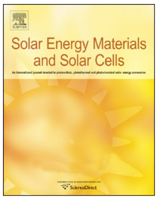
Solar Energy Materials & Solar Cells 153 (2016) 164–178

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat



Performance, limits and economic perspectives for passive cooling of High Concentrator Photovoltaics

Leonardo Micheli [a,*], Eduardo F. Fernández [b,c], Florencia Almonacid [b,c], Tapas K. Mallick [a], Greg P. Smestad [d]

[a] Environment and Sustainability Institute, University of Exeter, Penryn Campus, Penryn TR10 9FE, UK
[b] Centre for Advanced Studies in Energy and Environment, University of Jaen, Las Lagunillas Campus, Jaen 23071, Spain
[c] IDEA Solar Energy Research Group, University of Jaen, Las Lagunillas Campus, Jaen 23071, Spain
[d] Sol Ideas Technology Development, San José, CA 95150, USA

ARTICLE INFO

Article history:
Received 26 November 2015
Received in revised form
25 February 2016
Accepted 10 April 2016

Keywords:
Thermal materials
High Concentrator Photovoltaics
Cell temperature
Passive cooling
Electrical performance
Energy economics

ABSTRACT

This paper provides an analysis of the benefits of passive cooling for High Concentrator Photovoltaic (HCPV) systems in terms of costs and kWh annual energy yields. For the first time, the performance of the heat sinks has been related to the calculated energy yield of a standard triple-junction GaInP/GaAs/Ge HCPV cell in a system deployed at several suitable locations across the globe. Copper and aluminium heat sinks have been considered and their merits have been compared. The finite element analysis software package COMSOL was employed to gain insights regarding a simple flat plate heat sink. The cell temperature was found to have a linear dependence on the geometric concentration with a characteristic slope that increases with cell size (ranging from 10 to 0.25 mm). The results show the advantages of miniaturisation, and that the cooling of smaller cells can be accomplished using flat heat sinks. Within the considered range of geometric concentration ratios (up to 1000 ×), aluminium heat sinks are, in general, found to be preferred over copper, because of their lower densities and costs for the same thermal management. Closed-form thermal models based on the Least-Material (LM) approach have been utilised to design more complex finned heat sinks (operated under natural convection) that yield the best compromise between thermal performance and weight. For a 60 °C cell operating temperature, a greater kWh output is obtained, but an LM heat sink designed for a cell temperature of 80 °C has a material cost per unit energy that is between 50% and 70% less than the one designed for 60 °C. Heat sink costs between \$0.1 and 0.9 per W_p were estimated for a geometric concentration above 500 suns, depending on the cell's temperature and size. There are strong reductions in HCPV installation costs by limiting the dimensions of the cooling system at high concentrations.

1. Introduction

High Concentrator Photovoltaic (HCPV) systems use lenses or mirrors to concentrate sunlight by more than three hundred times on a solar cell [1,2]. For HCPV systems, the employment of high-efficiency multijunction (MJ) cells becomes more convenient than using large area traditional silicon cells [3]. Impressive progress has been recently reported with regard to MJ cells, which have achieved record-efficiencies up to 46% [4]. Despite this development, the largest part of the incoming solar energy is still converted into heat, which can lead to an increase in cell temperature [5,6]. Any photovoltaic cell is negatively affected by the increase of temperature and this becomes a non-negligible concern in HCPV systems, due to the high current densities and heat fluxes experienced [7]. Therefore, HCPV systems are generally coupled to a cooling system, able to remove the heat generated by the cell and to transfer it to an external medium. In order to keep the HCPV cells at temperatures ranging between 50 °C and 80 °C [8,9], different cooling systems have been proposed and explored experimentally in the past [10–13]. The present work focuses on passive cooling systems, as those solutions do not require any electrical or mechanical energy input to operate. Passive cooling technologies have been proved able to successfully handle the thermal management of single cell HCPV modules at high and ultra-high concentrations [13–17], thanks to the large surface available for heat transfer.

HCPV modules are typically placed on trackers. Since they use only the direct component of the sunlight, they have to follow the

---

* Corresponding author. Tel.: +44 0 1326259478.
E-mail addresses: l.micheli@exeter.ac.uk (L. Micheli), fenandez@ujaen.es (E.F. Fernández), facruz@ujaen.es (F. Almonacid), t.k.mallick@exeter.ac.uk (T.K. Mallick), inquiries@solideas.com (G.P. Smestad).

