Solar Energy Materials & Solar Cells ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

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

Modeling the performance of low concentration photovoltaic systems

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ARTICLE INFO

Article history:
Received 16 April 2009
Received in revised form
8 March 2010
Accepted 11 March 2010

Keywords:
Photovoltaic
V-trough concentration
Model
Sensitivity analysis

ABSTRACT

A theoretical model has been developed to describe the response of V-trough systems in terms of module temperature, power output and energy yield using as inputs the atmospheric conditions. The model was adjusted to DoubleSun® concentration technology, which integrates dual-axis tracker and conventional mono-crystalline Si modules. The good agreement between model predictions and the results obtained at WS Energia laboratory, Portugal, validated the model. It is shown that DoubleSun® technology increases up to 86% the yearly energy yield of conventional modules relative to a fixed flat-plate system. The model was also used to perform a sensitivity analysis, in order to highlight the relevance of the leading working parameters (such as irradiance) in system performance (energy yield and module temperature). Model results show that the operation module temperature is always below the maximum working temperature defined by the module manufacturers.

1. Introduction

With the climate change and energy security on the agenda of many countries, photovoltaic (PV) energy appears as a potential solution for the production of clean energy. However, the high price of this technology has been inhibiting its expansion. One approach to reduce its price is to use concentrators that increases the amount of light that falls upon the cells. Since the current created by the photovoltaic cells is proportional to the irradiance on the cells, more light on the cells will increase the electrical output, and thus allowing a reduction of the area of modules (which are the most expensive component of a PV system) needed for the same output energy. The replacement of the expensive modules by cheaper optical materials (e.g. lens or mirrors) can lead to a reduction in PV electricity cost [1–4].

Concentrator photovoltaic (CPV) technologies are usually classified according to its concentration factor into: low, medium and high concentration systems [5,6]. Low concentration photovoltaic (LCPV) systems with concentration factor below 10 suns [6–8] present two main advantages: they can make use of conventional high-performance flat-plate PV modules (1 sun) without significant performance losses and they are less demanding in terms of tracking accuracy than the higher concentration systems [3]. The amount of reflected radiation falling upon the modules strictly depends on the clearness index of the location [6,9]. And therefore, these systems can lead to notorious gains in output energy of commercial PV modules when installed in locations where direct radiation is a significant percentage of the global radiation (South Europe, Northern Africa, Southern states of the USA, etc.).

In this work we present a line-focus concentrator [6] with a V-trough design. These type of concentrators are particularly attractive since they are simple to manufacture and can integrate conventional PV modules [4,7,10]. The main requirement of these designs is the homogeneous distribution of radiation over the modules, which is assured by the uniform reflection of the mirrors' surface and the sun trackers [4–8,11,12].

Taking into account the previous requests, DoubleSun® system (a V-trough low concentration system) was developed by WS Energia [13]. The system makes use of two mirrors (mainly reflecting in the band of PV modules spectral response [14]), which along with a two axes-tracking system (accuracy of 2°) warrants a homogeneous illumination of 4–5 commercial modules (depending on dimension).

In the first section of this work we present a theoretical model, which has been implemented in a Matlab® simulation. The model was adapted to DoubleSun® specifications and a comparison between theoretical and experimental data has confirmed model validation. Finally, a sensitivity analysis of the model is conducted, in order to identify the most relevant parameters determining the system performance.

2. Model

The purpose of the present model is to estimate the performance of a V-trough system integrating commercial

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doi:10.1016/j.solmat.2010.03.010

modules. Such performance was evaluated in terms of temperature of the module, output power and energy yield. The input parameters are: the ambient temperature (T_{amb}); direct/global irradiance ratio (i_c); irradiance (I), for both fixed and 2-axis tracking systems; and also the monthly average wind velocity (v). The former data sets are mean daily profiles for each month and were taken from [9] while the latter is a mean monthly value and was taken from [18].

The AC power of a V-trough PV system is given by

$$P_{AC} = I\delta C\delta T\varepsilon_{mod}A_{mod}\varepsilon_{inv} \tag{1}$$

where I is irradiance, δC is the concentration coefficient, δT is the temperature efficiency of the system, ε_{mod} is the module efficiency under STC conditions, A_{mod} is the area of the modules and ε_{inv} is the efficiency of the inverter (which is a function of the output power [15] but for simplicity it may be considered constant, see Table 1).

