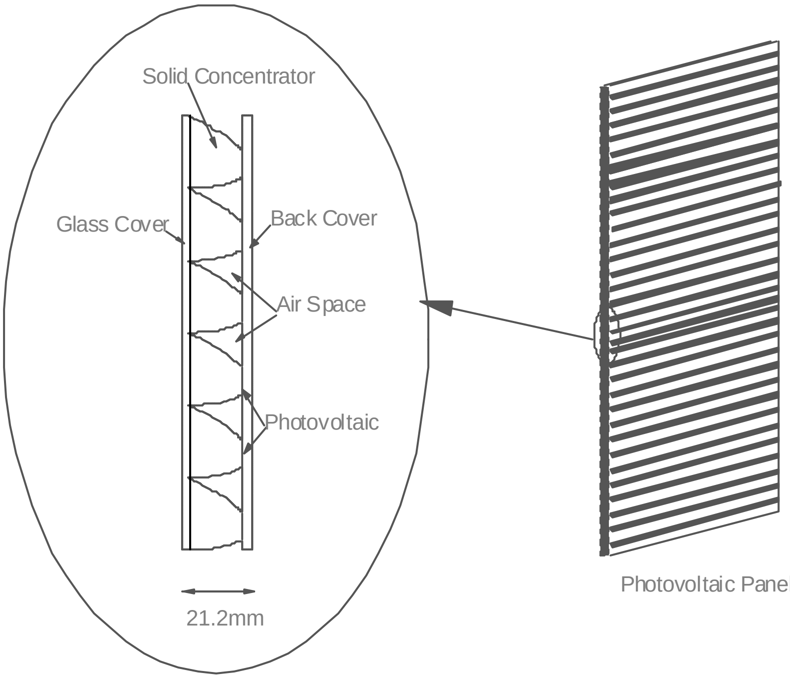

Figure 1. Schematic diagram illustrating the scale and design of the developed concentrator system.

Predicted Optical Performance

In the three-dimensional optical analysis undertaken all reflections were assumed to be specular. Losses resulting from reflection of the insolation at the aperture to the concentrator along with transmission losses due to absorption within the solid dielectric material are included in the analysis. For the ray trace calculations the concentrator was assumed to be fabricated from an high transmittance dielectric acrylic material with an extinction coefficient, α, of 4 m^{-1} and refractive index n=1.523, the concentrator was bonded to a sheet of low iron glass with similar optical properties. Total internal reflection (TIR) with an reflection efficiency of 1 occurs for all rays incident at the dielectric-air interface outside a 41.04° cone, rays incident within the cone are refracted and exit from the concentrator through the air-dielectric interface.

The direction of incident solar radiation on the concentrator reference axis system Z_c, E_c and S_c, (Z_c is the perpendicular to the concentrator aperture and E_c and S_c are the longitudinal, and parallel axis respectively) is defined by the two angles θ between the solar ray and the Z_c axis and θ_s between the projection of the solar ray on the S_c-E_c plane and the S_c axis. The calculated angular acceptance and optical efficiency for the concentrator design specified are presented in Figure 2 and 3 respectively. The contour plots are presented only for $0° \leq \theta_S \leq 180°$ since for linear concentrators symmetric values result for $-180° \leq \theta_S \leq 0°$. It can be seen from Figure 2 that due to the enhanced angular acceptance resulting from refraction at the concentrator entrance all rays are accepted over a wide range of incidence. Optical efficiencies of over 90% are achieved as shown in Figure 3.

Experimental CPC Fabrication

A range of materials and fabrication methods for the production of a CPC reflective-refractive concentrator system were investigated. To minimise the additional cost and weight of materials required the first option considered was modification of the underside of the protective glass cover. The glass covers used currently are tempered, to undertake the operations required to form the desired profile after tempering results in either glass fracture or loss of temper. To temper after production of the concentrator profiles may lead to distortions in the profile and increased optical losses. For concentrator panels, due to its good optical properties, low cost, durability and since the risks of delamination are well known from current photovoltaic systems, if a suitable fabrication method can be found glass would be an ideal material.

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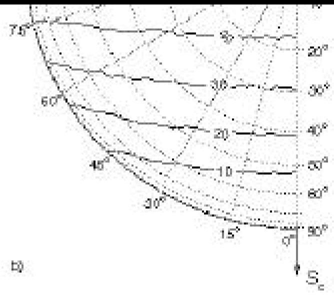

Figure 2. Predicted angular acceptance function for the developed photovoltaic concentrator design.

