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Efficiency and acceptance angle of High Concentrator Photovoltaic modules: Current status and indoor measurements

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A B S T R A C T

High Concentrator Photovoltaic (HCPV) modules (with concentrations higher than 300 times) have increased their conversion efficiency records up to more than 43% in the last years. This represents the maximum conversion efficiency by any type of photovoltaic (PV) module. Moreover, HCPV modules still have a theoretical potential for a significant efficiency growth. This work analyses the current status of efficiency records of HCPV modules and their evolution in the last 20 years, as well as the most efficient commercial HCPV modules, these last with up to around 34% efficiency nowadays. It is found that the efficiency growth of HCPV modules in the last years is considerably greater than that of other PV technologies like crystalline silicon (c-Si) or Thin Film. The values of efficiency, acceptance angle, geometrical concentration and power of current HCPV modules are gathered. Current efficiency values are typically centred in the range between 27% and 33%, whereas the current average of acceptance angle values is $\pm$ 0.9°. Regarding the geometrical concentration of the efficiency record HCPV modules, it is typically lower than 400× whereas current commercial HCPV modules work in the range of 500–1000×. Moreover, a total of 24 commercial HCPV modules were characterised indoors at the CPV solar simulator at the University of Jaén in order to compare the datasheets with the experimental data. The measurement results, including the efficiency and acceptance angle characteristics, are presented and compared with datasheet values.

1. Introduction

A High Concentrator Photovoltaic (HCPV) module is made up of solar cells, optical devices and peripheral components necessary to generate electricity. The most industrialised HCPV module is typically a closed box containing a series of interconnected concentrator photovoltaic solar cells and their respective concentrator optical systems. The solar cells inside the HCPV module are interconnected through a circuit with typically only two terminals exiting it. This circuit is isolated to prevent current leakages and, in addition, all the components in the HCPV module are protected from different meteorological phenomena. A HCPV module also incorporates others elements such as bypass diodes to avoid the overheating of cells, mainly due to mismatch among cells and the shading that may take place when HCPV systems are working under real operating conditions. Among the basic requirements needed by a HCPV module from the point of view of its operation, it has to be capable of permanently concentrating sunrays onto the solar cells when mounted on a 2-axis tracker, and collecting their generated current. These functions are to be performed without incurring in high losses and removing enough heat in order to maintain the solar cells at controlled working temperatures.

Regarding to the terminology, HCPV modules are designed to concentrate sunlight more than 300–500 times over the solar cell [1]. Broadly speaking, HCPV technology can be considered in the concentration range between 100 and 2000 times [2]. Other authors refer to the HCPV technology to concentration ratios over 400 times [3] or even over 500 times [4]. The authors of this work find more convenient to use the definition of most than 300 times of concentrated sunlight over the solar cell since, as it will be described later, most of efficiency records of HCPV modules are measured under concentrated light between 300 and 400 times.

In relation to the use of the HCPV modules in energy production plants, the worldwide cumulative installed capacity of the HCPV technology is approximately 370 MW [5]. Fig. 1 shows the cumulative installed capacity of HCPV technology detailed by manufacturer. It can be seen that the highest installed capacity by a manufacturer (Suncore) is around 140 MW, a value that is around twice as high as for the second highest manufacturer in terms of installed capacity (Soitec, formerly Concentrix). The third company with more installed capacity is Arzon Solar (formerly Amonix) with a total of 40 MW. Despite more than 10

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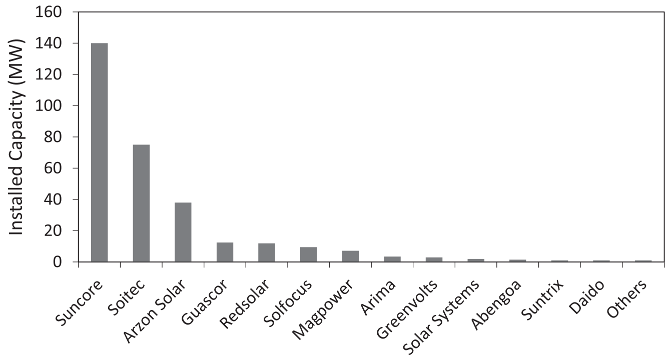

Fig. 1. Global installed capacity of HCPV technology by companies [5–7].

manufacturers have been installing HCPV plants in the last years, only three manufacturers installed the majority of the total HCPV capacity. The contribution of the other manufacturers to the total cumulative installed capacity is marginal.