The concentration coefficient is defined as

$$\delta C = 1+(C-1)\varepsilon_{opt}i_c \tag{2}$$

with ε_{opt} being the overall efficiency of the optics (determined from the mirrors' reflectivity, ε_R, and the optical configuration including specified maximum misalignment of the tracking system), i_c is the ratio between direct and global irradiance and C is the concentration ratio, which is defined as the area of the receiver seen by the sun (i.e. effective area) divided by the area of the module [7]. This equation assumes that only the direct component of the irradiation is reflected from the mirrors onto the module. In practice this is not so, and it is expected that a fraction of the diffuse light will also be reflected to the module. However, this small effect is possibly offset by the fact that, due to the acceptance angle of the V-trough system (2°), a fraction of the diffuse light will be prevented from reaching the modules. These effects were not considered in the model.

The temperature efficiency of the system is defined as

$$\delta T = 1+\sigma_T(T_{mod}-T_{STC}) \tag{3}$$

where T_{mod} is the temperature of the module, T_{STC}, the reference temperature (25 °C) under standard test conditions (STC) and σ_T, the temperature coefficient of the module, which is assumed constant in the temperature range of interest. Without active cooling schemes, i.e. if refrigeration is realised only by heat exchange between the module and the surrounding area, the module temperature may be determined using

$$T_{mod} = T_{amb} + \frac{T_{NOCT}-20}{800+h(v-1)(T_{NOCT}-20)}I \tag{4}$$

where T_{NOCT} is the temperature cells will reach when operated at open circuit in an ambient temperature of 20 °C, irradiance on cell surface I=800 W/m^2 and a wind speed of less than 1 m/s, and h is a convection parameter and v is the wind velocity. In Eq. (4), the convection was considered as a linear function of wind speed, which is responsible for the forced convection between the surface and the surroundings. The parameter h=6.62 W/m^2 °C was determined using wind data for typical days at the chosen location; it was within the range cited in the literature [16].

The model was implemented for the standard DoubleSun® configuration (tracking+concentration), a 2-axis tracking but no concentration (C=1) and fixed flat-plate configuration. Regarding the fixed flat-plate, we have considered that the system is oriented towards the south, i.e. the azimuth angle is 0°, and tilted by 35°, which is the inclination that optimizes the yearly energy production in the location of analysis. The location of analysis is Oeiras, Portugal (38°41′50″N, 9°18′30″′W), which presents a sunny climate with average daily global irradiation of 4.5 kWh/m^2 in a horizontal plane and annual average ambient temperatures of about 16.6 °C.

3. Model results

3.1. System performance

Using the model one may determine the yearly accumulated energy of the DoubleSun® solar concentration system compared with the 2-axes tracking and a fixed flat-plate PV systems (Fig. 1). From the results one may infer that the overall increased energy output of the DoubleSun® solar concentration system with respect to the fixed flat-plate system with optimum inclination is 1.86X, which results from both the tracking (25%) and the concentration (50%).

It is also particularly interesting to observe the monthly variation of the gain in the energy output due to the tracking and concentration (Fig. 1b). The ratio between the 2-axes tracking and the fixed flat-plate system (dark squares) highlights the advantage of tracking: a factor of 1.1 in the winter and 1.4 in the summer. The ratio between the DoubleSun® and the 2-axis tracking system with no concentration (dark diamonds) is almost constant throughout the year, at about 1.5. The small seasonal variations observed are directly correlated to variations in the ratio between direct and global irradiance (higher in the summer) and inversely correlated to the ambient temperature (colder in winter). Finally, the ratio between the DoubleSun® and the fixed flat-plate system (white dots) results from the effect of the tracking and the concentration. The gain in energy output varies between 1.7 (in the winter: shorter days and more diffuse light) and 2.1 (in the summer: longer days and more direct radiation).

3.2. Model validation

Model results were validated by the data sets presented in [9]. Moreover, model results compared with experimental data for irradiance, module and ambient temperature, DC and AC power delivered, etc. were collected for a DoubleSun® PV system installed at WS Energia Laboratory, Oeiras, Portugal (38°44′32.89″N, 9°18′10.12″W). The following discussion refers to typical measurements taken on September 22, 2008. More complete data and experimental details are provided elsewhere [17].

