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MODELING AND ANALYSIS

Experimental analysis and simulation of a production line for CPV modules: impact of defects, misalignments, and binning of receivers

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Abstract

An inherent characteristic of high concentrator photovoltaics (HCPV) modules is a tight mechanical tolerance caused by the narrow angular transmission of the optical system, typically below or close to 1°. Misalignments in the modules caused during the assembly process in the production line will degrade not only the electrical but also the angular performance of the module. Moreover, dispersion in the electrical characteristics of the elementary units comprising a module would lead also to power loss. Quality control and data analysis on the production line is of great significance for adjusting the production line and preserving the angular tolerance and the electrical performance. This is particularly critical during the set-up and tuning of an automated production line. This paper presents the results of a pilot production line for HCPV modules carried out within the European funded ECOSOLE project. Several quality controls were established, which are the binning of the photovoltaic receivers, the measurement of misalignments among the elementary units within every module, and the indoor electrical characterization of the modules. Collected experimental data during the tuning phase of the pilot line were used to validate a module performance model based on production parameters. Monte Carlo method is lately applied to the model to assess the influence of production defects of diverse nature and the adequacy of quality controls, in several manufacturing scenarios beyond the specific constrains of the ECOSOLE experience.

Introduction

The concentrator photovoltaic (CPV) module performance is governed by its subparts, namely the optical system [1] and the Photovoltaic (PV) solar cells [2], by means of the optical and the electrical efficiencies, respectively [3]. Moreover, the CPV module performance also depends on the accuracy attained in the module assembly which determines the allowed mechanical tolerances for the next manufacturing and installation stages, mainly at the tracker level. In this regard, there are different key points related to module manufacturing that affect the module quality and thus determine its efficiency, among them, the attaching of the secondary optical element (SOE) to the cell, the positioning of the receivers (referred to as the assembly comprising the photovoltaic solar cell, the substrate to which it has been attached also named cell carrier, and the SOE) on the back plate [4], or the attaching and alignment of the parquet of primary optical elements (POEs) to the module chassis [5].

In the framework of the European ECOSOLE project, which has received funding from the European Union's Seventh Framework Program, a CPV module, an inverter and a tracker have been designed and manufactured together with an automatic high precision module assembly line, equipped with quality control at different manufacturing stages [6, 7]. The project ended with the installation of several trackers fitted with the ECOSOLE modules made in the production line [8].

In this research, we investigate the influence of different defects that may be present in the CPV module reducing its efficiency. In addition, we study several critical manufacturing stages in which may be positive to perform some kind of measurement or quality control to keep a high module efficiency: binning of photovoltaic receivers prior to module assembly, misalignments and/or acceptance angle (AA) control and electrical characterization of modules.

Accumulated experience during every step of the module development and manufacturing has brought together data about the cell, the receiver, the module, and the assembly process characteristics. During the tuning of the ECOSOLE production line, the performance distributions of the different subparts of the module have been evaluated, by several quality controls, to improve the assembly process. The collected data (e.g., properties of the assembly process and module components) may be used to model the manufactured modules using the experimental statistical distributions of the production line. The model is based on the generation of the current-voltage (IV) characteristics of modules [9–11], which are then compared to the manufactured ones to determine the goodness of the model. In a second step, the statistical analysis of the manufactured modules may be performed by Monte Carlo method, which can be applied to multiple manufacturing scenarios [12, 13]. This analysis may allow, for example, to identify the most critical processes that decrease the module efficiency, and to evaluate the adequacy of quality controls at different module manufacturing stages.

Two different studies have been performed by Monte Carlo simulations, each one related to a different manufacturing scenario:

- Sensitivity of efficiency to module defects (receiver's current mismatch and optical misalignments) in the scenario of ECOSOLE pilot line (during its tuning).
- Module performance dependence on the binning of receivers in the scenario of a production line with an optimized assembly process.

The structure of this paper is described as follows. The installed equipment and the quality control procedures implemented in the pilot production line of ECOSOLE project are described in Section "Quality control and assembly line at ECOSOLE project". This includes the binning of solar cell receivers, the measurements of the misalignments among elementary units within every module, and the electrical characterization of the manufactured CPV modules. Section "Modeling the module performance at ECOSOLE manufacturing scenario" describes the model developed to generate IV curves of modules and to reproduce a given manufacturing scenario by Monte Carlo method. Not only the model is presented but also is validated by comparing it with experimental data obtained from the ECOSOLE pilot line. In Section "Sensitivity of efficiency to module defects", this model is used to perform a sensitivity analysis of the module efficiency to variation in manufacturing characteristics. In Section "Module performance dependence on the binning of receivers", the model is applied to a more general manufacturing scenario to evaluate, in particular, whether the binning of photovoltaic receivers is worth it and if so, how many classes must be used. Finally, Section "Conclusions" gathers together the most relevant conclusions.

Quality Control and Assembly Line at ECOSOLE Project

The main objective of the ECOSOLE project was to provide efficient and cheap energy generation based on CPV technology, while promoting collaboration and cooperation among European research centers and industrial companies.

The ECOSOLE module dimension is 1100 × 550 mm approximately and consists of 72 units series connected with each unit formed by a Silicone-on-Glass Fresnel lens aligned with a receiver based on an dielectric SOE and a triple-junction (3J) solar cell, leading to a geometrical concentration slightly higher than 1200×.

Although the ECOSOLE project covers many aspects, this paper focuses only on the work carried out for developing quality control and measurement equipment for the assembly production line of ECOSOLE module. In this task, the project coordinator BECAR (Italy) realized the CPV module assembly line, and the Instituto de Energía Solar (IES) of the Universidad Politécnica de Madrid (UPM, Spain) developed and installed quality control equipment at the module assembly line. In particular, three different tests were carried out indoors.

Binning of photovoltaic receivers

The motivation of binning in classes is to minimize mismatch losses in subsequent electrical association of photovoltaic receivers. Its need is subject to the dispersion of the population and the potential gain if modules are constituted by receivers of the same class.

Besides the initial dispersion of the photovoltaic solar cell population, the current mismatch between the receivers can occur for a variety of additional reasons: die bonding on substrates (cell carriers), performance dispersion of SOEs, or the gluing process of SOE over the cell (e.g., adhesive properties and thickness, accuracy on SOE position). Regardless of its origin, the receivers can be sorted before installation in the module to avoid this current mismatch. For this task, a receiver solar simulator (called "CIRCE") was developed by UPM and installed in BECAR facilities. This equipment provides a similar light beam to that impinging the receiver at operating conditions: concentration level and the spatial, spectral and angular distribution caused by the POE, in this case a Fresnel lens.

