THERMAL MANAGEMENT OF LOW CONCENTRATOR PHOTOVOLTAIC MODULES

JD Gerber, MA Benecke, FJ Vorster and EE van Dyk
Nelson Mandela Metropolitan University

Centre for Renewable and Sustainable Energy Studies

Abstract

Efficient thermal management of low concentrator photovoltaic (LCPV) modules ensures that the maximum power capabilities of the LCPV system are harnessed, and may substantially prolong the operating lifetime of the photovoltaic (PV) cells. A general understanding of the thermal transfer properties of PV modules is necessary to effectively design, construct, and implement viable LCPV systems.

The LCPV system under consideration uses a 7-facet reflector design and provides a geometric concentration of approximately 4.8X. The short circuit current increased by more than 300% under concentration, but cell temperatures in excess of 80°C were recorded without a thermal management system.

A thermal model based on one-dimensional heat transfer was developed and includes various energy dissipation mechanisms, such as convection and radiation. The results discussed in this paper will aid the design of a thermal management system to reduce the PV module temperature and maximize power output.

1. Introduction

Concentrator photovoltaic (CPV) systems use refractive or reflective optical elements to concentrate a large amount of solar energy onto a small area of PV material. CPV systems are therefore capable of substantially reducing the cost of electricity production. However, the increased temperature associated with these CPV systems places substantial strain on the PV module which may lead to rapid degradation. The open circuit voltage of the PV module is also reduced during these high temperature conditions, which leads to a corresponding loss in power output.

For these reasons, it is essential to gain an understanding of the energy transfer mechanisms of LCPV systems. A thermal model was developed to mathematically illustrate the various thermal transfer and dissipation mechanisms which occur within a LCPV system. In addition, an optical analysis of the LCPV system is also necessary to quantify the amount of energy incident on the PV module. Once the energy transfer mechanisms are adequately understood a thermal management system should be developed to combat the high temperature conditions associated with LCPV systems.

The purpose of this article is to discuss a LCPV system design which includes optical, electrical and thermal sub-systems, whilst focussing on the thermal properties needed to design a thermal management system in the future.

3.   Proposed model

3.1   Optical and electrical

The CPV system under investigation uses a 7-facet reflector system, providing a geometric concentration ratio of 4.8 (X_g=4.8). The reflector material has a reflectivity of approximately 0.9 within the photovoltaic sensitive electromagnetic spectrum. Theoretically an effective concentration ratio of 4.32 (X_e=4.32) is thus expected.

The PV module under investigation consists of 6 series connected mono-crystalline silicon cells. These cells are attached to an aluminium sheet using a thermally conductive and electrically insulating bonding material. Figure 1 shows the LCPV reflector design and the position of the PV module.
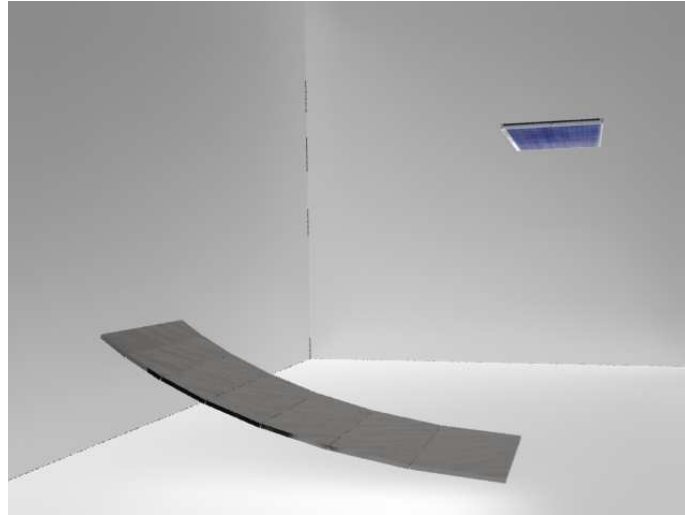