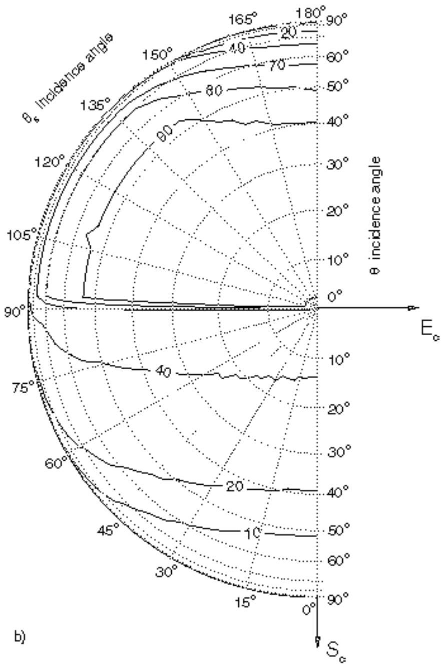

Figure 3. Predicted optical efficiency for the developed photovoltaic concentrator design.

Several plastics have suitable optical properties including acrylics and styrene. The major considerations are that the refractive index is in the range 1.5 to 1.6, and that the extinction coefficient is low. To minimise optical loses it is essential that the profile for the concentrator system produced in the plastic is accurate. Extrusion, pressing or resin casting methods may be used. Resin casting or pressing can achieve the desired profile accuracy with little distortion, with resin casting being most suitable for small-scale prototype manufacture.

Resin casting was used to produce the prototype systems. Moulds with the desired number and type of concentrators were fabricated by either peripheral milling or wire erosion and polished. The selected acrylic resin was subjected to vacuum to release and outgas any dissolved gasses. After combination with a suitable hardener the resin was introduced into the mould, further outgassed and then cured either at room temperature and pressure or at elevated temperatures. Resin casting can facilitate in one operation both encapsulation of the photovoltaic cells and bonding to the glass cover sheet and so could lead to a reduction in cost. Three prototype moulds were developed, two moulds based on a 3mm cell width with respectively 20 and 200 cells and one based on a 9mm cell width using 10 cells.

For the 3mm width cell systems two major problems were encountered. The first was that polishing the physically small concentrator profile to a sufficient finish proved difficult, thus resulting in reduced optical efficiency. The second was that the cells due to their light weight and the angle that they were inclined at in the cell string did not sit flat at the base of the concentrator moulds due to the effect of the flow of solder. In the casting process the effects of this were two fold:

- air entrapped beneath the cells made it difficult to remove all air bubbles,
- cells tended to rise up from the base of the concentrator during the casting process.

The performance measured experimentally for the 3mm cell based systems fell well short of that required, with concentration ratios in the range of 1.6 to 1.8 being achieved. Using the developed optical model it was found that movement of the cell by less than 0.4mm could result in a 40% reduction in radiation reaching the photovoltaic cell for some incidence angles. Thus for 3mm wide cells accurate cell location is essential to achieving the desired levels of performance. A ray trace diagram illustrating the effect of photovoltaic cell misplacement is given in Figure 4.

The 9mm width cell system had the following advantages

- the mould reflector profile could be polished readily to a mirror finish

- due to the increased cell width it was possible to locate the cells accurately at the base of the system, and
- due to the reduction in edge effects the cells' electrical conversion efficiency improved.

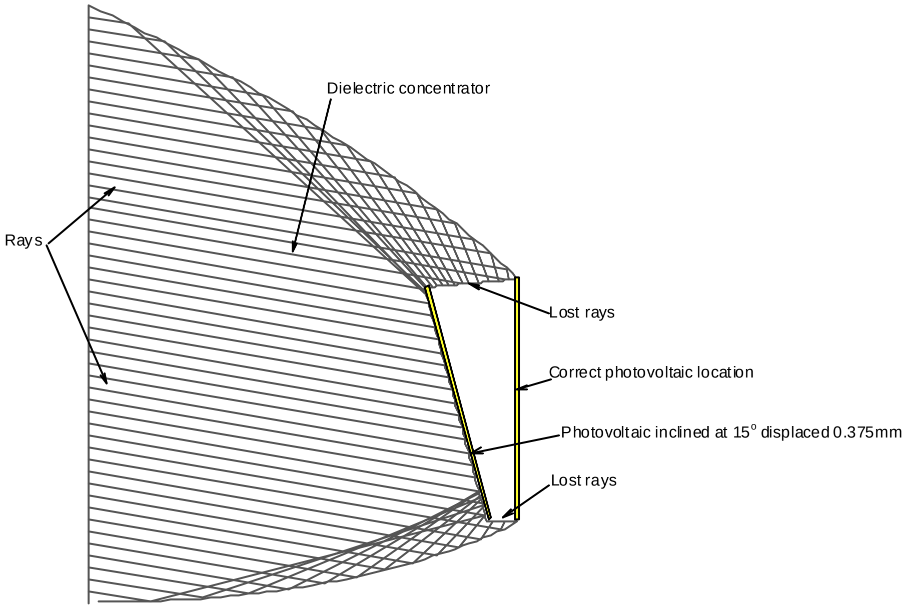

Figure 4. Example ray trace diagram illustrating the optical losses resulting from photovoltaic cell misplacement from the design location.