The receiver solar simulator measures the electrical properties (short-circuit current I_{sc}, maximum power P_{mp} and open circuit voltage V_{oc}) with a throughput of 245 MW/year. The I_{sc}, the P_{mp}, or the current at maximum power bias (I_{mp}) are the preferably parameters to classify the receivers. At ECOSOLE project, four different classes related to spaced slots of the same I_{sc} width (≈29 mA) were defined based on the system accuracy (<1%) and the receivers I_{sc} distribution (standard deviation $\sigma_R \approx 14$ mA, 1.3% with respect to mean value). Figure 1 presents the measured I_{sc} distribution.

Control of the AA of module and optical misalignments between units

Optical misalignments within a CPV module can be understood as defects that make the optical elements comprising the module stop sharing the same optical axis and thus produce light spilled out of the solar cell.

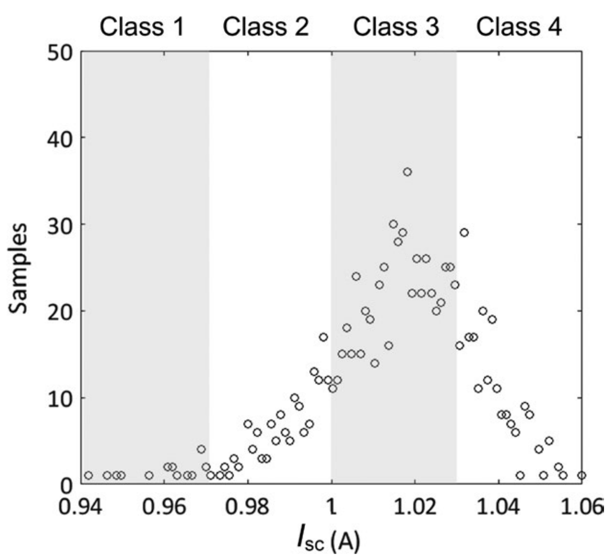

Figure 1. Distribution of the receiver's short-circuit current (I_{sc}) measured with the solar simulator CIRCE. The four different classes defined for receivers binning based on I_{sc} values are also indicated.

Two relevant different optical axes must be considered in a module (see Fig. 2). On the one hand, the "optimum optical axis" is defined as the pointing vector of the module to the sun that maximize the power generation. On the other hand, a CPV module has a mechanical reference provided by its fixing elements, so the normal vector to the plane defined by its fixing points corresponds to the "mechanical reference axis". While a constant offset among both axes (optimum optical and mechanical reference) in a module population would be corrected by the pointing system in the array (at tracker level), a statistical dispersion among both would require individual alignment of the modules in the array to prevent additional losses.

Every elementary unit in the module (comprised by a Fresnel lens and a photovoltaic receiver) has its own alignment (optical axis or pointing vector) with respect to the reference axis, either optimum optical or mechanical. Therefore, the misalignments between units within a module can be defined as the differences between their pointing vectors. These misalignments may produce current mismatch between units in a module that would decrease the module efficiency. The set of misalignments among units in the module determines its optimum optical axis, therefore, misalignments cause dispersion among the optimum optical and mechanical reference axes.

The misalignments may arise from many sources, for example:

- The positioning of the SOE over the cell. The misalignments produced (change in the optical axis of the unit) are expected to be low due to the associated mechanical tolerance. Its effect on receiver performance, if relevant, is detected by CIRCE measurements as a decrease in generated power.
- The positioning of receivers at the back plate of the module.
- The bending of the lens parquet.
- Displacement or rotation between the lens parquet and the back plane containing the receivers.

In this regard, the incorrect positioning of receivers at the back plate during the tuning phase of the assembly line was proven to be the largest source of misalignments [8].

The tolerances allowed in the assembly chain of a CPV module are intrinsically related to the angular tolerance of the optical system, which is quantified by the AA. It is defined as the pointing vector of the module (translated to an angle in a given direction) at which the output power decreases to 90% of its maximum (which corresponds to the optimum optical axis). In a good performing CPV module, its maximum power P_{mp} should be limited by the current of the worst cell (in terms of photo-generated

