The Design and Optical Optimisation of a Two stage Reflecting High Concentrating Photovoltaic Module using Ray Trace Modelling

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Abstract

The design and optical optimisation of a 500 suns concentrating photovoltaic system (CPV) to use with a high efficiency 10mm x 10mm multi-junction solar cell is presented. The advantage of using a multi-junction solar cell is the higher electrical conversion efficiency, which enhances the harvesting of the solar energy compared to that of a non-concentrating flat plate PV system. In this study, a concentrating system with a semi-parabolic dish is designed to use with a secondary parabolic reflector. It was found that increasing the radius and focal length of both reflectors improved optical efficiency and an inverse parabolic design of the secondary reflector is more advantageous than a non-inverse design. Results were obtained first for the case of a parallel light source and then with the introduction of practical uncertainties such as diverging light, misalignment, off focus and tracking error effects. Initial parallel light results gave an optimised optical efficiency of 76.63% from a source set to 1000 W/m^2 irradiance. Considering ±0.27° divergence of solar irradiance resulted in an optimised optical efficiency of 86.02% but at the cost of less uniform flux distribution upon the receiver. An absolute uncertainty of ±12.68% due to manufacturing and solar tracking error was also calculated.

Introduction:

The photovoltaic is a promising renewable energy technology but with a disadvantage of higher cost per unit energy output compared to that of conventional energy sources. Common commercially available flat plate solar modules have a maximum efficiency of ~23% [1] and although this value is increasing with the use of multi-junction solar cells which can reach up to ~40% efficiency, the cost of such photovoltaic material is expensive [1]. Thus a payback period of ~15 years or longer depending on the location is expected regardless of the conversion efficiency of the solar cell used. Concentration Photovoltaics can increase system efficiency without needing large quantities of expensive material for multi-junction solar cells and is also an effective method to lessen the demand on the silicon market [2]. There have been many proposed concentrator designs [3-5], however better concentrator system design and detailed research into the accuracy is required in the optics of solar systems, including error analysis of such designs to optimise for the highest efficiency in practical operation. Alexis Vossier et al. [6] proposed next generation 4-6 junction cells should be operated at ultrahigh concentration in order to lower CPV electricity costs. This will require optical optimisation to ensure uniform irradiance upon the intended PV material and avoid hot-spot heating which has been proven to cause irreversible destruction of the solar cell structure [7].

This study has been undertaken to design an optimised solar concentrator through the use of detailed ray trace modelling and analysis.

Concentrator Design Concept:

The proposed concentrator design employs the use of a primary parabolic collector and a smaller secondary parabolic reflector, both with co-incident focal points shown in Figure 1.

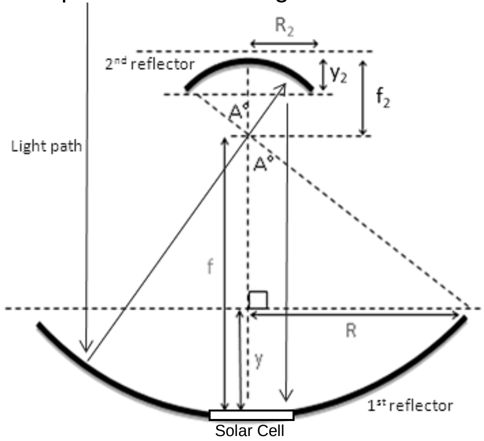

Figure 1: Theoretical focusing of parallel incident light using parabolic reflectors.

Angle A is the maximum angle light can make with the central axis after reflection from the primary reflector and so should be the minimum angle of the secondary reflector to ensure no light loss. The light hence received at the 10mm x 10mm solar cell placed in the base of the primary reflector will receive a uniform irradiance distribution where the concentration level depends on the open face area of the primary reflector.

Design Method and Calculations:

By limiting the secondary reflector open face area to that of the 11mm x 11mm receiver space made in the primary reflector base for the solar cell, shadowing effects were eliminated for the case of parallel incident light. Both parabolic reflectors were cut to square faces to reduce the optical losses in a square shaped solar cell. The radius of the secondary reflector was hence calculated to be 7.78mm. The required radius of the primary reflector to reach a concentration of 500 suns was calculated to be 158.31mm. Due to the relationship formed between both reflectors when angle A is kept equal as shown in Figure 1, the focal length of the secondary reflector is 0.049 times the focal length of the primary reflector.

Optical simulations were carried out following these restrictions for varying focal lengths of the primary reflector and for an inverse and non-inverse parabolic design for the secondary reflector.