Figure 1: Conceptual LCPV design

3.2   Thermal

The thermal model is based on the conservation of energy. Irradiance is the only incoming source of energy and is assumed to be constant over the entire cell area. According to the thermal model, energy may be dissipated through convection, radiation and used to perform electrical work. A small percentage of the energy may also be lost through reflection from the cell surface. All energy transfer mechanisms are assumed to be one-dimensional. Figure 2 shows the energy transfer mechanisms associated with a LCPV system.
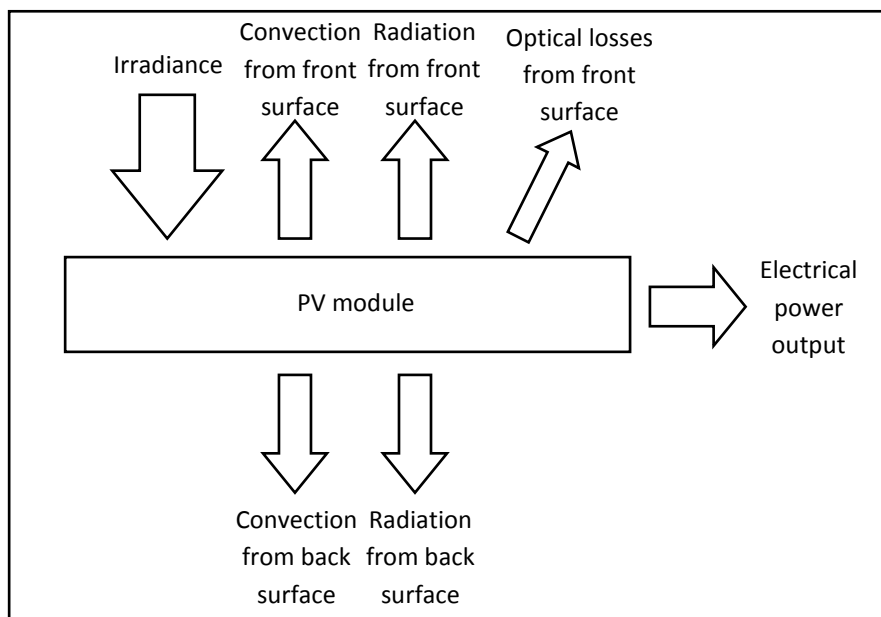

Figure 2: Thermal model

The thermal model can be used to quantify the energy dissipation and transfer under thermal equilibrium conditions when the temperature of the PV module is relatively constant.

At thermal equilibrium:

$$Q_{in} = Q_{out}$$

$$Q_{irr} = Q_{opt} + Q_{rad} + Q_{con} + Q_{elec}$$

In order to avoid mechanical damage and shading of the PV cells it is favourable to measure the temperature at the back of the PV module. The temperature of the front of the PV module can be easily solved via the thermal conductivity principles.

Energy dissipation through convection and radiation may be determined by the following equations:

$$Q_{rad} = A\varepsilon\sigma\left(T_b^4 - T_a^4\right)$$

$$Q_{con} = Ah(T_b - T_a)$$

h is the convective energy transfer co-efficient.

It is advantageous to calculate the energy dissipated through convection by monitoring the air flow and temperatures within the LCPV system. Owning to the complex geometry of the LCPV system, a complicated air flow pattern develops and thus calculation of h is not recommended. The energy dissipated through convection may then be determined by the following equation:

$$Q_{con} = \frac{\Delta m}{\Delta t} C (T_{out} - T_{in})$$

Q is the energy absorbed/dissipated per unit time by irradiance, convection, radiation and electrical work respectively.

4.   Research methodology

The constructed LCPV system was housed in an insulated box and mounted on a 2-axis tracker for all optical, electrical and thermal measurements. A current-voltage measurement system was used to obtain the IV characteristics of the PV module under standard and concentration conditions. This data was used to analyse the optical and electrical characteristics of the LCPV system. K-type thermocouples were used to measure the temperature of the back of PV module as well as the air temperature in 6 different areas within the LCPV system. Panel fans were used to simulate air flow across the PV module. This temperature data was used to determine the increase in air temperature as convection occurred from the surface of the PV module. Figure 4 shows the method used to calculate energy dissipated through convection.
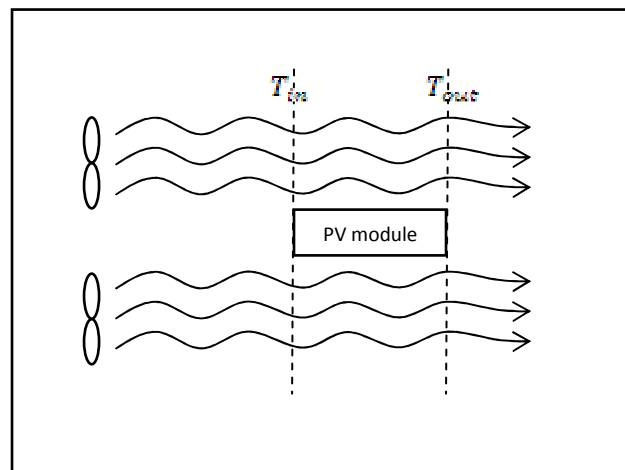