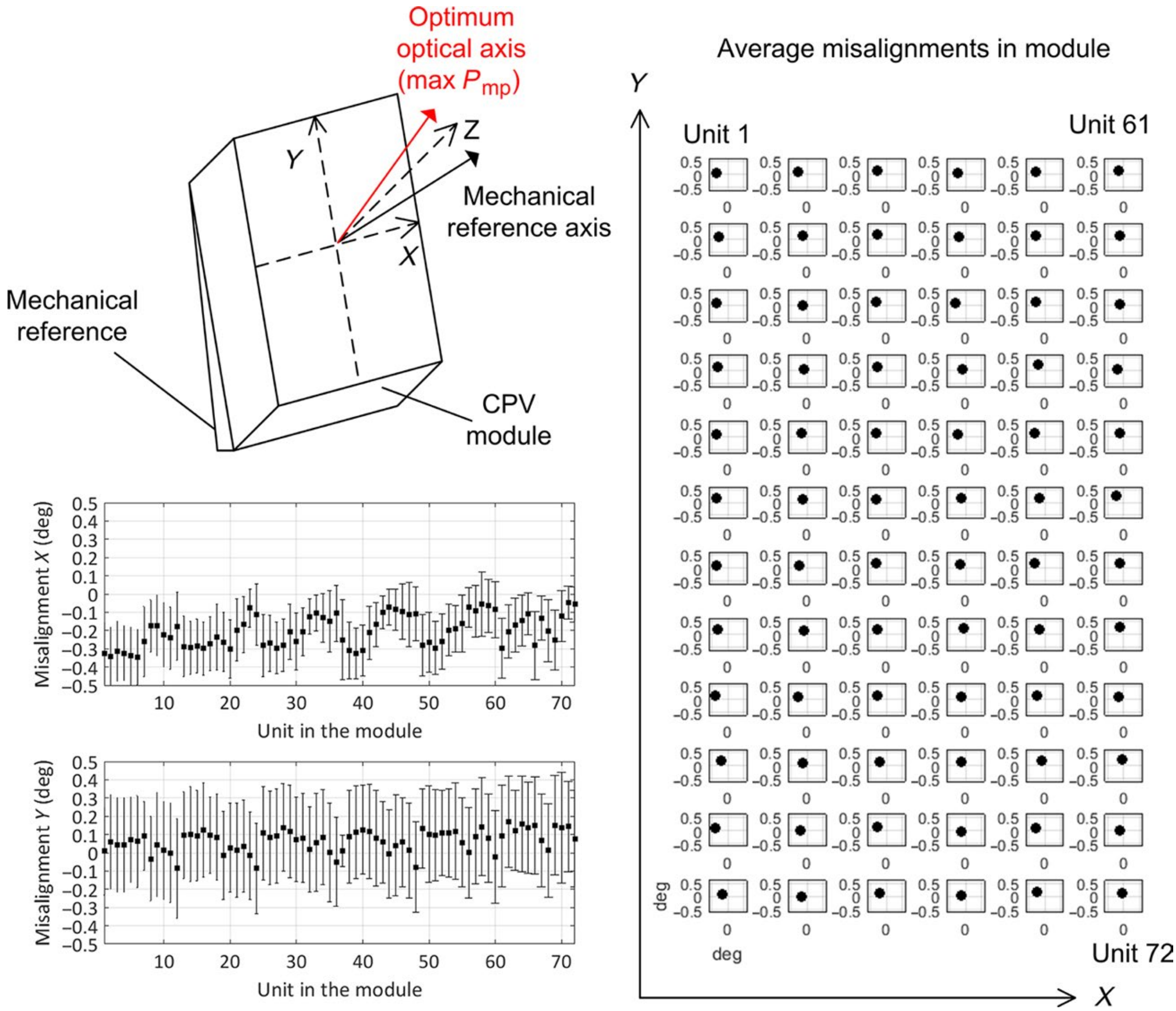

Figure 2. (Left-top) Definition of optimum optical and mechanical reference axes. Misalignments distribution measured with MOA: (left-bottom) average and standard deviation values for all the units (labeled from 1 to 72) in X direction (top) and Y direction (bottom); (right) average misalignments of the units (labeled from 1 to 72) in the module (front view).

current). In a worse case, the worst (or group of worst) cell is in reverse bias at the maximum power point because the loss of such cell (or cells) in terms of power is lower than the loss caused by its (their) current limitation over the whole string. In contrast, the short-circuit current I_{sc} of the module corresponds to the photo-generated current of the one of the best performing cells as the current excess is passing though the bypass diodes of the rest. Thus, the AA must be obtained based on P_{mp} and not on I_{sc} to avoid optimistic values. Obviously, the worst and best performing cells will change with the pointing of the module axis to the light source. The result of this module behavior is that misalignments between units within a module will cause not only a power loss but also a reduction on the module AA, thus reducing the angular tolerance of the module [14].

Preservation of the potential AA of the module in the assembly process (equivalently, to minimize misalignments among units) is highly desirable to maximize the allowed mechanical tolerances in the next system manufacturing stages (i.e., avoiding tight tolerance for the array frame and tracker). Thus, the characterization of the misalignments in a module is a key aspect in the quality control, and of greatest significance during the installation and commissioning phases of a production line. The Module Optical Analyzer (MOA, patent nº EP14717129.2) measures the misalignments between units in a module based on the luminescence inverse method [15, 16]. This equipment has been successfully tested in the CPV industry, for example, to evaluate vendor's quality [4], to study module performance with temperature [17], or to tune the assembly production line [8]. A MOA system was installed during the ECOSOLE project to perform a quality control of module misalignments with repeatability of 0.01° and a throughput of 90 MW/year.

Figure 2 (left) presents the average and standard deviation of the misalignments (pointing vectors) within units in the modules measured by MOA at the pilot line of ECOSOLE, for an example case of seven modules representing a particular configuration of the production line (same tuning of the production line and measurements conditions). More than 150 modules were manufactured within the ECOSOLE project but during the production several tuning processes were carried out to optimize the line. Thus, we have chosen this particular set of seven modules to illustrate the evaluated scenario. The first significant result is the existence of an average offset of about −0.2° in the X direction. This offset reveals that the mechanical reference axis is not coincident with the optimum optical axis (which would be close to 0 offset). This is due to the fact that the tuning of the production line was not completed while the measurements were performed. Nevertheless, this offset is not relevant since it can be corrected by the pointing system at the array level. The significant parameter is the dispersion among modules optical axes because it cannot be corrected and will result in power losses. The average misalignment is closer to zero for units in Y direction but with larger standard deviation. The average misalignment measured in the modules produced a pattern presented Figure 2 (right).

Control of modules (electrical characterization)

The electrical properties of the modules before the installation in the tracker have been measured by the solar simulator Helios 3198,[1] which measures the IV curve of a CPV module reproducing the sun conditions (similar angular size and spectrum) indoors [18]. The light system of the simulator, that consists of a Xenon flash lamp and a parabolic mirror, produces an angular size of 0.43° and a spectral matching ratio [19] of 1 (same ratio of currents, for top and middle subcells of a 3J solar cell, as under reference spectrum AM1.5D [20]) at the module aperture area (up to a circular shape of 2 m of diameter). The solar simulator installed at BECAR facilities was very useful not only in the module manufacturing process to control the efficiency but also during the tuning of the assembly line.

Modeling the Module Performance at ECOSOLE Manufacturing Scenario

Introduction to the model: IV curve generator

A model has been developed to generate module IV curves, and it has been applied to the case of modules manufactured in a particular instant during the tuning of the ECOSOLE production line. Thus, the validation of the model can be performed if comparing its results with the measurements realized at the ECOSOLE pilot line.

The general purpose of this model is to use it for reproducing a given manufacturing scenario by Monte Carlo method, by feeding the model with statistical distributions related to different module characteristics. To do that, IV curves of CPV modules are simulated, each one based on different parameters (e.g., receivers characteristics -I_{sc}, V_{oc}-, and misalignments) taken from realistic distributions. Figure 3 presents a flowchart of the Monte Carlo simulation for the analysis of CPV modules performance.

Based on the quality control performed in the ECOSOLE production line (from the binning of receivers in CIRCE), the electrical characteristic of the receivers, in particular the I_{sc}, P_{mp}, and V_{oc}, are known for a large number of manufactured modules. In order to simplify the statistical analysis, the measured distributions are approximated to Gaussian distributions. For the case of binning of receivers, it is assumed that all the receivers in a module have the same class randomly selected attending to the I_{sc} distribution.

The misalignments effect, whatever its origin, may be simulated by a decreasing factor of I_{sc}: every misalignment angle is translated to a loss factor (on current) based on the angular transmission curve (carefully characterized at the solar simulator for an elementary unit of a module). The particular distribution of misalignments for every elementary unit in the module has been determined from data collected with MOA, obtained from a set of modules (Fig. 2). Bending of lenses or receivers positioning produce nonuniform but repeatable patterns of misalignments between units. To simplify the statistical analysis, the 72 measured distributions (one for each elementary unit) are approximated to uniform or Gaussian distributions. The uniform (also referred as rectangular or continuous) distribution showed a better fitting during the tuning phase of the line, because the misalignments errors were not as repetitive as once the pilot line was fully tuned, as there are multiple variable factors that influence the module alignment. Conversely, the Gaussian distribution fits better once the pilot line is fully tuned.