Table 1
Model parameters of the systems used in the model: DoubleSun®, 2-axes tracking system and fixed flat-plate system.

Parameter	DoubleSun®	Flat-plate system with tracking	Flat-plate system fixed
A_{mod} (m^2)		3.54	
ε_{mod} (%)		16.0	
σ_T (%P_{max}/°C)		−0.30	
T_{NOCT} (°C)		44.2	
ε_{inv}		0.93	
ε_{opt}	0.84	–	–
C	1.94	1	1

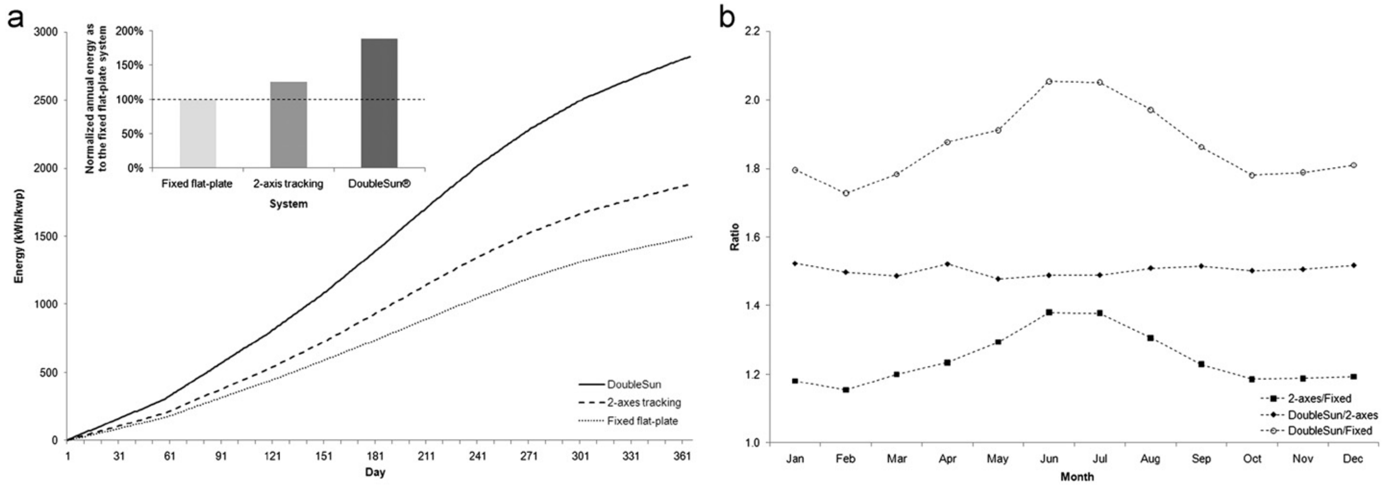

Fig. 1. Model results: (a) accumulated yearly energy produced by a fixed flat-plate, a 2-axes tracked PV system and DoubleSun® system; and (b) seasonal variation of the gain in the output energy.

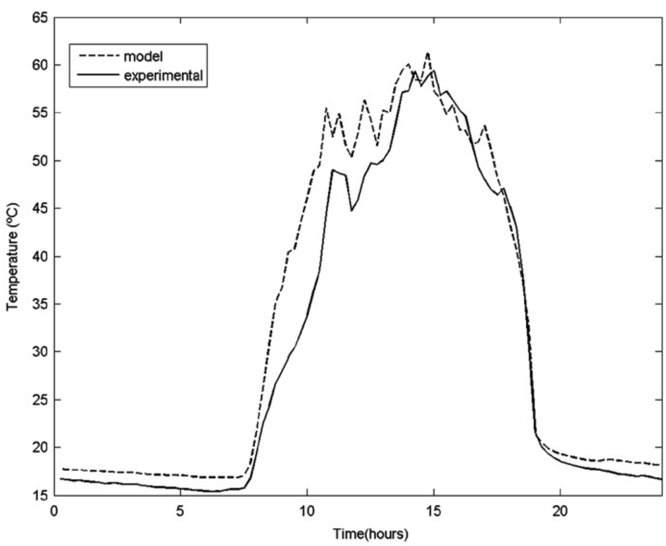

Fig. 2. Module temperature (°C) measured (solid line) and calculated (dashed line) for September 22, 2008.