The system functioned well optically with the image of the photovoltaics filling the entrance apertures to the concentrators over the predicted acceptance range of the systems, as shown in Figure 5. The thin lines of light are due to the 0.25mm gap between adjacent concentrator apertures.

Experimental Characterisation

To determine the angular response and level of concentration achieved with the laboratory prototype systems, experimental characterisation using a solar simulator was undertaken. The pulsed simulator developed used a low pressure pulsed xenon lamp collimated by a parabolic reflector. The test plane inclination could be varied in two planes to allow all possible angles of incidence to be investigated. Thermal effects on photovoltaic performance were minimised by the short duration of the pulse which could be varied within the range from one millisecond to one second. To enable a direct performance comparison to be made, adjacent to and in the same plane as the concentrator system a string of ten cells with a low iron glass flat cover were mounted. The short circuit current, proportional to the intensity of incident radiation was accurately determined from the constant intensity central region of the simulator flash. The ratio of the measured short circuit current for the concentrator and the flat photovoltaic system represents the concentration achieved and is plotted against that predicted using the developed model in Figure 6, the accuracy of the experimental measurements was within ±1%. It can be seen that the agreement is excellent with concentrations in excess of 2.20 achieved for a range of over 40°

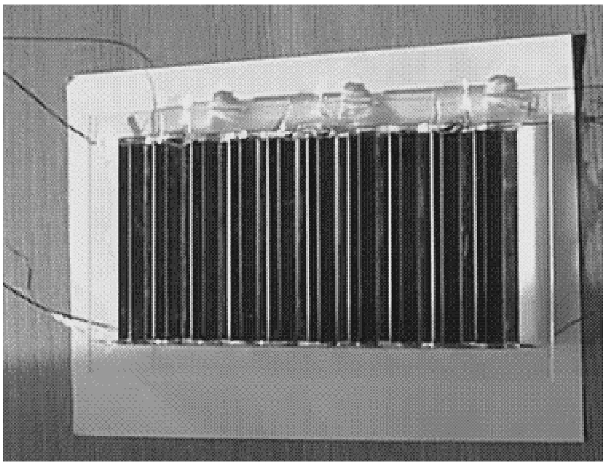

Figure 5. Photograph of a fabricated concentrator element using a 9mm wide photovoltaic cell.

Predicted Thermal Behaviour

The electrical conversion efficiency of photovoltaic systems in general decreases by 5% for every 10°C temperature rise; it is therefore essential that the temperature attained by the developed system in operation is similar to that for standard systems. A finite element analysis was undertaken in which the temperatures were predicted for a flat plate system and a concentrator system with similar applied boundary conditions of front and back heat loss coefficients, incident insolation intensity and electrical conversion efficiency. An isotherm plot for the concentrator system is presented in Figure 7. For the 9mm cell concentrator, a rise in maximum temperature of less than 5°C over that for a standard system is predicted corresponding to a drop in electrical efficiency of less than 2.5%. The heat transfer coefficients from the front and back surfaces of the systems were 10 and 5$Wm^{-2}K^{-1}$ respectively to an ambient temperature of 20°C. Insolation intensity was 600Wm^{-2} and electrical conversion efficiency was 16%.

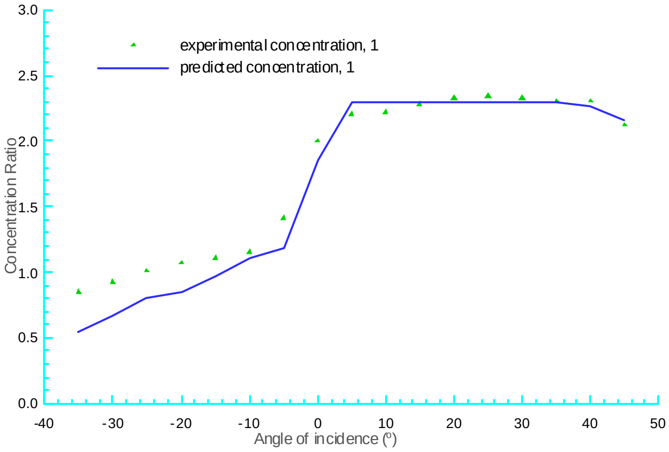

Figure 6. Variation of predicted and experimentally determined concentration ratio for the developed photovoltaic concentrator system.