A detailed characterization of an individual optical system-cell unit (i.e., a reference elementary unit) of

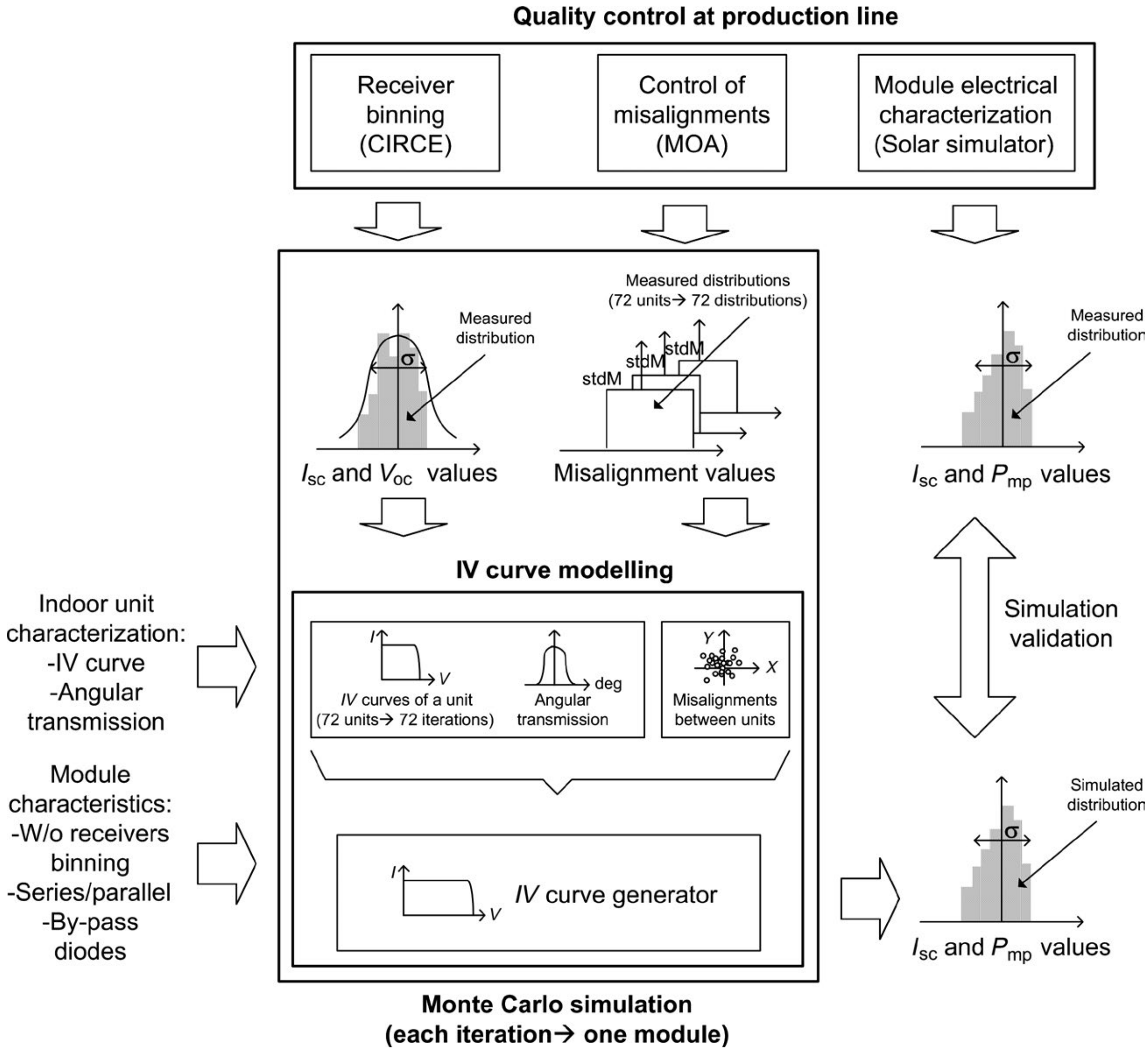

Figure 3. Flowchart of the Monte Carlo simulation for the analysis of CPV modules performance depending on receivers and misalignment characteristics.

ECOSOLE module was performed at the CPV solar simulator to obtain its IV curve and angular transmittance (and AA). The IV curve of a given unit in the module may be simulated if randomly selecting the I_{sc}, the V_{oc} and the misalignment (translated to a decreasing factor of current) from the available realistic distributions, and normalizing the IV curve of reference to these values. This operation is performed for all the units in the module to reproduce the IV curve of the whole module. For doing that, the parallel/series module connection (in ECOSOLE case, all units in series), the binning of receivers (four classes), and a bypass-diodes (one per unit) are considered. With a large number of module simulations (100), the average P_{mp} and I_{sc} of simulated modules (and the standard deviation) are obtained. To validate the simulation, these results are compared with P_{mp} and I_{sc} real (measured) values in the production line.

Validation of the model: simulation results versus measurements

To validate the model, a particular moment during the tuning of the ECOSOLE production line has been chosen. Several representative modules manufactured and measured in this moment were selected to define the characteristics to be used as inputs in the simulation (Figs. 1 and 2, receivers distribution of σ_R = 1.3% and misalignment distribution of std_M = 0.16° in average, respectively).

Figure 4 shows some measured IV curves and simulated IV curves (related to the average, maximum and minimum values of the simulated P_{mp} values) for the case of binning of receivers. It shows a reasonable fit between the simulated and measured IV curves that validates the model. The lack of light uniformity provided by the solar simulator at the module aperture has been included in the simulation, and modeled as a loss factor following a Gaussian distribution of $\sigma_{N\text{-}U}$ = 2.5%.

For this particular moment during the tuning of ECOSOLE production line, simulation predicts that the binning of receivers has only a slight effect (lower than 1%) on the module power generation if comparing average P_{mp}. In the ECOSOLE production line, the module performance is clearly dominated by misalignments among units. It must be pointed out that these measurements were carried out during the set-up and first weeks of the manufacturing line, and they are a proof of the existence of a large room for improvement in terms of alignment.