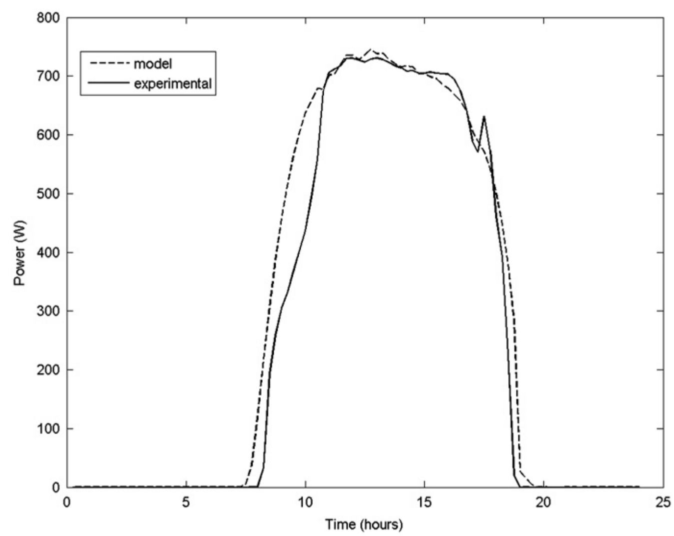

Fig. 3. System AC output (W) measured (solid line) and calculated (dashed line) for September 22, 2008.

Fig. 2 compares the measured and calculated module temperature. The calculated temperature is almost always higher than the measured temperature. This difference has been attributed to the radiation heat transfer from the front and back surfaces of the module, which are neglected in this model.

Thorough comparison between measured and calculated AC power has shown a good agreement between experimental and model data [17], except for the summer morning hours when the system was partially affected by shadows from the surrounding trees (Fig. 3). The model was validated since the mean daily difference for all the analyzed days lied below 2.7%, if disregarding the early and late shading. However, when taking into account all the day, i.e. including shadings, we observe a difference of 8%, as exemplified by Fig. 4.

4. Sensitivity analysis

The aim of the sensitivity analysis was to determine the weight of the different model parameters on the performance of the DoubleSun® solar photovoltaic concentration. This study may be

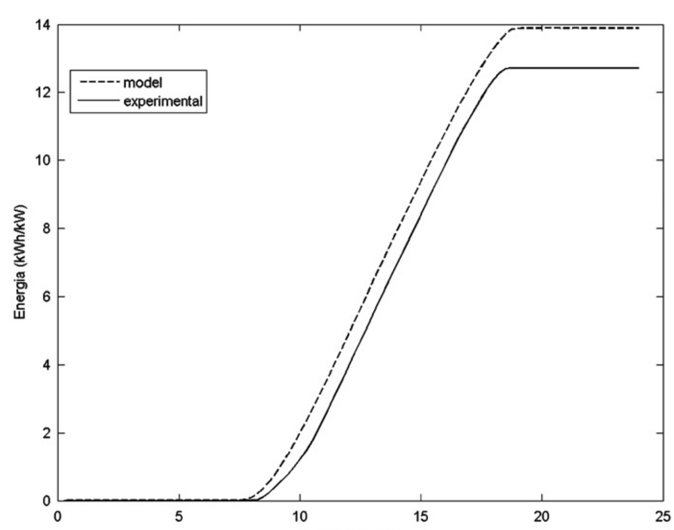

Fig. 4. Accumulated energy (kWh/kWp) measured (solid line) and calculated (dashed line) for September 22, 2008.

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used as a design tool for the DoubleSun® PV system but it is also relevant for LCPV project implementation in general. For convenience, all data refer to the Oeiras site, on September 22. Table 2 shows the standard set of model parameters against which the sensitivity analysis was carried out.

The two most relevant factors determining the performance of the DoubleSun® system are the global irradiance and the efficiency of the system, which depends on their temperature. Fig. 5 shows the change to the energy yield as a function of the variation of the global irradiance. We may observe that, naturally, the energy yield increases considerably with global irradiance. Beyond a 25% increase in global irradiance, the module temperature starts affecting its efficiency and the rate of increase of the energy yield is increasingly reduced. Above +50%, the temperature of the modules reaches 80 °C, their maximum operating temperature. It should be pointed out that these are unrealistic global irradiance levels (any value over 100% means an irradiation above the solar constant) and they are only helpful to illustrate how the DoubleSun® solar concentration system in normal operation is far from reaching the critical temperature. The variability of irradiance refers to different latitudes but also to the existence of clouds, which may reduce, significant and instantaneously, the global irradiance and therefore the power output of the system. As a safety measure, the Doublesun® tracker deviates the modules from the correct position if critical temperatures are achieved by the temperature sensor.