http://dx.doi.org/10.1016/j.solmat.2016.04.016

Nomenclature

Symbol	Definition units
A	area (m$^{2)}$
C_{geo}	geometric concentration (×)
C_{m}	cost per unit of mass (USD/kg)
c_{macHS}	cost of machined heat sink (USD)
DNI	Direct Normal Irradiance (W/m$^{2)}$
E	annual energy yield (kWh)
E_{b}	incident direct normal spectral distribution (W/m^2 nm)
$E_{\mathrm{b,\ ref}}$	direct reference spectrum (W/m^2 nm)
$F_{\mathrm{i,j}}$	view factors between the surfaces i and k ($0 \le F_{\mathrm{i,j}} \le 1$) (dimensionless)
g	gravitational acceleration (m/s$^{2)}$
H	fin height (m)
h_{c}	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
L	fin length (m)
l	distance between the heat source and the heat sink (m)
L^*	characteristic length (m)
LCOE	levelised cost of the electricity ($/kWh)
MBE	mean bias error (%)
N	useful life of the system years
n_{fin}	number of fins (dimensionless)
p	pitch of the fin array (m)
P	electrical power output (W)
Pr	Prandtl number (dimensionless)
Q	heat power (W)
R	thermal resistance (K/W)
Ra_{L}	Rayleigh number (dimensionless)
RMSE	root mean square error (%)
s	spacing between fins (m)
SF	spectral factor (dimensionless)
SR	spectral response (A/W)
t	fin thickness (m)
T	temperature (K)
T^*	nominal temperature (K)
t_{b}	fin base thickness (m)
TF	thermal factor (dimensionless)
W	fin base width (m)

Greek letters

α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient of air (1/K)
γ	power temperature coefficient (%/K)
ε	emissivity ($0 \le \varepsilon \le 1$) (dimensionless)
η_{cell}	cell electrical efficiency ($0 \le \eta_{\mathrm{cell}} \le 1$) (dimensionless)
η_{fin}	fin efficiency ($0 \le \eta_{\mathrm{fin}} \le 1$) (dimensionless)
η_{opt}	optical efficiency ($0 \le \eta_{\mathrm{opt}} \le 1$) (dimensionless)
θ_{b}	difference of temperature between the heat sink and the ambient (K)
ν	mean kinematic viscosity of air (m^2/s)
ρ	density (kg/m$^{3)}$
σ	Stefan–Boltzmann constant (W/m^2 K$^{4)}$

Subscripts

amb	ambient
c	convection
cell	cell
HS	heat sink
k	conduction
opt	optimal value according to the LM approach
surr	surrounding fluid

Abbreviations

AM	Air Mass
DBC	Direct Bonded Copper
HCPV	High Concentrator Photovoltaics
LM	Least-Material (approach)
MJ	Multi-Junction (cells)

Sun's apparent motion in order to keep the direct component of sunlight focused on the cells [18]. This said, limiting the weight of the tracked components becomes particularly important in order to reduce the load on the tracker and thus its energy consumption and its volume. Along with the intrinsic weight of the system, the tracker is required to withstand wind forces, whose torque effect increases with the weight of the solar modules and the supporting structure [19]. Misalignments between the optics and the cells, caused by the actions of wind on the trackers, can strongly affect the energy production [20]. So, in addition to the lower energy consumption, a reduced weight of the module would allow reducing the cost of fabrication of the tracker, since less material would be required to support lighter structures. Heat sinks are generally made of aluminium, which can represent more than 60% of the weight of an HCPV system [21]. Therefore, the best compromise between the weight and the performance of the heat sink has to be realized in order to limit the load on the tracker and, at the same time, to enhance the electrical output of the HCPV system. Moreover, the contribution of the heat sink to the cost of the energy cannot be neglected [22]. Recent studies [23,24] concluded that HCPV can already be more profitable than standard flat PV in high Direct Normal Irradiance (DNI) regions. Additional reductions in cost have to be achieved in order to further improve the cost competitiveness of HCPV. Optimised, light-weight passive heat sinks can positively affect the cost of HCPV by reducing the volumes of the materials, minimising the energy consumption of the tracker and enhancing the electrical performance of the cells.

One of the most common passive cooling solutions in HCPV is the use of a metal plate heat sink. Araki et al. [15] first demonstrated the possibility of cooling a 500x cell by using an aluminium plate. Min et al. [25] proposed a model to predict the behaviour of a single 3 mm × 3 mm cell by taking into account a fixed heat transfer coefficient of 5 W/m^2. Renzi et al. [26] studied the outdoor performance of a 5.5 mm × 5.5 mm cell under a geometric concentration of 476 ×. The authors found that the aluminium plate reached a temperature between 55 °C and 65 °C, but no information on the cell temperature was given. Gualdi et al. [27] showed that flat plates can keep cells with dimensions smaller than 4 mm below a temperature of 80 °C. The use of fins is considered the easiest way to enhance the heat transfer between a surface and a surrounding fluid [28]. Fins are widely used in several fields where cooling is required [29], from electronics to industrial applications. The use of fins has been investigated for CPV applications [30–32]. Natarajan and his collaborators [30] showed that fins are a more effective way to reduce the solar cell temperature than a flat back plate and identified the optimum fin dimensions for a 10 × CPV system. Do et al. [31] experimentally investigated the behaviour of passive finned heat sinks for different tilt angles. The authors