Sensitivity of Efficiency to Module Defects

Once the model has been validated, it is used to perform a sensitivity analysis of the module efficiency by varying the input data: the statistical distributions (receiver's characteristics I_{sc}, and misalignments) of the production line. For doing this, the IV curves of ECOSOLE modules (100) have been simulated (as explained in previous section) under two different scenarios (modules have pure series connection):

CASE 1: Sensitivity to receiver distribution. In this scenario, the simulation is performed for three Gaussian distributions (Fig. 5) of receivers, of σ_{R1} = 1.1· σ_R and σ_{R2} = 1.8· σ_R, where σ_R = 1.3% is the value of the ECOSOLE line.

CASE 2: Sensitivity to misalignment distribution. The module contains misalignments distributions as those presented in Figure 2. The simulation is performed for three uniform (also referred as rectangular or continuous) distributions of std_M = 0.16° std_{M1} = 0.7·std_M and std_{M2} = 1.5·std_M, where std_M = 0.16° is the value obtained for the ECOSOLE line. The receivers in the module have the distribution of the ECOSOLE production line (approximated by a Gaussian, σ_R = 1.3%), and are mounted in the module with and without previous binning (based on I_{sc} values).

The effect of the nonuniform illumination (due to the solar simulator properties) is not included in the following simulation results, as we prefer to evaluate only performance losses associated to module manufacturing issues.

The Figure 6 shows an example of simulated IV curves (related to the average P_{mp} of the simulated values) of modules related to the two cases (CASE 1 and CASE 2) described above with binning of receivers, and the histograms of the simulated P_{mp} values.

Figure 6 shows the effect of current mismatch produced by misalignments: the IV curve of CASE 2 (effect of misalignments between units comprising the module) shows a steep slope that leads to a loss of power if compared with CASE 1 (where only the effect of receiver distribution has been taken into account). These results are obtained

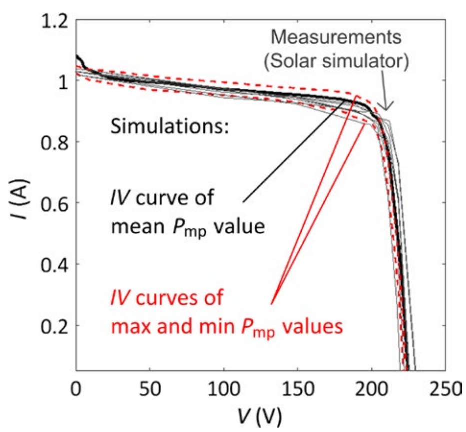

Figure 4. Examples of IV curves measured at the solar simulator and simulated IV curves (related to average, maximum and minimum of simulated P_{mp} values) including the effect of nonuniformity of light in the solar simulator (Gaussian distribution $\sigma_{N\text{-}U}$ = 2.5%).

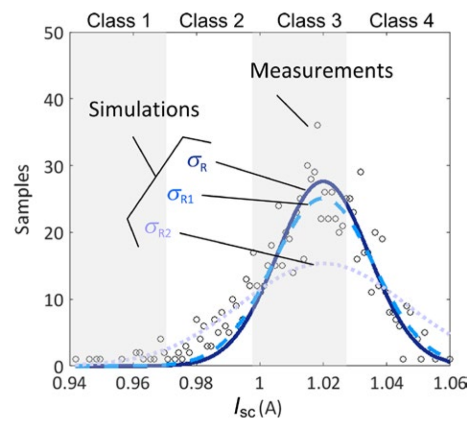

Figure 5. Receivers distributions (I_{sc}) used as input in the simulation: the measured distribution is approximated to a Gaussian distribution. Several Gaussian distributions (with different sigma values) are used to study the sensitivity of efficiency to the distribution of the receiver's short-circuit current.

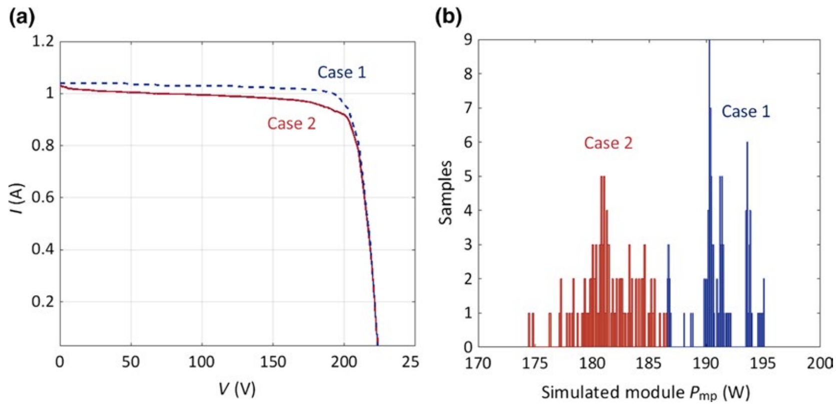

Figure 6. (a) Examples of simulated IV curves (related to the average P_{mp} simulated values) of modules with binning of receivers for: CASE 1 (receiver distribution Gaussian σ_R = 1.3%) and CASE 2 (receiver distribution Gaussian σ_R = 1.3%, and misalignments distributions uniform std_M = 0.16°); (b) Histogram of simulated P_{mp} values of CASE 1 and CASE 2. Results simulated without including the effect of nonuniformity of solar simulator (σ_{N-U} = 2.5%).

