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Multiphysics modelling and experimental validation of high concentration photovoltaic modules

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ABSTRACT

High concentration photovoltaics, equipped with high efficiency multijunction solar cells, have great potential in achieving cost-effective and clean electricity generation at utility scale. Such systems are more complex compared to conventional photovoltaics because of the multiphysics effect that is present. Modelling the power output of such systems is therefore crucial for their further market penetration. Following this line, a multiphysics modelling procedure for high concentration photovoltaics is presented in this work. It combines an open source spectral model, a single diode electrical model and a three-dimensional finite element thermal model. In order to validate the models and the multiphysics modelling procedure against actual data, an outdoor experimental campaign was conducted in Albuquerque, New Mexico using a high concentration photovoltaic monomodule that is thoroughly described in terms of its geometry and materials. The experimental results were in good agreement (within 2.7%) with the predicted maximum power point. This multiphysics approach is relatively more complex when compared to empirical models, but besides the overall performance prediction it can also provide better understanding of the physics involved in the conversion of solar irradiance into electricity. It can therefore be used for the design and optimisation of high concentration photovoltaic modules.

1. Introduction

High Concentration Photovoltaic (HCPV) technology aims to reduce the cost of electricity by replacing the amount of expensive semiconductor material with relatively less expensive optical elements [1]. Although the room for improvements is still large, this technology has already shown promising results at locations with high solar energy resource and favourable economic scenarios [2].

Nowadays, photovoltaic concentrators are largely based on high efficiency multijunction III-V solar cells made up of several p-n junctions, usually a lattice-matched gallium indium phosphide/-gallium indium arsenide/germanium (GaInP/GaInAs/Ge) structure to improve the absorption of the spectrum, and thus, to increase the cell efficiency (η_{cell}) [3]. The optical configuration usually consists of primary and secondary optical elements. The primary optics concentrate the irradiance, while the secondary optics aim to improve the uniformity of the light on the solar cell surface and to increase the acceptance angle of the module [4]. In addition, concentrators typically use a passive cooling mechanism to remove waste heat from the cells [5].

As in any other type of power generation, the modelling of the electrical output of HCPV technology is crucial for optimisation [6] and monitoring purposes. Moreover, such models are useful for the evaluation of the profitability and competitiveness of the HCPV technology [7]. The electrical modelling of HCPV is inherently different and more complex, and the understanding of the performance under real operating conditions is clearly lower [8] compared to conventional photovoltaics. The performance of concentrator modules is strongly affected by spectral variation due to the use of multijunction solar cells and optical assemblies [9]. Moreover, the current-voltage (I-V) characteristics are significantly affected by the input irradiance and operating cell temperature (T_{cell}) [10]. The direct measurement of T_{cell} of HCPV modules is not possible in the majority of cases without damaging the concentrator due to supporting elements surrounding the cell. As such, T_{cell} measurements are usually estimated by using indirect methods, i.e. methods based on direct electrical measurements on the concentrator and methods based on atmospheric parameters [11].

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Nomenclature

A_{cell}	cell area, mm^2
AM	air mass
AOD	aerosol optical depth
C_p	heat capacity, J/(kg K)
CR_{geo}	geometric concentration ratio
DNI	direct normal irradiance, W/m^2
EQE	external quantum efficiency
FF	fill factor
GNI	global normal irradiance, W/m^2
h	conv. heat transfer coeff., W/(m^2 K)
I	current, A
k	thermal conductivity, W/(m K)
n	diode ideality factor
P_{mp}	maximum power output, W
PW	precipitable water, cm
q_{heat}	heat power, W
R_s	series resistance, Ω
T	temperature, °C
T_{SoG}	transmittance of SoG
V	voltage, V
WS	wind speed, m/s

Greek letters

γ	constant
η	efficiency
κ	constant A/(cm^2 K^4)
λ	wavelength, nm
ρ	density, kg/m^3

Subscripts

amb	ambient
HS	heat sink
in	inside the monomodule
mp	maximum power
oc	open-circuit
opt	optical
sc	short-circuit

Abbreviations

Ag	silver
Al_2O_3	aluminium oxide or alumina
AlN	aluminium nitride
ARMSE	absolute RMSE
BPI	Black Photon Instruments
CSTC	Concentrator Standard Test Conditions
CTJ	concentrator triple-junction
Cu	copper
DBC	direct bonded copper
FEA	finite element analysis
GaInAs	gallium indium arsenide
GaInP	gallium indium phosphide
Ge	germanium
GMRES	Generalised Minimal RESidual method
HCPV	high concentrating photovoltaic
MAE	mean absolute error
MBE	mean bias error
N	number of datapoints
NRMSE	normalised RMSE
RA	receiver assembly
RMSE	root mean square error
Si	silicon
SMARTS2	Simple Model of the Atmospheric Radiative Transfer of Sunshine, version 2
Sn	tin
SoG	silicon-on-glass
TC	thermocouple
TIM	thermal interface material

Bearing the above in mind, the scientific community has devoted considerable efforts in developing models tailored to the specific features of HCPV technology [12]. Empirical models based on outdoor measurements have been published elsewhere: examples include models based on the direct normal irradiance (DNI), Z-parameter and module temperature [13]. Another model reported in literature is based on the DNI, ambient temperature (T_{amb}) and air mass (AM) [14]. Nevertheless, the majority of such models are focused on the estimation of the maximum power (P_{mp}) [15]. These methods are easy to implement by solar test labs and manufacturers but require an experimental setup to obtain the regression coefficients. A disadvantage of these models is that, since they do not take into account the detailed geometry, materials and design of the modules, they do not consider the fundamental relationships implicated in the electrical conversion of the concentrator modules. This usually leads to a poor understanding of the HCPV device under study and therefore, module optimisation is not possible [16]. One of the most advanced models that takes into account the geometry and physical mechanisms of a HCPV system is the YieldOpt [17]. This model combines SMARTS2 (The Simple Model of the Atmospheric Radiative Transfer of Sunshine, version 2) [18] which simulates the input spectral irradiance, ray tracing and a finite element analysis (FEA) model to calculate the spectral optical efficiency as a function of temperature, and a SPICE network model to calculate the I-V characteristics. A function to calculate the external quantum efficiency (EQE) at any temperature is also included. YieldOpt also takes into account the alignment of the tracker and module. The P_{mp} prediction is then corrected to compensate for other losses that occur in the field, such as the losses due to inhomogeneous irradiance on the solar cell's surface. Steiner et al. [17] reported very low normalised root mean square errors (NRMSE, between 2.6% and 3.9%) in the P_{mp} predictions. The disadvantage however of this integrated modelling approach is the requirement of a large set of outdoor equipment, the lack of information regarding the coupling of ray tracing with the FEA model and also the heat transfer [19] within the module is not considered. Another advanced model is the Syracuse which was used by Chan et al. [20] to calculate the performance of a CPV module in Japan. The model was extended to include aerosol optical depth (AOD) and precipitable water (PW); the latter was calculated by the relative humidity and T_{amb}. The atmospheric parameters were then imported to SMARTS2 [18] to calculate the DNI. A function is incorporated to calculate the EQE at varying temperature. The model accounts for non-uniformities on the solar cell's surface. It was concluded that the modelling procedure can predict the energy yield of a CPV system within 2%. The Syracuse model [21] simulates the operation of a solar cell using fundamental physics and therefore a detailed knowledge of the composition and structure of the multijunction solar cells is required. In addition, outdoor measurements are required to obtain some of the parameters and details about the T_{cell} estimation are not provided.