Figure 3: Convective energy dissipation analysis
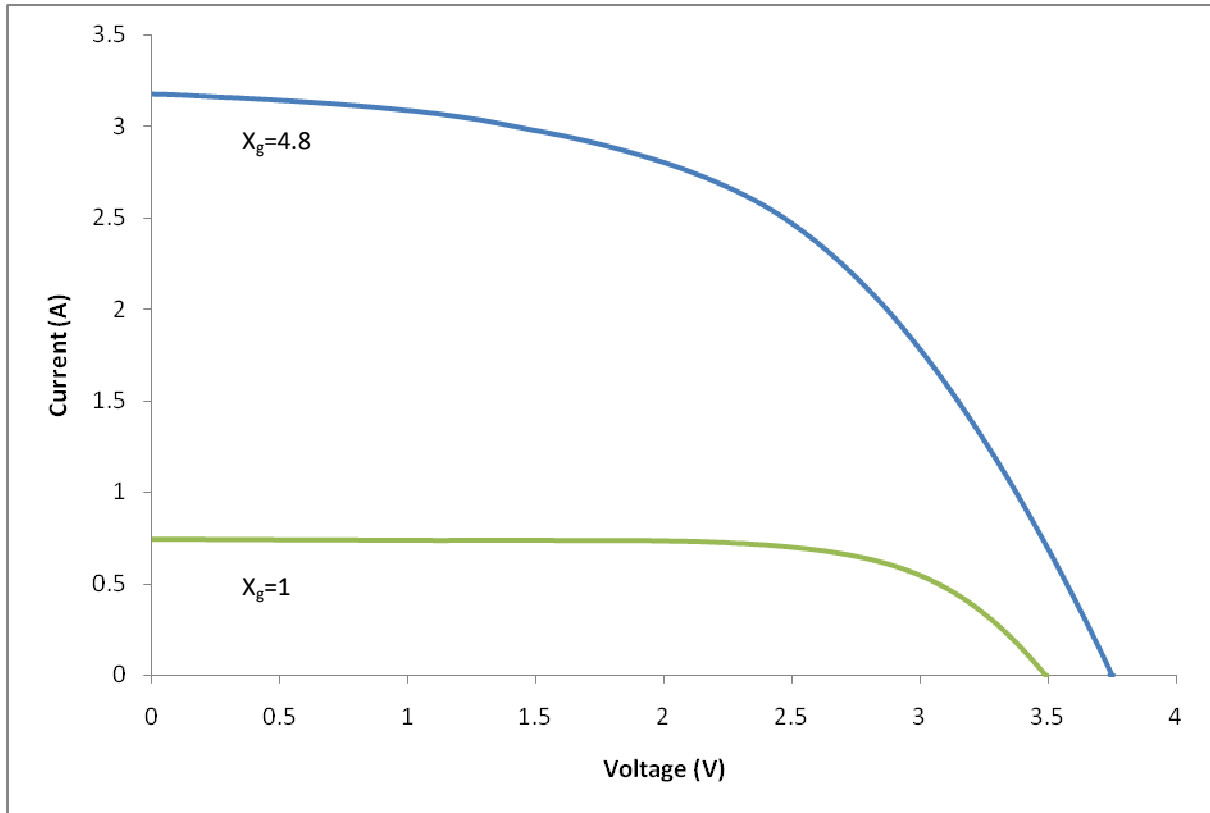
5. Results
5.1 Optical and electrical

Figure 4: IV characteristics under standard and concentration conditions at solar irradiance of 1000 W/m^2

Table 1: Geometric and effective concentration ratios of LCPV system

	$X_g=1$	$X_g=4.8$	Experimental X_e	Theoretical X_e
Short Circuit Current (A)	0.74	3.18	4.30	4.32
Power (W)	1.79	6.18	3.45	