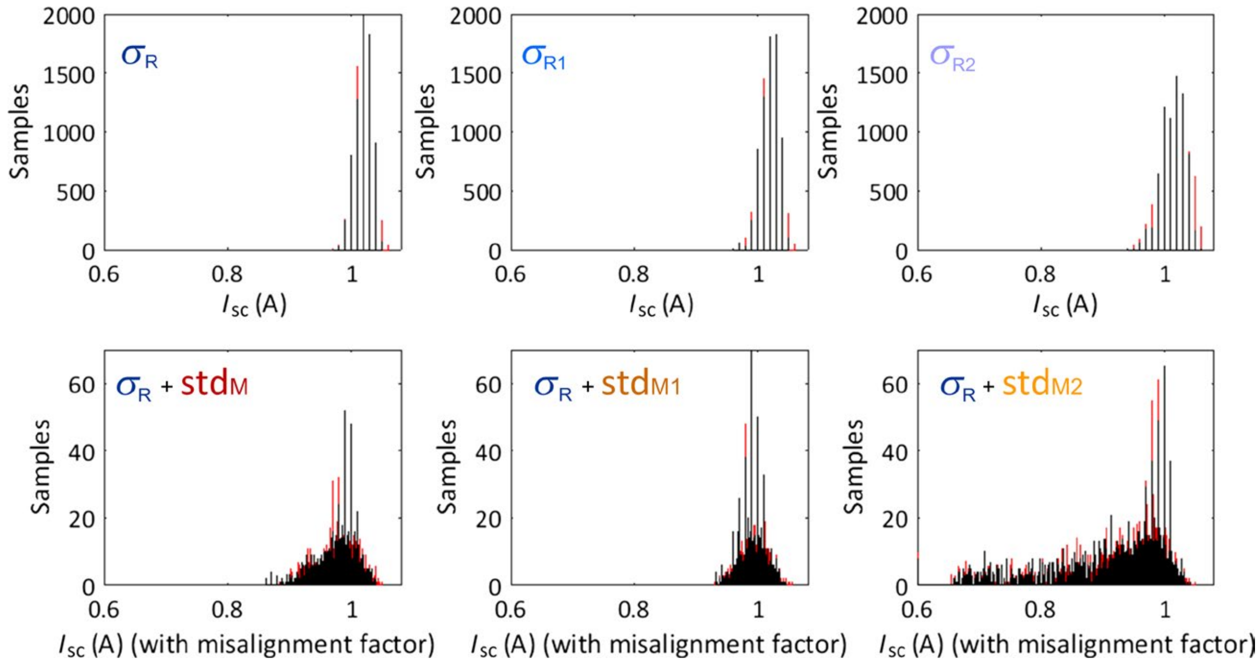

Figure 7. (Up) I_{sc} distribution of 100 simulated modules (72 receivers each) with binning (in black) and no binning (in red) of receivers related to different receivers distributions (σ_R, σ_{R1}, σ_{R2}); (Down) I_{sc} distributions (with applied misalignment factor) related to different misalignments distributions (std_M, std_{M1}, std_{M2}) and a given receivers distribution (σ_R). Results simulated without including the effect of nonuniformity of solar simulator (σ_{N-U} = 2.5%).

for a similar set of receiver's distribution and misalignments factors, independently on the binning (Fig. 7 shows similar red and black distributions). Figure 7 shows how the influence of receiver's distribution and misalignments is in the I_{sc} of the units comprising the CPV modules.

Figure 8 summarizes the results (average and standard deviation values of P_{mp} and I_{sc}) of the two simulated cases (CASE 1 and CASE 2) with receivers binning. Figure 8 shows the sensitivity of the module performance (P_{mp} and I_{sc}) to changes in the receiver and misalignments distributions: the simulation is performed for three different distributions in each of the two cases. Not only the average value but also the standard deviation is presented in the figure. The average value gives an idea of the losses related to the simulated scenario and the standard deviation gives an idea of the module mismatch that causes the simulated scenario (which could add significant power losses at the system level when modules are installed in a tracker).

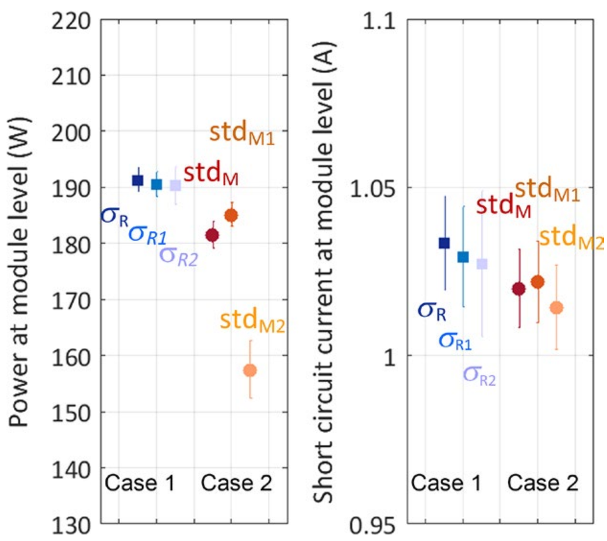

Figure 8. P_{mp} and I_{sc} results (average and standard deviation marks) of Monte Carlo simulations with binning of receivers: CASE 1 in squares (receiver distribution, $\sigma_R = 1.3\%$, $\sigma_{R1} = 1.1\cdot\sigma_R$, $\sigma_{R2} = 1.8\cdot\sigma_R$), CASE 2 in circles (receiver distribution $\sigma_R = 1.3\%$ misalignments distributions uniform $std_M = 0.16°$, $std_{M1} = 0.7\cdot std_M$, $std_{M2} = 1.5\cdot std_M$). Results simulated without including the effect of nonuniformity of solar simulator ($\sigma_{N\text{-}U} = 2.5\%$).

Table 1 summarizes the results on the sensitivity of the module efficiency to different distributions of receivers (I_{sc}) and misalignments. The effect of varying each parameter is translated to a power loss and a standard deviation. Regarding the power loss, the values of the table correspond to the average power loss of the population of modules compared to the reference case ($\sigma_R = 1.3\%$, $std_M = 0°$). So it must be understood as a minimum value at the module level, since the increase in the standard deviation would also cause additional losses at the array (tracker level) when many modules are electrically connected, for instance, to a single inverter.

The results presented in this section are related to the ECOSOLE production line during its set-up phase which should be understood as a starting point for any given assembly process. The influence of the misalignments on the module performance is very evident, and thus the need of performing a quality control at this stage. This quality control can be implemented using the MOA [21] and a solar simulator for CPV. However, the need of binning of receivers does not seem to be so relevant. Because this last conclusion is also derived from the ECOSOLE project experience, and at this moment limited

Table 1. Summary of relative losses (ε) and relative variation in module P_{mp} depending on the receiver distribution (σ_R) and the misalignment distributions (in average) of the elementary units in the module (std_M). Results simulated without including the effect of nonuniformity of solar simulator ($\sigma_{N\text{-}U} = 2.5\%$).

