CONTRIBUTIONS TO THE KNOWLEDGE BASE ON PV PERFORMANCE: EVALUATION OF THE OPERATION OF PV SYSTEMS USING DIFFERENT TECHNOLOGIES INSTALLED IN SOUTHERN NORWAY

Hans Georg Beyer, Georgi Hristov Yordanov, Ole-Morten Midtgård, Tor O. Saetre, Anne Gerd Imenes

1University of Agder, Faculty of Engineering and Science, Grimstad, Norway
2Teknova AS, Kristiansand, Norway
3NTNU, Trondheim, Norway

ABSTRACT

To assist in establishing an accepted knowledge base on PV-modules and systems performance using a representative range of technologies, devices have to be installed at diverse locations, covering a broad range of environmental conditions. For the example of a high latitude location, modules and systems are installed and under investigation in southern Norway (Kristiansand region) by the University of Agder in cooperation with industrial partners. This paper presents first results of the analysis of module performance. The operational behavior of the modules is used to derive a modeling scheme applicable for performance prediction. This use is demonstrated by giving the expected annual performance of different module technologies for a set of sites in southern Norway.

INTRODUCTION

In view of the rapidly developing PV-market and the broad range of PV-technologies that are nowadays offered to the consumers, it is necessary to gain information on the performance of the products. This - besides aspects related to environmental issues as related to the use of hazardous materials - covers mainly the energetic performance in view of energy gain in relation to installed capacity and the respective costs.

In contrast to the well-defined standards for the power characterization of the components, the standards for the characterization of the energetic performance are still in discussion. To support their development, international activities as e.g. the EU-PERFORMANCE project [1] had been performed or are newly active (i.e. Task 13 of the IEA PVPS program [2]). One of the goals of this effort is the establishment of commonly accepted procedures to predict the lifetime energy gain of the different PV-technologies at a specific location in a comprehensive way. This has to include the response of the system to the varying environmental conditions (irradiance and temperatures).

PROJECT

To assist in establishing the required data and knowledge base, PV-modules and systems using a representative range of technologies have to be operated and analyzed at diverse locations covering a broad range of environmental and operation conditions. For the example of a high latitude location (58° 20' North) with moderate climatic conditions (annual radiation sum on a horizontal surface ~900 kWh/m²), modules and systems are installed and under investigation in southern Norway (Kristiansand region) at the University of Agder (for location see Fig. 1) in cooperation with industrial partners. University of Agder is Norwegian contributor to IEA Task13.

Figure 1 Location of the test site in Grimstad (Southern Norway).

The test bench at the University of Agder

At the new campus of the University of Agder in Grimstad, a test bench for module performance has been installed in November 2010. Both new and aged modules are under investigation. Represented technologies cover crystalline silicon of various cell designs, thin-film devices of CIS and amorphous silicon material as well as a cSi/aSi hetero-junction (HIT) module. The modules are mounted on a flat roof platform (see Fig. 2) facing almost to the south, with a small deviation of 7° to the east.

Figure 2 Impression of the PV test bench at University of Agder.
Current-voltage characteristics (I/V curves) of ten PVmodules are recorded simultaneously each minute. The sweep time used is 1 second. The corresponding environmental and module parameters are extracted to form the 1-minute data set. Between the sweeps, the modules are continuously operated at maximum power point (MPP) conditions in order to maintain realistic module temperatures. Irradiance and modules’ powers are sampled at a resolution of 0.01 s during this MPP-tracking phase. These irradiance data form the real-time data set, whereas the modules’ powers are stored as 1-second averages. Detailed analysis of the I/V curves for an in-depth characterization of the crystalline modules is given elsewhere [3,4]. In this paper, we concentrate on the analysis of the MPP data. The parameters from the 1-minute data set used in this study are given in Table 1.

Table 1: List of parameters used.

<table>
<thead>
<tr>
<th>Operation conditions</th>
<th>Electrical parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-plane irradiance</td>
<td>short circuit current, (I_{SC})</td>
</tr>
<tr>
<td>(Pyranometer), (G)</td>
<td>open circuit voltage, (V_{OC})</td>
</tr>
<tr>
<td>ambient temperature, (T)</td>
<td>voltage at MPP, (V_{MPP})</td>
</tr>
<tr>
<td>back of module</td>
<td>power at MPP, (P_{MPP})</td>
</tr>
<tr>
<td>temperature, (T_{mod})</td>
<td></td>
</tr>
</tbody>
</table>

Analysis of the MPP power in dependence of irradiance and module temperature

In the following we will use the data recorded in March and April 2011 for the modules listed in Table 2. Models to predict the modules MPP power for given irradiance and module temperatures are derived from this set. The basic modeling scheme is taken from the findings of the Performance project [1]. Model parameters are derived from the data for one month. The second month is used for model validation. The applicability of the model is shown by its application for the prediction of the annual performance at Grimstad and 3 other locations in southern Norway, giving a first insight in the performance difference of the technologies investigated.

