Energy 87 (2015) 77–85

Contents lists available at ScienceDirect

Energy

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

Model for estimating the energy yield of a high concentrator photovoltaic system

Eduardo F. Fernández [a, b, *], P. Pérez-Higueras [a, b], F. Almonacid [a, b], J.A. Ruiz-Arias [a, c], P. Rodrigo [d], J.I. Fernandez [a, b], I. Luque-Heredia [e]

[a] Centre of Advanced Studies in Energy and Environment, University of Jaen, Campus Las Lagunillas, Jaen 23071, Spain
[b] IDEA Research Group, University of Jaen, Campus Lagunillas, 23071 Jaen, Spain
[c] MATRAS Research Group, University of Jaen, Campus Lagunillas, 23071 Jaen, Spain
[d] Engineering Faculty – Panamericana University, 101 Josemaría Escrivá de Balaguer, 20290 Aguascalientes, Aguascalientes, Mexico
[e] BSQ Solar, C/ del Vivero 5, Madrid 28040, Spain

ARTICLE INFO

Article history:
Received 29 December 2014
Received in revised form
16 February 2015
Accepted 21 April 2015
Available online 23 May 2015

Keywords:
HCPV systems
Modelling
Energy yield
Outdoor characterization

ABSTRACT

The prediction of the energy yield of HCPV (high concentrator photovoltaic) systems is crucial to evaluate the potential and promote the market expansion of HCPV technology. Currently, there is a lack of experience in the modelling of these kinds of systems due to the special features of such technology. In this work, a practical model based on simple mathematical expressions and atmospheric parameters is introduced. The proposed model takes into account the main important parameters which influence the output of a HCPV system such as cell temperature, spectrum and efficiency of the inverter and other losses of the BOS (balance of system). The results obtained are validated using the data of a HCPV installation located at the University of Jaen in southern Spain and monitored daily every minute since 2011. The model accurately predicts the monthly energy yield with a deviation ranging from 4.07% to −0.47% and the annual final energy yield with a deviation of 0.9%.

1. Introduction

The aim of HCPV (high concentrator photovoltaic) technology is to decrease the cost of electricity by reducing the semiconductor material by the use of cheap optical devices [1]. Nowadays, HCPV technology is largely based on the use of high efficiency III–V MJ (multi-junction) solar cells. These cells consist of several junctions (usually three) with different band gap energies for maximizing the absorption of the incident solar irradiance in order to increase the efficiency of the device [2,3]. MJ solar cells play an important role in HCPV technology because they are the part of the system which has more influence on the final efficiency. Because of these, MJ solar cells based on new materials and more junctions are continuously being under study [4–8]. Usually, the optical devices consist of a POE (primary optical element), usually Fresnel lenses, and a SOE (secondary optical element). The POE collects direct sunrays and concentrates them on the solar cell surface, and the SOE receives the light from the primary one to homogenize light and improve the angular acceptance angle [9,10]. A HCPV module is made up of a particular number of MJ solar cells and optical devices, and peripheral components necessary to generate electricity and dissipate the heat produced due to the high temperatures achieved by the solar cells working under concentration. Passive cooling is used in the majority of the cases because of its simplicity and reliability. There are a large number of configurations in order to implement a grid connected system, however the typical system consists of several HCPV modules interconnected in series and parallel mounted on a high accuracy pedestal two-axis solar tracker connected to a high efficiency inverter and other BOS (balance of system components) [11–13]. Due to the efficiencies forecasted and already reached by MJ solar cells, HCPV modules and systems [14–18], HCPV represents a potential alternative technology to conventional flat photovoltaic systems in the energy generation market with a cumulative installed capacity that could go from 358 MWp in 2014 to more than 1 GWp in 2020 [19].

As in other type of energy production system, the estimation of the energy yield of HCPV systems is a crucial task for designing, monitoring, life cycle assessment and to analyse the economic profitability of such technology and therefore to evaluate its

* Corresponding author. IDEA Research Group, University of Jaen, Campus Lagunillas, 23071 Jaen, Spain. Tel.: +34 953213518.
E-mail address: fenandez@ujaen.es (E.F. Fernández).

http://dx.doi.org/10.1016/j.energy.2015.04.095
0360-5442/

potential and promote its market expansion [20–24]. However, at the present the models tailored to the special features of this technology and their validation with real data of HCPV systems are scarce [25,26]. In Ref. [25] a model to predict the system output developed by Amonix Inc. based on the spectral response of MJ solar cells, spectral irradiance, transmission losses, soiling and other losses of the system is outlined. However, the procedure used to estimate the energy output based on the parameters commented is not given, and therefore the application of that procedure is only limited at the Company. The model is validated with real data of a system located at Nevada (USA) during 2009 and 2010 over 16 months. Also, although the accuracy of that model is not questioned here, a detailed analysis of the performance of the model is not reported. In Ref. [26] a simple and useful model based on atmospheric parameters and different empirically obtained coefficients for predicting the average hourly AC power of a HCPV system is introduced. The output is derived from the AC power of the system under standard irradiance and temperature conditions as a linear function of the direct normal irradiance with two additional corrections in module temperature and spectrum (through the air mass). The authors make several assumptions such as the consideration that the rest of the losses of the system are lumped in the AC the power of the system under reference conditions. The performance of the model is validated with the average hourly AC power of a HCPV system located at Sede Boqet (Israel) for two weeks (first weeks of June and December).