P_{mp} = 191W Maximum (average) power (Reference case: $\sigma_R = 1.3\%$, $std_M = 0°$, and binning of receivers)		Binning of receivers	No binning of receivers	Conclusion
CASE 1 ↑σ_R Effect of variation in σ in receivers distribution: $\sigma_R = 1.3\%$ $\sigma_{R1} = 1.4\%$ $\sigma_{R2} = 2.3\%$ For $std_M = 0°$	P_{mp} Average value of simulated modules	Relative losses (ε) with respect to reference case: ε = 0% $\sigma_R = 1.3\%$ ε = 0.4% $\sigma_{R1} = 1.4\%$ ε = 0.5% $\sigma_{R2} = 2.3\%$	Relative losses (ε) with respect to reference case: ε = 0.5% $\sigma_R = 1.3\%$ ε = 0.6% $\sigma_{R1} = 1.4\%$ ε = 1.3% $\sigma_{R2} = 2.3\%$	The effect of binning is only visible if considering large receivers distributions (losses of 0.5% vs. 1.3%)
	σP_{mp} Standard deviation of simulated modules	Relative variation with respect to average of simulated case: 1.1% for $\sigma_R = 1.3\%$ 1.2% for $\sigma_{R1} = 1.4\%$ 1.7% for $\sigma_{R2} = 2.3\%$	Relative variation with respect to average of simulated case: 0.2% for $\sigma_R = 1.3\%$ 0.2% for $\sigma_{R1} = 1.4\%$ 0.4% for $\sigma_{R2} = 2.3\%$	Modules have worse but more similar power if no binning: high probability of a cell with low current at every module
CASE 2 ↑std_M Effect of variation in std in misalignments distribution: $std_M = 0.16°$ $std_M1 = 0.11°$ $std_{M2} = 0.24°$ For $\sigma_R = 1.3\%$	P_{mp} Average value of simulated modules	Relative losses (ε) with respect to reference case: ε = 5.1% $std_M = 0.16°$ ε = 3.2% $std_{M1} = 0.11°$ ε = 17.7% $std_{M2} = 0.24°$	Relative losses (ε) with respect to reference case: ε = 5.6% $std_M = 0.16°$ ε = 3.7% $std_{M1} = 0.11°$ ε = 16.8% for $std_{M2} = 0.24°$	If large misalignments, the effect of binning has almost no advantage
	σP_{mp} Standard deviation of simulated modules	Relative variation with respect to average of simulated case: 1.3% $std_M = 0.16°$ 1.1% $std_{M1} = 0.11°$ 3.2% $std_{M2} = 0.24°$	Relative variation with respect to average of simulated case: 0.8% $std_M = 0.16°$ 0.3% $std_{M1} = 0.11°$ 2.8% $std_{M2} = 0.24°$	Modules have worse but more similar power if no binning: high probability of a cell with low current at every module Difference is reduced if considering misalignments

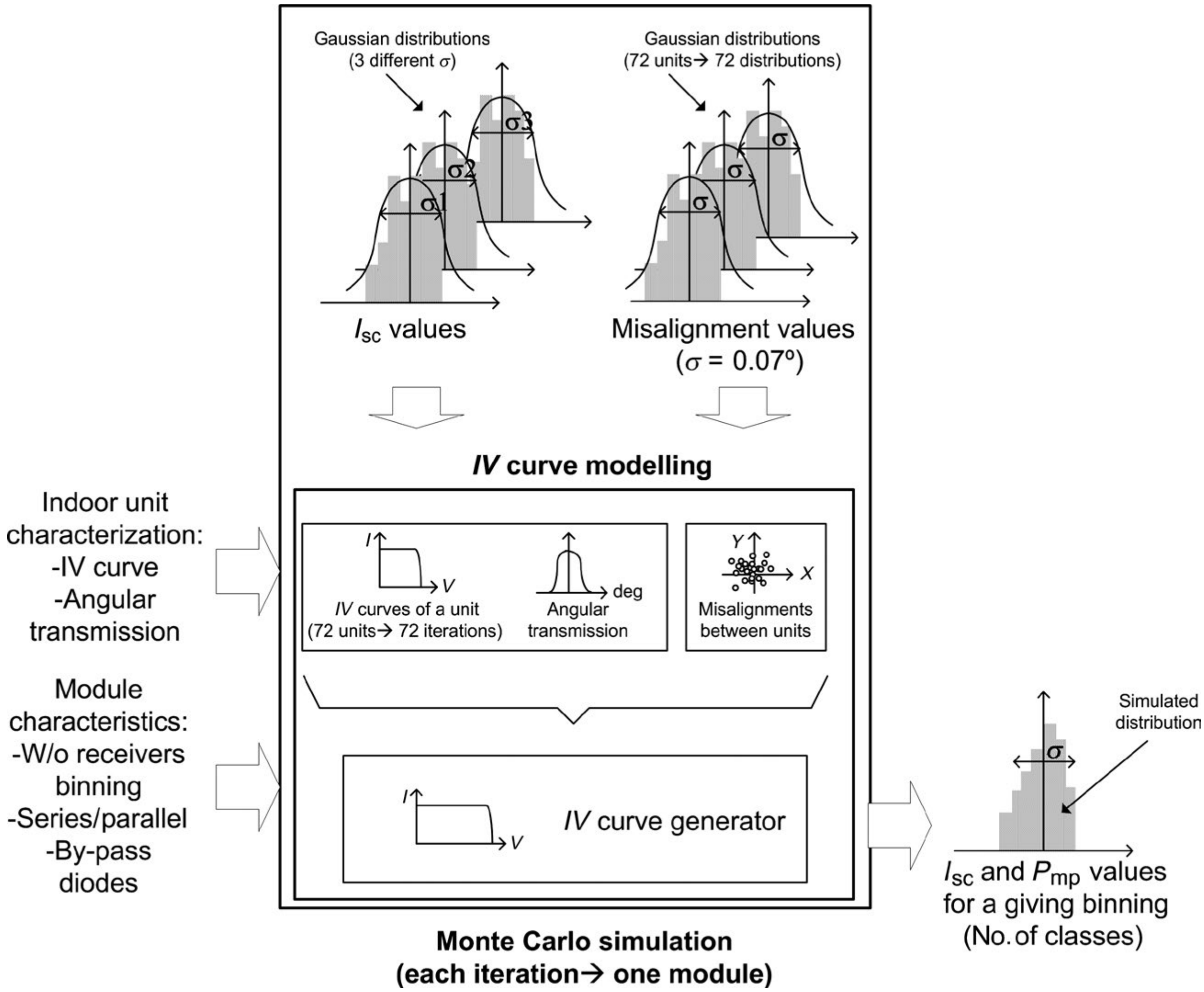

Figure 9. Flowchart of the Monte Carlo simulation for the analysis of the adequacy of binning of receivers before being installed at the CPV module.

to this case, the real need of these characterizations at the production line cannot be inferred. The following section will try to analyze the adequacy of receivers binning prior to installation in the module while simulating a slightly different manufacturing scenario in which misalignments have a lower impact on the module performance.