THE MODELLING SCHEME

Model description

The scheme used is based on the application of an semi-empirical model describing the dependency of the MPP power output of the module as function of irradiance and temperature (see e.g. [5,6]). It represents one of several semi-empirical approaches to describe the shape of the efficiency surfaces \(\eta_{mpp}(G,T)\) as compared in the EU-Performance project [1]. The model is given by:

\[
\eta_{mpp} = (a_1 + a_2 G + a_3 \ln(G \cdot m^3) \cdot (1 + \alpha(T_{mod} - 25^\circ C)))
\]  

The parameters \((a_1, a_2, a_3\) and \(\alpha)\) of this model can either be gained from appropriate data sheet values or measured data from outdoor tests or operation. The model is well tested for cSi, CIS and CdTe modules and is in operational use for system monitoring purposes [6].

The direct application of this model for modules using amorphous silicon material (aSi) give less satisfactory results. Reasons may be traced back to problems in modeling the basic dependency of current generation on the incoming irradiance \(I_{SC}(G)\), the remarkable spectral dependency of this relation for aSi material being named here [7]. This may be illustrated by Fig. 3, showing the scatter of MPP power of the aSi module versus the pyranometer measured irradiance. In contrast, the dependency of the MPP power on short-circuit current gives a comparatively clear pattern (see Fig. 4).

Figure 3 Power at MPP vs. in-plane irradiance for the aSi module.

Figure 4 Power at MPP vs. short-circuit current for the aSi module.
To deal with this problem, the model is enhanced by subdividing into the two modeling steps: determination of the short-circuit current in dependence of meteorological conditions and determination of the MPP-power from the short-circuit current. The efficiency model \( \eta_{\text{MPP}}(G,T) \) used above is replaced by a model for the response of the MPP-power to the short-circuit current

\[
\frac{P_{\text{MPP}}}{I_{\text{SC}}} = (a_1 + a_2 \cdot I_{\text{SC}} + a_3 \ln(I_{\text{SC}} \cdot \frac{1}{\text{mA}})) \cdot (1 + \alpha(T_{\text{mod}} - 25^\circ C))
\]

For the detailed modeling of the short-circuit current, knowledge of the spectral composition of the irradiance would be necessary. In absence of spectral data, it was shown that information on spectral effects can be approximated by using available information on airmass and clearness index as indicators on the main factors influencing the spectral composition [7,8]. A stripped down version of this approach, applicable for the data at hand is given by the analysis of the dependency of \( I_{\text{SC}} \) on irradiance, airmass (AM) and temperature, modeled by:

\[
I_{\text{SC}} = c_0 \cdot G \cdot \exp(c_1 \cdot AM) \cdot (1 + c_2 (T_{\text{mod}} - 25^\circ C))
\]

It should be noted that the airmass dependency in (3) also acts as a place holder for all angular effects. Fig. 5 gives the performance of this simple approach, showing the empirical \( I_{\text{SC}} \) vs. \( G(\text{airmass}) \) data together with the modeled data for the same set.

\[
P_{\text{MPP}} = c_0 \cdot G \cdot (1 + c_1 (T_{\text{mod}} - 25^\circ C))
\]

(4)

MODEL TEST

The data measured at the test bench are used to determine the model parameters of the schemes described above for the different modules. For this purpose the solver option of excell® is used in a least-square scheme for the differences of measured and modeled power output. Data from one month are used for the parameter identification, data for the second month for validation. Basic data for the modules analyzed are given in Table 2.

<table>
<thead>
<tr>
<th>Type</th>
<th>nameplate power</th>
<th>status</th>
</tr>
</thead>
<tbody>
<tr>
<td>cSi</td>
<td>217 W</td>
<td>new</td>
</tr>
<tr>
<td>cSi</td>
<td>300 W</td>
<td>new</td>
</tr>
<tr>
<td>CIS</td>
<td>109 W</td>
<td>new</td>
</tr>
<tr>
<td>aSi</td>
<td>64 W</td>
<td>aged</td>
</tr>
<tr>
<td>HIT</td>
<td>240 W</td>
<td>new</td>
</tr>
</tbody>
</table>

cSi modules

Fig. 6 gives the data for one of the cSi modules recorded in April. It has to be noted here, that these data are one-minute data subject to quite high statistical scatter. In addition, it may be remarked, that in the one minute data set irradiances well above expected clear sky irradiances appear. This type of “over-irradiances”, by cloud influences are e.g. discussed by [9].

![Figure 5 Ratio of short-circuit current to irradiance vs. airmass for the aSi module, month of March.](image)

![Figure 6 Power at MPP vs. in-plane irradiance for the cSi1 module.](image)
These data — after a filtering for incidence angles lower than 30° — are used for identification of the model parameters as described above. Fig. 7 gives the resulting modeled values for $\eta_{\text{MPP}}(G,T)$. The regression line for this set proves the quality of the modeling. The cumulated energy differs by less than one percent.

Applying the same parameter set to the data set from March results in an almost identical match. The monthly sums differ by 1.7%. Fig. 8 gives the respective scatter plot proving the applicability of the modeling scheme for this module.

