ABSTRACT: Buyers and sellers of photovoltaic modules have to agree with a reasonable uncertainty on the power of the modules exchanged during transactions. INES/CEA has developed a new module reception method to estimate the difference between the power sold by a module manufacturer and the real power bought by a customer. The procedure is based on the use of the flash-tests of the manufacturer and on the test of a limited number of modules at a reference laboratory. The number of modules and the uncertainty of the results are calculated thanks to Monte Carlo statistical simulations. During the Martinique’s PV Performance project, this method has been applied to a 228 kWp roof-integrated photovoltaic system of SMEM, the company in charge of the distribution of electricity in the Martinique Caribbean Island. 16 modules selected among 1460 modules have been tested at the Callab, the reference laboratory of the Fraunhofer Institute of Solar Energy in Freiburg. The method has shown with a 99 % confidence level that there is a difference from 2.3 to 3.9 % between the total power of the modules estimated from the reference laboratory’s measurements and the power directly calculated with the manufacturer’s flash-tests. The corrected power of the modules will be used for the monitoring of the 228 kWp system with the MOTHERPV SYST method.

Keywords: photovoltaic modules, photovoltaic system power, Martinique’s PV Performance project, MOTHERPV SYST method

1 INTRODUCTION

It is well known that the determination of the real power of individual modules at standard test conditions (watt-peak, noted Wp) is not easy. During tests by an independent laboratory (see [1]), differences as high as 4 % could be seen between the power measured by a manufacturer and by the laboratory even for very common technologies as crystalline silicon cell modules. For large photovoltaic systems, an additional problem has to be addressed. Obviously, the greater the number of tested modules, the more accurate the prediction of the total power of the system, but, for economical and time reasons, it is not possible to test all the modules. The cost of the tests has to be compared to the possible loss or gain due to the knowledge of the real power.

The quality control procedures for the test of the conformity of a production have been normalized since a long time ([2]) but they are not adapted for the photovoltaic module production, where it is normal to have great variations in the power of the produced (and sold) modules and where these variations do not follow Gaussian distribution functions. Nevertheless, very few works have been performed recently to test the power of a global set of photovoltaic modules.

CIEMAT ([3]) performs extensive test campaigns, which are remarkable by the number of tested modules. These campaigns use the flash-tests of the manufacturer and the test at the laboratory of a given percentage of the modules (typically between 1.5 and 2 %) to estimate the difference between the manufacturer’s tests and laboratory’s results. No uncertainty is given.

The point of view of [4] is different. The objective of the proposed method, which relies also on the flash-tests of the manufacturer and on the test of a limited set of modules at the laboratory, is slightly different. The question is to decide if a shipment of modules is acceptable, i.e. if the power of enough modules satisfies the specification given in a datasheet.

The present work describes a new module reception method, which proposes an estimation of the total power of a set of modules, associated with a confidence level. This confidence level depends on the number of tested modules, which is much lower than the number of tested modules proposed in the standard methods, because they do not take into account the flash-tests of the manufacturer. The method has been already applied several times. It has been improved and applied to the estimation of the power of a 228 kWp roof-integrated photovoltaic system during a common work with SMEM, the company in charge of the distribution of electricity in the Martinique Caribbean Island.

2 MODULE RECEPTION METHOD

2.1 Description

The manufacturer provides the customer with a datasheet of the flash-tests of all the modules, including at least a module identifier, the measured power of the module at the factory and, if possible, its production date.

The manufacturer and the customer agree to a common reference test laboratory and a CL common confidence level of the results, typically 95 % or 99 %.

The manufacturer provides the customer with the datasheet of the flash-tests of all the modules, including at least a module identifier, the measured power of the module at the factory and, if possible, its production date.

The customer determines the number of modules to be tested, depending on his financial possibilities, his confidence in the manufacturer’s quality system and on the observed spread of the modules’ power and production date (the greater the spread, the more modules to be tested). For this task, an expert is recommended.