In this paper, a detailed model for the prediction of the energy yield of a HCPV system based on atmospheric parameters in order to facility its application at a desired location is introduced. The energy output of a system is calculated from the peak power of a HCPV module using simple mathematical expressions which takes into account the main parameters that affect the output of a HCPV system. The cell temperature influence is quantified as a function of air temperature, direct normal irradiance and wind speed. The spectral effects are taken into account with a correction based on air mass. Also, an additional spectral correction based on aerosol optical depth for locations with high turbidity is proposed. The model also considers the instantaneous variations of the efficiency of the inverter as a function of the input DC power. Furthermore, other additional losses of the DC part and the AC part of a HCPV system are taken into account and considered separately. A detailed description of the procedure to estimate all the coefficients necessaries for the application of the model is also provided. The results in the estimation of the energy yield of a HCPV system are validated using the measured data of an installation with a nominal power of 1.35 kWp, located at the campus of the University of Jaen in southern Spain and monitored daily every minute since 2011.

2. Model description

In this section, the model for estimating the energy yield of a HCPV system is introduced. This section is divided in two subsections. In the first subsection, the model of the DC part of a system is proposed and derived from the model of a HCPV module. In the second subsection, the AC part of a system is modelled and the final model for the estimation of the energy yield of a HCPV system is proposed.

2.1. Modelling of the generator

A typical HCPV generator consists of several modules interconnected in series and parallel mounted on a two-axis solar tracker. The first step for modelling the output of a HCPV generator is the finding of an accuracy and simple equation for the estimation of the maximum power of a HCPV module (P_{module}) based on atmospheric parameters. The maximum power of a HCPV module can be expressed with the following function [27,28]:

$$P_{module} = f(DNI, T_{cell}, S_b) \tag{1}$$

where DNI is the direct normal irradiance, T_{cell} is the cell temperature and S_b is the spectral distribution of the direct normal solar irradiance. Taking this into account, the maximum power of a HCPV module can be easily estimated with the following equation [29]:

$$P_{module} = \frac{P^*}{DNI^*} DNI\left(1 - \delta\left(T_{Cell} - T^*_{cell}\right)\right)(1 - \varepsilon(AM - AM_U)) \tag{2}$$

where P^*, DNI^*, T^*_{cell} are the maximum power, direct normal irradiance and cell temperature at reference conditions; δ is the cell temperature coefficient of the maximum power, AM is the air mass, ε is the air mass coefficient of the maximum power of a HCPV module and AM_U is defined as the umbral air mass. This equation estimates the maximum power as a function of the irradiance and cell temperature using the well-known equation used in conventional photovoltaic technology [30,31] with an additional spectral correction based on air mass. Several experiments over different HCPV modules from different manufacturers have demonstrated that the influence of air mass can be considered negligible for $AM \leq AM_U$ and can be corrected with a linear coefficient for $AM > AM_U$ [29,32,33]. The rationale behind this can be found in Ref. [34] where the influence of different atmospheric parameters on the performance of different HCPV modules has been investigated. For low AM values, the top and middle junctions of the MJ solar cells almost generate the same current (current-matched condition) and because of this the influence of AM on the power output of HCPV modules is almost negligible. However, as the AM increases the top junction starts limiting the current resulting on an overall linear decreasing of the performance of HCPV modules.

Equation (2) has been used to predict the power output of several HCPV modules in different climate conditions showing an accurate match between actual and estimated data [35]. However, although AM is the main atmospheric parameter that affect the spectral distribution and the performance of HCPV modules, there are other parameters which could affect their electrical output [36]. In particular, AOD (aerosol optical depth) has shown a non-negligible effect at locations with high turbidity [37,34]. Because of this, Equation (2) could have an important uncertainty at sites with extremely high aerosol optical depth values. Hence, it is appropriate to introduce an AOD correction in this equation. The influence of AOD on the performance of HCPV modules has been also studied in Ref. [34] and the same behaviour than under AM variations has been found. The influence on the performance of HCPV modules for low AOD values is almost negligible since the top and middle junctions of the MJ solar cells generate almost the same current (current-matched condition). Also, as the AOD increases the top junction starts limiting the current resulting on an overall linear decreasing of the performance of HCPV modules. Taking this into account, Equation (2) could be rewritten with an additional AOD spectral correction as:

$$\begin{aligned} P_{module} = {} & \frac{P^*}{DNI^*} DNI\left(1 - \delta\left(T_{Cell} - T^*_{cell}\right)\right)(1 - \varepsilon(AM - AM_U)) \\ & \times \left(1 - \varphi\left(AOD_{550} - AOD_{550,U}\right)\right) \end{aligned} \tag{3}$$

where φ is the aerosol optical depth coefficient of the maximum power of a HCPV module, AOD_{550} is the aerosol optical depth at 550 nm and $AOD_{550,U}$ is the umbral aerosol optical depth at 550 nm