Ideal Case Scenario Results:

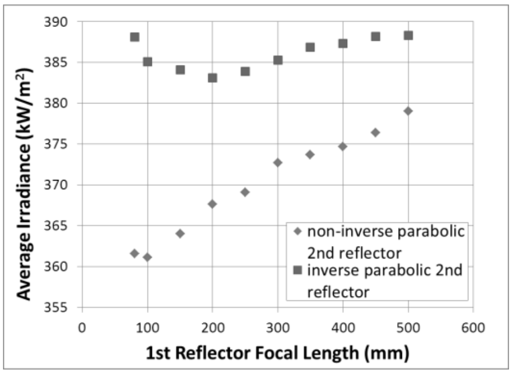

Figure 2: Recieved average irradiance at 10mm x10mm active area of solar cell.

The inverse parabolic reflector design was chosen to be more advantagous than the non-inverse parabolic design for the secondary reflector due to higher average irradiance levels, hence higher optical efficiencies, and a smaller system size as the focal point is located outside the system as shown in Figure 3.

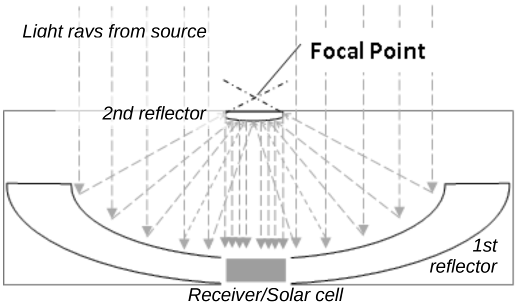

Figure 3: System Set-up for Inverse parabolic secondary reflector design.

Irradiance peaks were found to form along the x=0 and y=0 of the irradiance distribution for the inverse parabolic reflector. For the non-inverse parabolic reflector these peaks formed on the boundary of the distribution which was not included in 10mm x10mm active cell area. Hence received irradiance was higher for the inverse rather than non-inverse secondary reflector design. These peaks were found for focal lengths of 200 mm and above for the primary reflector. As the primary reflector focal length as increased, the x=0 and y=0 irradiance peaks increased whilst the remaning area of irradiance decreased and unified. These irradiance peaks are potential hot-spot risks. The optimum irradiance distribution was found for a primary reflector focal length of 270 mm with an optical efficiency of 76.63% (Figure 4).

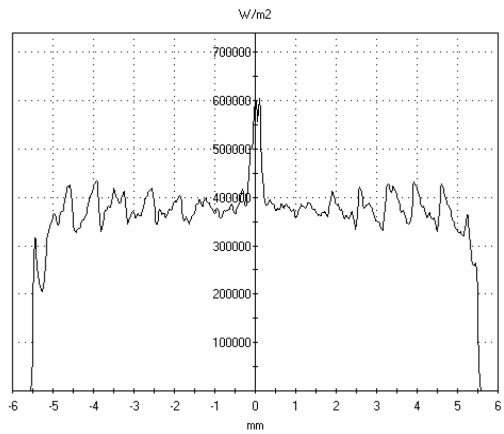

Figure 4: Irradiance line profile for inverse parabolic secondary reflector and primary reflector focal length of 270 mm.

Simulating Practical Uncertainties:

Considering the natural divergence of solar light, ±0.27°, the simulated light rays diverged after reflecting from the secondary reflector so as they were not directly incident upon the solar cell which resulted in an optical efficiency drop to ~4%. Deliberate vertical separation of the focal points of the two reflectors did not compensate for this divergence as expected due to the small radius and focal length of the secondary reflector. The second reflector radius was investigated and an increase in radius was found to allow a higher degree of convergence and hence a higher optical efficiency as shown in Figure 5.

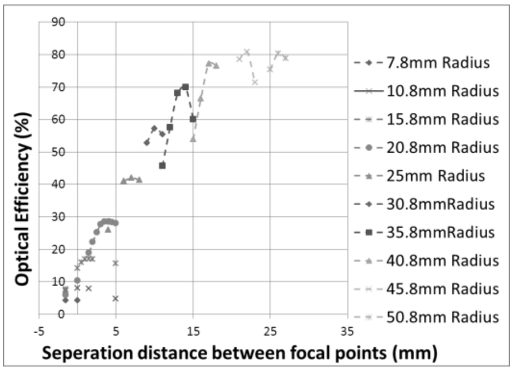

Figure 5: Effect of increasing second reflector radius.

The increase in optical efficiency was due to the increased focusing of the irradiance distribution upon the solar cell which, due to the solar light divergence, was Gaussian in shape. For uniform irradiance distribution a second reflector radius of 30mm was found to be most effective but had an optical efficiency of 55%. As the radius was increased, less of the cell active area was illuminated and so a compromise had to be made between high optical efficiency and uniform irradiance distribution. A radius of 42mm for the secondary reflector was chosen as optimum, with a positive focal point separation distance of 18.5mm and a first reflector radius of 228.91 mm to maintain 500 suns concentration. An optical efficiency of 86.02% was obtained and an irradiance distribution shown in Figure 6.