Although the CPV technology has been developed some decades ago, current CPV (especially HCPV) is a relative new technology with a smaller market than conventional PV. This is mainly due to the higher electricity generation costs of the HCPV respect to the conventional PV systems [8]. In order to make HCPV more competitive and increase the market, the costs associated to the HCPV systems need to diminish. One way to lower costs is to reduce the total amount of material involved in the HCPV systems, particularly, reducing the quantity of most expensive materials and also replacing them by less expensive materials as far as possible. In order to achieve this costs decrease, among other possibilities, the next improvements are indicated:

i. To increase the concentration since the total amount of expensive semiconductor material is decreased by replacing it with less expensive concentrator optics.
ii. To increase the efficiency since, in this way, HCPV modules can be smaller while maintaining their generated power. Therefore, less material will be needed for a HCPV module, also smaller tracker systems, less wire connections, less land area, etc.
iii. To increase the misalignment tolerance, or acceptance angle of HCPV modules, since less accurate and expensive tracker systems will be needed.

Therefore, to increase concentration, efficiency and acceptance angle it is needed to reduce the cost of electricity generated by HCPV systems. Moreover, these three parameters can be considered as merit figures from the point of view of costs, besides economical parameters.

Thus, this work is intended to serve as a review of current HCPV modules, placing an emphasis on their efficiency and acceptance angle characteristic. Moreover, indoor characterisation results (using a CPV Solar Simulator) of different commercial HCPV module technologies, including the measurement of the efficiency and the acceptance angle characteristic, are presented. These measurement results will be useful to validate the data given by the manufacturers and also to provide more information about the HCPV modules.

The literature concerning different aspects related to HCPV modules is extensive. For instance, there are many publications about multi-junction solar cells [9] and optical concentrator systems [2,10]. In those works, a lot of information dealing with concentrator solar cells efficiency and with the acceptance angle of the concentrator optical systems is delivered. Nevertheless they rarely provide much information concerning efficiency and acceptance of HCPV modules. It is possible also to find in the literature many works about different theoretical models that calculate electrical parameters of the HCPV modules under different conditions [11–14]. Nevertheless, those theoretical models allow to estimate efficiency only of the specific HCPV module used for validating the model. However, some works can be found in which some efficiency and/or acceptance angle data of HCPV modules are given [1,7,15], although those data are either limited or not up-to-date. Additionally, some works include information related to prototypes of HCPV modules [16] but those have been not considered in this work since this is limited to commercial ones.

Besides, detailed information about commercial HCPV modules is limited since manufacturers usually consider it as confidential, and therefore, e.g. less precise data are given in company brochures, or even HCPV modules' datasheets are absent in manufacturer's websites. Moreover, many manufacturers have ceased their activity and closed their websites. Considering the information related to HCPV modules, it is very limited in quantity, despite HCPV market still exists. In fact, nowadays, some of the referred companies in Fig. 1 do not manufacture HCPV modules since they either have closed down, or moved their business to conventional PV, or transferred their technology to other companies – like in the case of Soitec to Stace (Saint-Augustin Canada Electric Inc.) and Daido to BSQ Solar. Nevertheless, this work includes the HCPV modules of those companies in order to provide a global vision of the HCPV modules technology. Thus, there is currently a lack of information on module specifications, features, performance, designs, etc. In addition, most of the published data are incomplete. For all those reasons, it is worthy to compile some useful information about HCPV modules like in this work.

This paper is structured as follows. In the Section 2, the key definitions for this current status analysis, related to HCPV modules, are described, namely, efficiency, acceptance angle and concentration-acceptance angle product (*CAP*). In the Section 3, the evolution of efficiency values of HCPV modules in the last 25 years is presented and also record measurement values are analysed. In the Section 4, the current status of commercial HCPV modules is shown and analysed in terms of efficiency and acceptance angle. In the Section 5, indoor measurement results are presented and analysed, as well as the experimental setup is described. In the Section 6, the summary and conclusions are exposed.

2. Definitions

In this section, the definitions involving the key magnitudes, needed for understanding the performance of HCPV modules, are described.

2.1. Efficiency

In order to have a deep view of the efficiency, it is worthy to analyse its definition. The efficiency of a HCPV module, η, is defined as the relation between the electric power produced by the module, P_{output}, and the incoming irradiance, P_{input}, (Eq. (1)):

$$\eta = \frac{P_{output}}{P_{input}} \tag{1}$$

Concerning the energy conversion process, concentrator solar cells are the only elements in a HCPV module that generate electrical energy. The efficiency of a solar cell, η_{CELL}, can be expressed in terms of the global irradiance, G, impinging on its surface, the solar cell's area, A_{cell}, and the electrical power provided by the cell, P_{cell} (Eq. (2)):

$$\eta_{CELL} = \frac{P_{cell}(W)}{G\left(\frac{W}{m^2}\right)\cdot A_{cell}(m^2)} \tag{2}$$

Applying this definition to HCPV modules, the overall module efficiency, η_{MOD}, is related to the electrical power generated, P_{mod}, when an incoming direct normal irradiance, DNI, is collected at the module's surface, A_{mod} (Eq. (3)):

$$\eta_{MOD} = \frac{P_{\mathrm{mod}}(W)}{DNI\left(\frac{W}{m^2}\right)\cdot A_{\mathrm{mod}}(m^2)} \tag{3}$$

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