For the second cSi module the results are a little less convincing. Application of the parameters set derived for April to data set for March results in a deviation of 3% in the cumulated energy. Fig. 9 gives the temporal evolution of measured and modeled cumulated energy for that month.

CIS

For the CIS module the same procedure results in a difference of 2 percent. The evolution of the cumulated energy is given in Fig. 10. Deviations of a few percent in modeled and measured energy had also been reported in the round robin tests ‘same module different time period’ as performed in the Performance project for cSi and CIS modules [10].

For the second CIS module, month of March. Model parameters are derived from the data set of the month of April.
Modules using amorphous silicon material

For the aSi and the HIT modules, the modeling scheme taking into account the airmass for deriving a value the short-circuit current is used.

\textbf{aSi}

For the aSi module, the model as given in Fig. 5 is used. The parameters of the $P_{\text{MPP}}/I_{\text{SC}}$ model are determined for the March data set resulting in an initial model error of less than one percent. The application to the April data set gives disagreement of 3%. The test for the $P_{\text{MPP}}/I_{\text{SC}}$ model confirms (see Fig. 11) again, that the uncertainties are caused by the model for the short-circuit current.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure11.png}
\caption{Ratio of MPP-power to short-circuit current vs. the short-circuit current from measurement and model for the aSi module, month of April. The model parameters are derived from the data set for the month of March.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure12.png}
\caption{Energy gain cumulated over consecutive samples for the modeled and measured sets for the HIT module, month March. Model parameters are derived from the data set of the month of April.}
\end{figure}

\textbf{HIT}

The application of the same procedure for the HIT module is currently less satisfactory. The model derived for the April data leads to an error in energy gain for March of 7%. See Fig. 12 for the evolution of the cumulated energies. Exchange of the month for parameter determination and test does not give a more positive result.

Conclusions from the module test

Based on the small data set available up to now, it may be concluded that both, the measurement set-up and the modeling approach are valuable tools. The performance of the tools for the power modeling for modules based on cSi, CIS and aSi material is quite satisfactory. For the modeling of the HIT technology, further model development seems to be necessary to reach a modeling quality comparable to those for the other technologies. However, the power at STC conditions given by the model confirms with a deviation of less than 2% to the nameplate STC power (for the module cSi this deviation to nameplate power is +1%, for the CIS module -6%; for the modules cSi2 and aSi the respective values are -15% and -26%).

\textbf{OUTLOOK}

Parameter sets derived from a more comprehensive data set should be used to predict the DC-performance of the different technologies to allow for general statements of their relative benefits. Here, a short example of such a scheme based on the current preliminary results is given. For the cSi, CIS and aSi modules analyzed, the expected DC-yield and DC-performance ratio (PR, DC) values for 4 locations in southern Norway are derived (see Table 3). The sites taken into account are Grimstad (58°20’ North, 8°35’ East), Oslo (59°55’ North, 10°45’ East), Stavanger (58°56’ North, 5°44’ East) and Bergen (60°23’ North, 5°20’ East). The meteorological data are generated with the Meteonorm tool [11]. The data sets comprise irradiance on an inclined plane, ambient temperature, and the respective data for the solar geometry to derive the airmass. The ambient temperature is transformed to a module temperature assuming the installation of the modules at a free standing rack using a model as e.g. described in [6]. For the module orientation, the optimal slope for the sites as indicated by the PVGIS server [12] is used.

For the performance ratio, the results gained are given in Table 3. It should be noted, that the PR given is based on the STC-power as determined from the models derived in the test. It is obvious that for the different modules there is no remarkable difference in the performance ratio in this sample.
Table 3 Estimated values for the DC-Performance ratio of the modules inspected at 4 locations in Norway

<table>
<thead>
<tr>
<th></th>
<th>PR_DC</th>
<th>cSi1</th>
<th>cSi2</th>
<th>CIS</th>
<th>aSi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grimstad</td>
<td>0.97</td>
<td>0.97</td>
<td>0.96</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>Oslo</td>
<td>0.97</td>
<td>0.97</td>
<td>0.96</td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td>Stavanger</td>
<td>0.95</td>
<td>0.96</td>
<td>0.95</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>Bergen</td>
<td>0.95</td>
<td>0.96</td>
<td>0.94</td>
<td>0.96</td>
<td></td>
</tr>
</tbody>
</table>

CONCLUSIONS

We have presented results from a PV test bench in southern Norway (58°20' North). It could be demonstrated, that the data gained could be used to derive validated models for the power output of the modules that are applicable for the modeling of the yield and the performance ratio. It has to be stated, that the absolute values of the performance ratio stated here need additional approval, as the basis for the model derivation and test has to be enlarged. In addition, the module test needs regular repetition, to trace the onset or continuation of a possible degradation process of the modules.

REFERENCES

[1] Ch. Reise, Four years of PERFORMANCE – was it worth the effort?”, Twenty-third EUPVSEC, Valencia, Spain, 2008, pp. 3110-3115