According to the chosen confidence level and number of modules to be tested, a multiplying coefficient k is determined (see paragraphs 3 and 4).

Modules are selected in order to be representative of the whole population in terms of power and production date. Last but not the least they have to be easily
Gaussian law. It may also follow a uniform distribution

The mathematical problem can be described as follows: “given a random variable following a given distribution, a set of \( N \) random elements in the population and a \( k \) multiplying coefficient, what is the probability that the average of the random variable – zero – lies in the interval \([\text{avg} - k\text{.stdev}, \text{avg} + k\text{.stdev}]\), where \( \text{avg} \) and \( \text{stdev} \) are respectively the average value and the standard deviation of the \( N \) random elements”.

The Monte Carlo method has been used to give a solution to the problem.

According to the result, the manufacturer and the customer may decide to take it into account by any mean (to correct the total price of the modules, to add or subtract modules…)

2.2 Theoretical justification of the method

The measurement of the power of modules by a manufacturer and by a reference laboratory may differ because of many reasons: the flash-testers may be different among different laboratories; the lamps used may be different (time of cooling of the modules after production, recalibration of the flash-testers policy, change of the lamps schedule, training of the people testing the modules…).

These differences may be systematic (biases) and random. For high numbers of tests, differences are averaged and only the biases remain. Anyway, the better the quality control of the manufacturer, the better the repeatability of the difference between manufacturer’s and laboratory’s results.

CIEMAT has observed that the use of laboratory’s reference modules by the manufacturer may bring a better repeatability to the difference, even if sudden shifts may occur (see Fig. 6 in [3]). So, in the best cases, the difference in percentage between the power measured by the manufacturer and by the reference laboratory may differ by a value in the interval \([\text{avg} - k\text{.stdev}, \text{avg} + k\text{.stdev}]\).

According to the result, the manufacturer and the customer may decide to take it into account by any mean (to correct the total price of the modules, to add or subtract modules…).

3 MONTE CARLO METHOD

3.1 Description

Two distribution functions have been created using Excel, with 65536 elements in each population: one standard normal Gaussian distribution and one uniform distribution with a zero average and a standard deviation of one. The values of their average, of their standard deviation and of their cumulative distribution function have been verified.

Then, 8 times 100 000 random sets with respectively 2, 4, 6, 9, 16, 25, 36 and 49 elements have been created. Their average value \( \text{avg} \) and their standard deviation \( \text{stdev} \) have been calculated and the results have been stored in a database. Then, SQL queries have calculated the probability density function of the average and of the standard deviation in order to be able to visualize the behavior of these values. A last program has determined by dichotomy, for each given percentages \( p \), the \( k \) multiplying coefficient giving that \( p \% \) of the total population of 100 000 elements would verify \([\text{avg} - k\text{.stdev}, \text{avg} + k\text{.stdev}]\).

3.2 Results

Fig. 1 to 4 present the probability density function of the average and standard deviation of 2, 4, 9, 16 and 49 random elements chosen among 65536 elements following a given distribution function.

*Figure 1: Probability density function of the average of 2, 4, 9, 16 and 49 random elements of a standard normal Gaussian distribution. As expected, these functions are also Gaussian distributions with a standard deviation of \( 1/\text{sqrt}(N) \), where \( N \) is the number of elements.*
Figure 2: Probability density function of the standard deviation of 2, 4, 9, 16 and 49 random elements of a standard normal Gaussian distribution. For low numbers of random elements, the experimental standard deviation may be a lot lower than 1, the real standard deviation of the distribution.

Figure 3: Probability density function of the average of 2, 4, 9, 16 and 49 random elements of a uniform distribution with $\text{avg} = 0$ and $\text{sd} = 1$. For large number of random elements, these functions are almost identical to the function seen in Fig. 1 a standard normal Gaussian distribution.