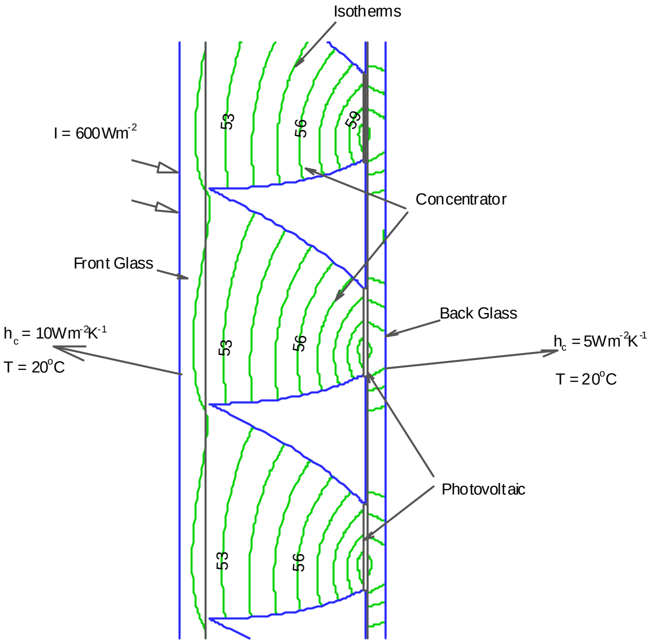

Figure 7. Predicted isothermal contour plots for a concentrator using 9mm wide photovoltaic cells. Front and back covers are 3mm and 2mm wide glass sheets respectively with heat transfer coefficients from the front and back surfaces of 10 and 5Wm^{-2}K^{-1} to an ambient temperature of 20°C. The incident direct insolation level is 600Wm^{-2}, incident at an angle of 5° above the perpendicular to the glass cover. The cell electrical conversion efficiency is 16%.

Annual Performance Prediction

Combining details of the optical efficiency with direct and diffuse insolation data, predictions of the annual performance of the system in comparison to a flat plate system were made. The values given are for the energy reaching the photovoltaic surface before conversion to electrical energy. Based on a square metre of aperture area for systems located in London with vertical orientation the predicted annual collected energy is 1749.1MJ for the concentrator and 1978MJ for a standard PV system. If a comparison is made based on a square metre of photovoltaic area the value of energy collected for the concentrator system becomes, 4320.9MJ i.e 2.18 times greater than that for an equivalent area of photovoltaic material in a flat PV system. For Crete based on aperture area for a vertical orientation the value of annual collected energy is 2981.9MJ for the standard PV system and 2767.7MJ for the concentrator. If a similar comparison is made based on photovoltaic area the value for the concentrator system becomes, 6943.7 i.e. 2.32 times greater than that for an equivalent area of photovoltaic material in a flat PV system. The variation in performance results from the different diffuse to direct insolation fractions in the two locations.

Cost Implications

At the present time PV cells comprise approximately 30% of the total cost of a standard photovoltaic system. The developed designs can reduce the PV cell material required for a building integrated photovoltaic façade by up to 60%, while maintaining a similar electrical output. The cost of materials required to produce the concentrator system for a 0.6 by 1m panel could range realistically from £17.50 to £70.00, depending on the system design used. The upper cost limit is based on using the resin with the optimum optical properties purchased in very small quantities for one-off, single system laboratory production. The cost of producing the concentrators will be strongly production volume dependant, for large volumes the individual unit cost incurred by using casting or press moulding techniques is in general low if automated manufacture processes are used. All other operations required are similar to or have an equivalent operation in standard PV production. It may be possible to reduce the requirement for front protective covers, and thus system cost by using suitable coatings on the castings. The saving in PV material for a standard 36 cell panel may be up to £75.00, (costs of PV material have changed rapidly recently). It is clear that for a system with a resin cost of £70.00, the concentrator system is not cost effective, however for the lower resin cost of £17.50 savings would be significant, potentially up to 40% of the PV material cost, giving a total system cost reduction of around 12%.

Conclusions

The theoretical and experimental performance of a prototype concentrating photovoltaic façade element has been presented. The measured experimental performance closely approximates that predicted. The additional temperature rise that would occur during operation, predicted using finite element techniques, over that for a standard non-concentrating flat photovoltaic system is less than 5°C. The system developed requires less than 41% of the photovoltaic material used in a standard flat module and for a climate with a similar direct to diffuse insolation mix to that of the UK over 88% of a flat modules electrical output. For climates with a smaller diffuse insolation component this latter value will be higher.

Acknowledgment

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