Eqs. (1) and (3) show that the energy yield depends linearly on the module temperature through its (negative) temperature coefficient. Fig. 6 shows the change to energy yield due to variation of the temperature coefficient of the module. The effect of the temperature coefficient on the energy yield is striking: replacing modules with $-0.3\%/^{\circ}C$ by modules with $-0.5\%/^{\circ}C$ leads to a loss of 8% in energy yield.

Fig. 7 shows the effect of changing the ambient temperature. Using Eq. (4), the module temperature is directly computed from the ambient temperature. We may see that the rate of decrease of the energy yield with temperature is 1%/3 °C. Normal operation of the modules, $T_{mod} < 80\,^{\circ}C$, requires ambient temperatures below 40 °C.

Mirrors reflectivity, direct/global irradiance ratio and concentration factor all have the same effect on the energy yield of the system since they are actually different representations of the amount of irradiance arriving from the mirrors to the modules. The response is linear for small variations (1% increase per 3% increase in irradiance from mirrors) but the slope decreases for large increase in the mirror irradiance due to the increase in the

Table 2
Standard set of model parameters.

Parameter	Value
I	895.1 W/m^2
σ_T	$-0.3\%P_{max}/^{\circ}C$
T_{mod}	68.5 °C
T_{amb}	25.7 °C
ε_R	93%
C	1.9
i_c	0.7

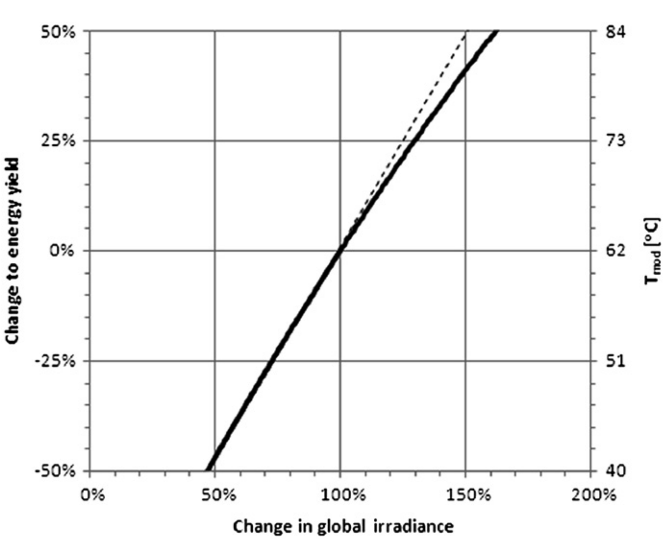

Fig. 5. Change in energy yield and module temperature (T_{mod}) due to variation in global irradiance. Linear fit to small variations is shown in dashed line.

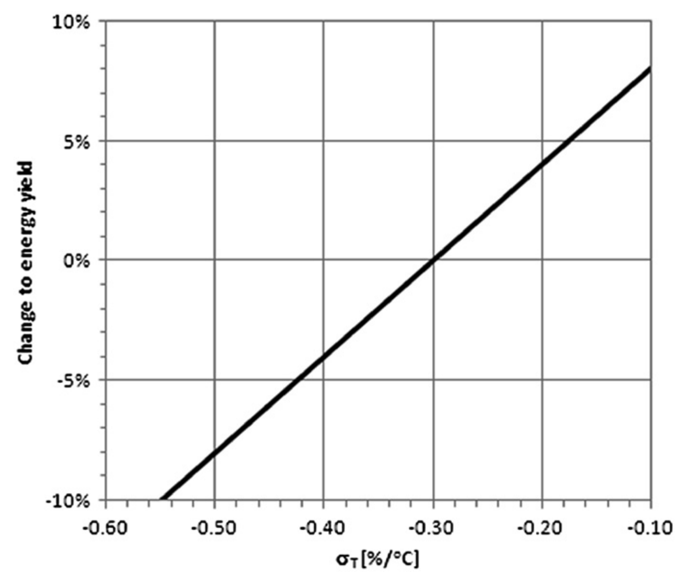

Fig. 6. Change to energy yield due to change in temperature coefficient (σ_T) of modules.