Figure 4 shows the IV characteristics measured at geometric concentration ratios of 1 and 4.8 respectively. Table 1 shows the effective concentration ratios associated with short circuit current (I_{sc}) and power. The experimental concentration ratio is almost identical to its theoretical counterpart when analysed with respect to I_{sc}. This result indicates a satisfactory optical design and construction. However, the experimental concentration ratio with respect to power is lower than expected. This observation may be explained by increased resistive loses at higher currents.
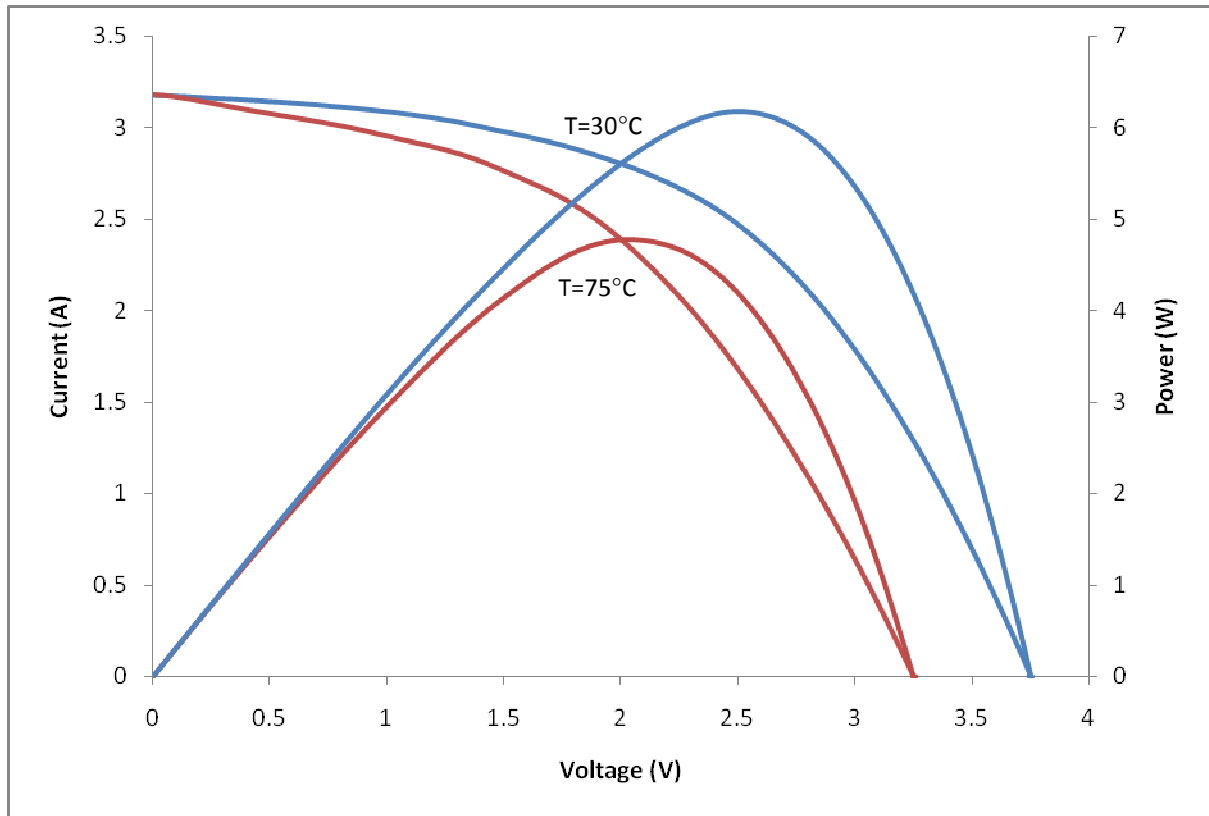
5.2 Thermal

Figure 5: IV characteristics showing power loss at elevated temperatures

Table 2: Open circuit voltage and maximum power losses at elevated temperatures

	30℃	75℃	% Loss
Open Circuit Voltage (V)	3.75	3.25	13
Power (W)	5.66	4.38	23

Figure 5 shows the IV characteristics measured at 30℃ and 75℃ respectively. Table 2 shows the open circuit voltage (V_{oc}) and power losses associated with higher operating temperatures. The power capabilities of the LCPV system are reduced by almost a quarter when operating at higher temperatures. These results clearly illustrate the need for an efficient thermal management system to maximize the power output of a LCPV system.

Table 3: Thermal analysis of LCPV system

Irradiance	850 W/m²
Concentration ratio	4.14
Effective irradiance	3419 W/m²
PV Cell temperature	60°C
Radiation	295 W/m²
Air temperature difference	2.2°C
Air flow speed	1 m/s
Convection	3020 W/m²
Total energy dissipated	3315 W/m²

Table 3 shows the various parameters evaluated to analyse energy dissipation within the LCPV system. PV cell temperature is assumed to be the same as the back of PV module temperature due to the high thermal conductivity of the materials used. Radiation accounts for a small amount of the dissipated energy. A large amount of energy is dissipated through convection. The remainder of the energy is most likely dissipated in the form of reflection. For this reason it would be advantageous to design a thermal management system which maximizes convective energy dissipation. Such a thermal managements system may include heat sinks and forced air flow. According to the data in table 3, an appropriate empirical convective energy transfer co-efficient is 43 W/m.K. This indicates that a heat sink with an effective fin area of approximately twice the PV module area is required to maintain a cell temperature of 40°C. Further cooling will als o be provided by forced air flow.

6.   Conclusion

The LCPV system under investigation had an effective I_{sc} concentration ratio of 4.30, which agreed very well with the theoretical prediction. The LCPV system managed to increase the power output by approximately 250%. However, the high temperatures associated with the LCPV system reduced the power output by 23%. Convection is the dominant form of energy dissipation in the LCPV system, accounting for more than 85% of the energy dissipated. For this reason, heat sinks and forced air flow are suggested to combat the high temperatures.

7.   References

1)   "Fundamentals of Heat and Mass Transfer", Fourth Edition, FP Incropera and DP DeWitt
2)   "Investigation of Low Concentrator Photovoltaic Modules and Systems", MSc Dissertation, 2010, BA Butler