Figure 4: For a uniform distribution, the probability density function of the standard deviation tends more quickly to a Gaussian distribution around the true value, 1, than for a Gaussian distribution. The reason is that in a standard normal Gaussian distribution, some values may be far from zero, which is not the case with a uniform function with a standard deviation of 1.

The major result of this study is that the probability function of the average of $N$ random elements does not depend a lot on the shape of the distribution function of the random variable.

Fig. 5 and 6 show the standard deviation of $N$ random elements as a function of their average value.

Figure 5: There is a large spread in the couples (average, standard deviation) of $N$ random elements of a standard normal Gaussian distribution. For example, for 4 elements, the experimental average may be -1 and the standard deviation 0.5, far from the value of the distribution (0, 1). For larger number of elements, experimental values are gathered around the value of the distribution.

Figure 6: For a uniform distribution with $\text{avg} = 0$ and $\text{sd} = 1$, the spread in the couples (average, standard deviation) of $N$ random elements is more limited, since the interval of the possible values is limited, but it still
exists. For large number of elements, the behavior is similar to the behavior of a standard normal Gaussian distribution.

Fig. 7 shows the probability that, given a multiplying coefficient \( k \), the average value of a random variable lies in the interval \([\text{avg} - k \cdot \text{stdev}, \text{avg} + k \cdot \text{stdev}]\), where \( \text{avg} \) and \( \text{stdev} \) are respectively the average value and the standard deviation of the 16 random elements. As expected, the greater \( k \), the greater the probability to get the average value of the random variable in the interval (this can be easily seen in Fig. 5 and 6).

![Graph showing probability versus multiplying coefficient](image)

**Figure 7:** There is a 90% confidence level that a random sample of 16 elements (average \( \text{avg} \), standard deviation \( \text{stdev} \)) of a random distribution with an average value of \( \text{AVG} \) verifies the formula \( \text{avg} - 0.45 \cdot \text{stdev} \leq \text{AVG} \leq \text{avg} + 0.45 \cdot \text{stdev} \), but only a 30% confidence level that the random sample verifies the formula \( \text{avg} - 0.10 \cdot \text{stdev} \leq \text{AVG} \leq \text{avg} + 0.10 \cdot \text{stdev} \). The behaviors of the Gaussian distribution and of the uniform distribution are almost identical.

Tables I and II show the results of the Monte Carlo simulation for 4 to 49 elements randomly selected in a standard normal Gaussian distribution and in a uniform distribution with \( \text{avg} = 0 \) and \( \text{stdev} = 1 \).

It is remarkable to see that the \( k \) multiplying coefficient does not vary a lot for the two distributions, even for relatively small sizes of the sample of \( N \) elements. If the distribution shape is not known, the greater multiplying coefficient will be chosen.

### Table I: Normal Gaussian distribution: multiplying coefficient versus a defined confidence level and the size of the sample

<table>
<thead>
<tr>
<th>Confidence</th>
<th>4</th>
<th>6</th>
<th>9</th>
<th>16</th>
<th>25</th>
<th>36</th>
<th>49</th>
</tr>
</thead>
<tbody>
<tr>
<td>95.0</td>
<td>1.86</td>
<td>1.16</td>
<td>0.82</td>
<td>0.55</td>
<td>0.42</td>
<td>0.34</td>
<td>0.29</td>
</tr>
<tr>
<td>99.0</td>
<td>3.36</td>
<td>1.84</td>
<td>1.20</td>
<td>0.76</td>
<td>0.57</td>
<td>0.46</td>
<td>0.39</td>
</tr>
<tr>
<td>99.5</td>
<td>4.26</td>
<td>2.20</td>
<td>1.37</td>
<td>0.85</td>
<td>0.63</td>
<td>0.51</td>
<td>0.42</td>
</tr>
<tr>
<td>99.9</td>
<td>8.06</td>
<td>3.23</td>
<td>1.80</td>
<td>1.04</td>
<td>0.77</td>
<td>0.60</td>
<td>0.50</td>
</tr>
</tbody>
</table>