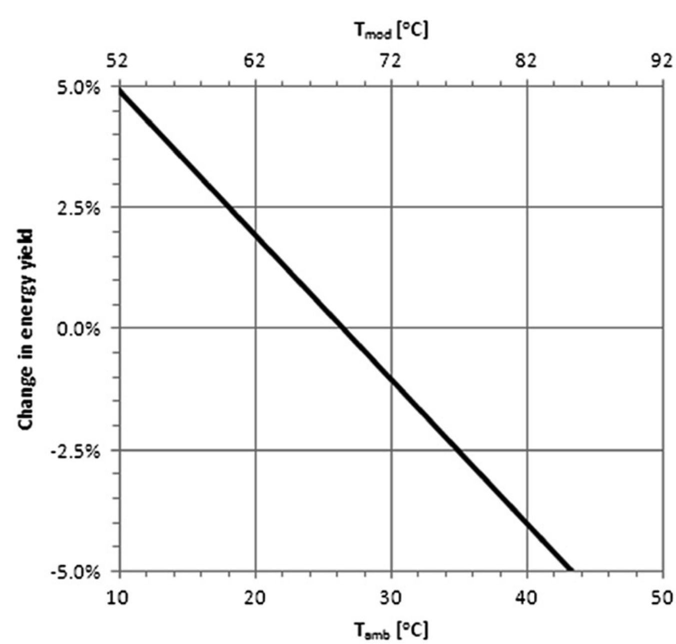

Fig. 7. Change in energy yield and module temperature (T_{mod}) due to change in ambient temperature (T_{amb}).

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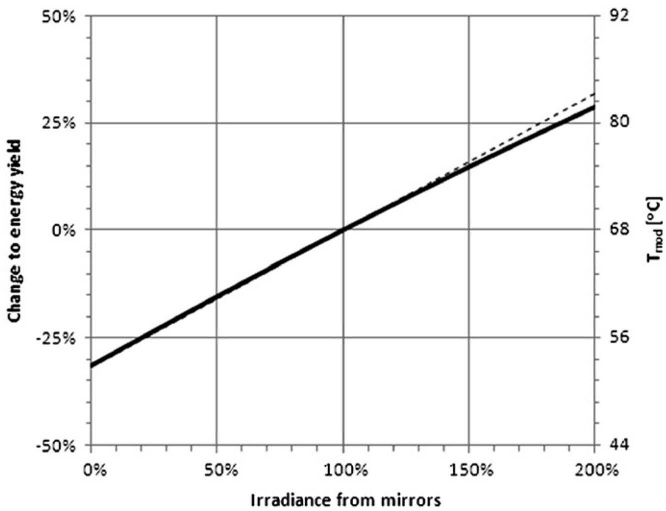

Fig. 8. Change to energy yield and module temperature (T_{mod}) due to variation in the amount of irradiance from mirrors, which may be caused by increase in reflectivity, direct/global irradiance ratio or concentration factor. Linear fit to small variations is shown in dashed line.

module temperature. These results, shown in Fig. 8, suggest that an improvement of the mirrors' reflectivity (which is already in the order of 0.93 and will always be below 1.00, by definition) would only provide a minor improvement of the system performance although it would probably require a significant additional cost. Sensitivity to direct/global irradiance ratio suggests careful planning when choosing a site to install the DoubleSun® system; unsurprisingly, sites with clear skies are preferred. As far as concentration factor is concerned, and because the specified operating temperature range for the modules is below 80 °C, these results recommend that above a concentration factor of 2.8 (which corresponds to the 200% increase shown in Fig. 8) a cooling system is added to the PV system.

5. Conclusions

DoubleSun® is a non-actively refrigerated V-trough PV system with a concentration factor of almost ×2 mounted on a dual-axis tracking system. A numerical model to determine the energy yield of the DoubleSun® solar concentration system was developed. Model results have shown an increased overall energy output of 86% attributed to both the tracking (25%) and concentration (50%).

The model was validated against experimental measurements collected at Oeiras, Portugal, in terms of module temperature and energy production. The calculated module temperature almost always lies below the module temperature registered at the laboratory. This difference is related to the radiation heat transfer from the surfaces, which are being neglected in the presented model. Despite this difference, good agreement between model predictions and experimental data verifies the validity of the model.