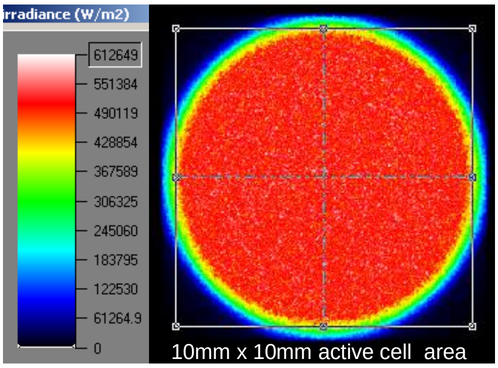

Figure 6: Irradiance distribution at the solar cell due to a secondary reflector radius of 42 mm.

The lack of irradiance at each corner of the solar cell active area could degrade the performance of the solar cell but further practical testing is required.

Solar Tracking Uncertainty:

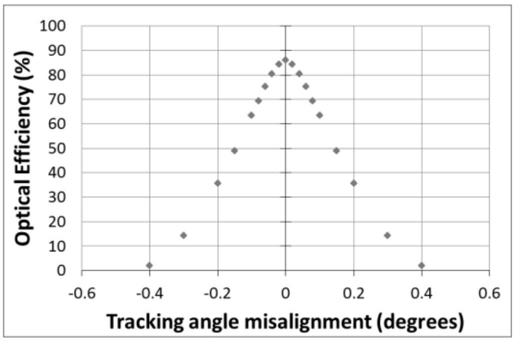

Figure 7: Simulated effect of tracking error in both axes.

Due to the symmetry of the design the tracking inaccuracy effect, as shown in Figure 7, was mirrored on all sides and decreased with increasing offset tracking angle. In typical high concentration systems tracking accuracy must be in the ± 0.1° range to deliver approximately 90% of the rated power output. [8-10] A tracking variation of 0.1°-0.2° from the median is common although dependent on degree of alignment, tuning and calibration of the tracking system. [10] The proposed system requires an increased degree of tracking accuracy of ±0.06° to lower the absolute error range in optical efficiency to ±10.90%.

Manufacturing Uncertainty:

The positioning error in the secondary reflector with respects to the primary reflector can be described in the horizontal and vertical separation distance between the focal points of both reflectors. An alteration in vertical separation from the optimum 18.5mm between the two reflectors resulted in a decrease in optical efficiency due to the irradiance distribution spreading out. Assuming a manufacturing positioning accuracy of ±0.1mm, the optical efficiency will vary by ±0.69% (absolute value).

An error in the horizontal positioning of the secondary reflector had a similar effect to the solar tracking inaccuracy where the irradiance distribution would be moved across the cell area in the opposite direction of the implemented error. Assuming again an accuracy of ±0.1mm resulted in an absolute optical efficiency error of ±1.09%.

Overall System Uncertainty:

The combination of errors is difficult to ascertain theoretically especially with sources of error not considered such as the final module enclosures glass cover reflectance, temperature variation within the enclosure, weather variation, time of day and site location. The direct addition of the uncertainties was employed to maximise uncertainty predictions and compensate for errors not considered, although the errors detailed earlier could compensate for each other if in the appropriate directions. A total uncertainty range of 12.68% was calculated for the optical efficiency of the optimised design considering solar divergence.

Conclusion

An optimised optical efficiency of (86.02 ± 12.68) % was found for the proposed two stage reflecting high concentrating photovoltaic module using ray trace modelling. The design will require a higher degree of manufacturing and tracking accuracy due to the use of two parabolic reflectors. Any theoretical optical modelling carried out for solar concentrator systems should always consider ±0.27° diverging light conditions due to the large difference in results for parallel light. Parabolic reflectors of large radiuses are desirable as the results obtained here suggest they greatly improve light manipulation control and so can obtain higher optical efficiency's and more uniform irradiance if used accordingly. Detailed optical efficiency optimisation as well as a comprehensive error analysis due to tracking and manufacturing uncertainty has also been carried out in this study. Experimental analysis of the designed concentrating system is to be carried out to validate theoretical modelling. It will also be interesting to investigate the effect of non-uniform distribution of energy flux and hot spot formation. The results presented provide a good characterisation of how the irradiance distribution is altered by design dimensions for parabolic reflectors and could be used to measure in detail the size and severity of hot spots with irradiance distribution uniformity.

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