### Table II: Uniform distribution: multiplying coefficient versus a defined confidence level and size of the sample

<table>
<thead>
<tr>
<th>Confidence</th>
<th>Size of the sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>95.0</td>
<td>2.24 1.25 0.84 0.55 0.42 0.34 0.29</td>
</tr>
<tr>
<td>99.0</td>
<td>4.70 2.21 1.30 0.79 0.58 0.47 0.39</td>
</tr>
<tr>
<td>99.5</td>
<td>6.27 2.74 1.53 0.89 0.65 0.51 0.43</td>
</tr>
<tr>
<td>99.9</td>
<td>11.05 4.32 2.16 1.14 0.81 0.62 0.52</td>
</tr>
</tbody>
</table>

### 4 APPLICATION OF THE MODULE RECEPTION METHOD TO SMEM’S MODULES

#### 4.1 Description

SMEM bought 1460 mono-crystalline modules from a module manufacturer, for a total power of 258 kWp. Most of these modules were used for a 228 kWp roof-integrated photovoltaic system at Rivière Salée, Martinique Island.

The modules were produced in October and November 2008. They were all flash-tested by the manufacturer and their nominal power lied between 173 and 183 Wp. The manufacturer provided the flash-test datasheet.

SMEM decided that a confidence level of 99.0% was convenient for this first test of the manufacturer’s modules and that, according to the cost of the test of the modules and to the desired confidence level, 16 modules should be tested. The chosen multiplying coefficient was 0.79 (see table II).

16 modules were selected according to the procedure described in the paragraph 2. This task was less difficult than expected, partly thanks to the good collaboration of the manufacturer who accepted to fetch the selected modules.

Then, the modules were sent to the chosen reference laboratory, the Callab laboratory from the ISE Fraunhofer Institute in Freiburg, Germany. They were flash-tested and the result of the tests was sent to SMEM in a datasheet.

INES/CEA calculated the average and the standard deviation of the difference between Callab’s and manufacturer’s tests and provided the final result to SMEM.

#### 4.2 Results

Fig. 8 shows the spread of the difference between the measurements of the manufacturer and the Callab.

There is no obvious outlier in the measurements. All the data seem compatible with a uniform distribution. There is no visible effect related to the power or the manufacturing date of the modules.

The final result of the module reception method was that, with a 99% confidence level, the total power of the sold modules differed by a value between 2.3 and 3.9% from what was announced by the manufacturer.
The difference between the flash-tests of the manufacturer and the power measured by the reference laboratory varies between 1.9 and 5.1%. The average difference is 3.1%, the standard deviation is 1.0%. These 16 flash-tests allow the determination with a great accuracy of the total power of the modules of a 228 kWp roof-integrated photovoltaic system.

Thanks to the module reception method, a corrective coefficient of 3.1% was adopted and the power of all the modules was calculated by using this corrective coefficient. This new power will be used for the future monitoring of the SMEM’s photovoltaic 228 kWp system with the MOTHERPV SYST method [5].

5 CONCLUSION

During a common work, the Martinique’s PV performance project, a new module reception method has been successfully applied by INES/CEA, the French National Solar Institute, and SMEM, the company in charge of the distribution of electricity in the Martinique Caribbean Island. This method determines the total power (watt-peak) of a photovoltaic system and the related uncertainty by using the factory flash-tests of all the modules and by testing in a reference laboratory the power of a very limited set of carefully selected modules.

The method is based on a Monte Carlo simulation. The method had been successfully applied to a 228 kWp SMEM’s photovoltaic system. It allowed the determination with a given confidence level of the difference between the total power of the modules announced by the manufacturer and the total power measured by the reference laboratory.

The new power the modules was calculated. It will be used for the future accurate monitoring of SMEM’s photovoltaic systems with the MOTHERPV SYST method, within the Martinique’s PV performance project.

6 REFERENCES