Finally, a sensitivity analysis of the different model parameters was conducted. Results show that, as expected, global irradiance is the key parameter for the system performance. Model data also highlights the relevance of the temperature coefficient of the modules: replacing modules with −0.3%/°C by modules with typical −0.5%/°C leading to a loss of 8% in energy yield. As anticipated, increased module temperature due to high ambient temperature, high temperature coefficient or high irradiance decreases the system energy output. It is shown that the module temperature may be kept within the specified operating range (below 80 °C) for ambient temperatures below 40 °C. Increasing the concentration ratio (or, similarly, improving the reflectivity of the mirrors or moving the system to a site with a more favorable direct/global irradiance ratio) will improve performance but, if beyond a critical value, requires the use of a cooling system.

Acknowledgements

The authors would like to acknowledge the support of WS Energia, Taguspark and ADI (Agência de Inovação Portugal). This work has been partially supported by FCT grants: SFRH/BD/45328/2008.

References

[1] B. van der Zwaan, A. Rabl, Prospects for PV: a learning curve analysis, Sol. Energy 74 (2003) 19–31.
[2] J. Nilsson, Optical design and characterization of solar concentrators for photovoltaics, Division of Energy and Building Design, Department of Architecture and Built Environment, Lund University, Faculty of Engineering LTH, 2005, pp. 15–18.
[3] S. Kurtz, Opportunities and challenges for development of a mature concentrating photovoltaic power industry, Technical Report, NREL/TP-520-43208, 2009.
[4] C.S. Sangani, C.S. Solanki, Experimental evaluation of V-trough (2 suns) PV concentrator system using commercial PV modules, Sol. Energy Mater. Sol. Cells 91 (2007) 453–459.
[5] Y. Tripanagnostopoulos, M. Souliotis, S. Tselepis, V. Dimitriou, Th Makris, Design and performance aspects for low concentration photovoltaics, 20th EUPVSEC, 6–10, Barcelona, Spain, 2005.
[6] A. Luque, V. Andreev, in: Concentrator Photovoltaics, first ed., Springer, Berlin, Heidelberg, New York, 2007 (Chapter: 1 and 6).
[7] N. Fraidenraich, Design procedure of V-trough cavities for photovoltaic systems, Prog. Photovolt. 6 (1998) 43–54.
[8] A. Bett, F. Ferrazza , J. Herzog , A. Marti , W. Wettling , Report EU photovoltaic technology platform, SRA, WG3 "Science, Technology and Applications", 2006.
[9] M. Šúri, T.A. Huld, E.D. Dunlop, H.A. Ossenbrink, Potential of solar electricity generation in the European Union member states and candidate countries, Sol. Energy 81 (2007) 1295–1305.
[10] N. Martin, J.M. Ruiz, Optical performance analysis of V-Trough PV concentrators, Prog. Photovolt. 16 (2008) 339–348.
[11] M. García, L. Marroyo, E. Lorenzo, M. Pérez, Experimental energy yield in 1.5X and 2X PV concentrators with conventional modules, Prog. Photovolt. 16 (2008) 261–270.
[12] F.H. Klotz, H.-D. Mohring, C. Gruel, M. Alonso Abella, J. Sherborne, T. Bruton, P. Tzanetakis, Field test results of the Archimedes photovoltaic V-trough concentrator system, <http://builditsolar.com/Projects/PV/Archimedes-MSA.pdf>.
[13] <www.ws-energia.com>, February 2009.
[14] <http://www.mirosolar.com/4270kksp.html>, February 2009.
[15] <http://www.sma.de/en/products/solar-inverters/sunny-boy/sunny-boy-1100-1700.html>, February 2009.
[16] A.D. Jones, C.P. Underwood, A thermal model for photovoltaic systems, Sol. Energy 70 (2001) 349–359.
[17] F. Reis, Development of Solar Concentrators for Large Photovoltaic Plants, M.Sc. Thesis, IST, Personal communication, 2008.
[18] <http://snirh.pt/>, March 2009.

Please cite this article as: F. Reis, et al., Sol. Energy Mater. Sol. Cells (2010), doi:10.1016/j.solmat.2010.03.010