Module Performance Dependence on the Binning of Receivers

A second simulation based on the Monte Carlo method has been performed to study the impact of receivers binning in a real/fine-tuned manufacturing scenario of a CPV module. There are several differences with respect to previous simulated scenario of the ECOSOLE pilot production line:

- The distribution of receiver's short-circuit current is expected to be wider than that measured with CIRCE in the ECOSOLE project, since in the project, the receiver population belonged to only one supplier and the photovoltaic solar cells came from the same bunch (only a few wafers). Three different Gaussian distributions are analyzed: $\sigma_1 = 4.2\%$, $\sigma_2 = 3.4\%$, $\sigma_3 = 2.1\%$.
- After a proper adjustment of the production line, misalignments distributions are expected to follow a narrower Gaussian distribution instead of uniform distributions as previously simulated. Based on the pattern of Figure 2, misalignments are modeled by Gaussian distributions with a conservative value of $\sigma_M = 0.07°$ (average of all units distributions).
- The number of classes used for the receiver binning may be larger than 4 as a large production of modules will allow different classes of systems. In this

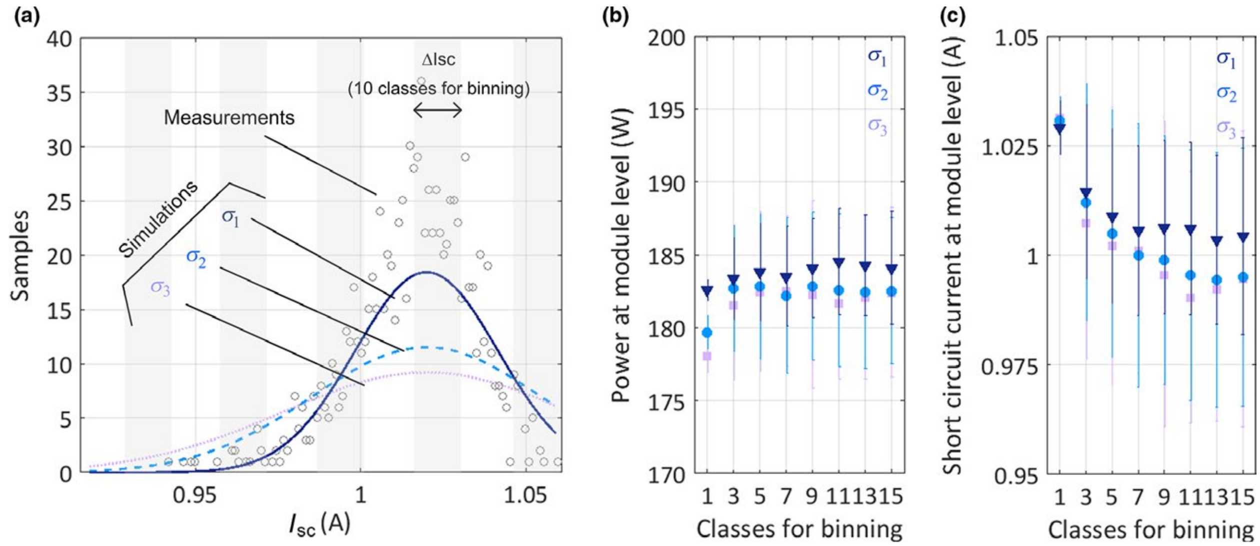

Figure 10. (a) Receivers distributions (I_{sc}, Gaussian of σ_1 = 2.1%, σ_2 = 3.4%, σ_3 = 4.2%) used as input in the Monte Carlo simulation compared to the measured distribution in ECOSOLE project; (b) P_{mp} and I_{sc} results (average and standard deviation marks) of Monte Carlo simulations for different number of classes in the binning (from 1 up to 15) and three different receivers distribution (I_{sc}, Gaussian of σ_1 = 2.1%, σ_2 = 3.4%, σ_3 = 4.2%). In all the simulations the effect of misalignments is represented by Gaussian distributions of average σ_M = 0.07°. Results simulated without including the effect of nonuniformity of solar simulator ($\sigma_{N\text{-}U}$ = 2.5%).

simulation, the assumed number of classes is varied from 1 up to 15.

The IV curves of modules have been simulated (100) to study the effect of receivers binning on P_{mp} and I_{sc}. The simulation procedure is described by the flow-chart shown in Figure 9.

Figure 10b shows the average and standard value of P_{mp} and I_{sc} values of modules with receivers binned into different classes. The three modeled receiver distributions are presented in Figure 10a. The distribution is divided uniformly to cover a given range (ΔI_{sc}) for each class.

The evolution of the power with the number of classes can be explained as follows. The larger the number of classes, the narrower the range of values for each class (ΔI_{sc}). The result of the simulation shows that the average value of P_{mp} rises with the number of classes as cells in the module are more similar. This is due to the fact that the power is closely linked to the worst cells of the module which limit the P_{mp} bias point. Without binning or with few classes, the probability of having cells with very low I_{sc} at every single module is high, which limits the power of the module.

The behavior of the I_{sc} differs from P_{mp} because I_{sc} is linked to the best performing cells of the module. Without binning the probability of having cells with very high I_{sc} at every single module is high, which results in a good performing module in terms of I_{sc} (but not in P_{mp}).

The improvement undergone by the binning process depends on the number of classes and the distribution characteristic. For both cases, P_{mp} and I_{sc}, the average value saturates as the number of classes increases which imposes an optimum number of classes given a particular distribution. For the case under study, 7–9 classes seem to be proper numbers for receivers binning.

Conclusions

A model has been developed to generate module IV curves, and it has been applied to the case of a real pilot production line and showed good agreement with experimental data. This model has been proven to be an excellent tool to study a given manufacturing scenario by Monte Carlo method, while feeding the model with statistical distributions related to different module characteristics.

For the simulated module (pure series connection), the misalignments in CPV modules is a key quality parameter since large values lead to very significant power losses. For instance, relative power loss is up to 17% for very wide misalignment distributions of σ_M = 0.24° and no zero offset, and 3% if conservative misalignment distributions of σ_M = 0.11°.

When losses are strongly dominated by misalignments (σ_M > 0.1°), binning of receivers does not show a clear advantage. However, in a manufacturing scenario where misalignments are controlled and minimized (σ_M < 0.07°), the binning of receivers may add a P_{mp} improvement of 2.5%, in the order of that wasted due to misalignments.

Consequently, the following conclusions can be derived related to quality control on production:

- The advantage provided by binning of receivers depends on the defined number of classes. For a given manufacturing scenario, there is an optimum value (around 9 for the case under study) that maximize the P_{mp} gain.
- The quality control of misalignments may be crucial to minimize the impact of the main source of P_{mp} losses. This measurement can also be useful to determine if the modules mechanical reference axis is coincident with the optimum optical axis. If they differ, the tracker pointing should be corrected accordingly.
- The electrical characterization of modules is not only convenient in a preliminary tuning phase, but also if modules are sorted to have several classes of trackers. If modules are not sorted in different classes, the electrical control of modules can still be used to minimize losses at the tracker level. It must be remembered that differences among manufactured modules (expressed by the standard deviations marks in the simulated cases) may be translated to losses if modules are connected to a single inverter.

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Conflict of Interest

None declared.

Note

[1] http://solaraddedvalue.com/en/category/productos/helios-3198/

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