EFFECTIVE EFFICIENCY AND PERFORMANCE RATIO AS ENERGY RATING SYSTEM FOR PV MODULES

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ABSTRACT: PV module energy rating assessment can be expressed by an annual effective efficiency and a module performance ratio, which both weight the module specific data by location specific data. Two approaches are presented: (i) a more accurate one with hourly averaged data over a year and a model of PV module and (ii) a simplified approach with annual hourly averaged irradiance histogram and the module specific data represented by normalized conversion efficiency as a function of irradiance at the average daylight ambient temperature. Five PV modules are evaluated by both approaches in Ljubljana for different tilts and tracking schemes. Differences arise from different distribution of annual solar energy as a function of irradiance for a specific case, but performance ratio results are only weakly dependent on the specific location, the tilt angle of the module or the tracking scheme. We have shown that PV modules with lower effective series resistance exhibit better performance at higher irradiation (e.g. in tracking schemes) and PV modules with lower $G_{sh}$ perform better at low irradiation (e.g. fixed installations).

Keywords: PV module, modeling, energy rating

1 INTRODUCTION

Single defined tests, such as standard test conditions (STC) with one-sun irradiance ($G_0 = 1 \text{ kW/m}^2$, AM1.5 spectrum) and cell temperature ($T_j$) of 25 °C or PTC (PVUSA Test Conditions) with the same irradiance but ambient temperature ($T_{amb}$) of 20 °C, are not sufficient protocols for energy rating and comparing PV modules under field conditions. Some groups have suggested inclusion of spectral change effects in energy rating of modules by rating them for typical days [1,2]. Such approach treats temperature and irradiance variations including spectral changes on a daily basis accurately, but does not render accurate energy rating over a year.

To predict the effective efficiency averaged over a typical year of operation at given location for given installation site with precision an average over time-dependent irradiance, ambient temperature, and solar-irradiance-angle distributions at the installation site is required (Fig. 1). In this paper, such an approach is implemented by means of hourly averaged data and compared to a straightforward procedure [5] used previously to evaluate PV modules’ field performance by means of intensity dependent normalized conversion efficiency. Both approaches quantify results in annual effective efficiency and performance ratio of a PV module. We explain both assessment procedures for various installations in Ljubljana, Slovenia, in Central Europe. Different installation schemes include fixed installations with different tilts, tilted 1-axis tracking and 2-axis tracking. We have done this comparison for several PV modules currently being marketed. We will demonstrate how differences in irradiation impact the effective efficiency in the field and discuss the approaches for PV module energy rating.

2 PROCEDURES TO ASSESS MODULE FIELD PERFORMANCE

Instead of single-defined test efficiency we introduce effective efficiency ($\eta_{eff}$), which can be calculated as an annual ratio of total available electrical energy generated ($EE$) divided by annual solar energy per unit area ($SE$):

$$\eta_{eff} = \frac{EE}{SE} = \frac{\int_{year} \eta(G,T_{amb}) \cdot G \cdot dt}{\int_{year} G \cdot dt}$$

where $G$ is time-dependent irradiance ($\text{W/m}^2$), $T_{amb}$ is time-dependent ambient temperature (°C). Formally, the spectral profile and incidence angles for different irradiance conditions should also be included, and the integral done over wavelength as well.

We refer to the effective-efficiency to STC-efficiency ratio as the PV module’s annual performance ratio ($PR_{M}$), which can also be expressed as:

$$PR_{M} = \frac{\eta_{eff}}{\eta_{STC}} = \frac{Y_{M} \cdot G_{h}}{SE}$$

where $Y_{M}$ is the PV module's annual yield (kWh/yr/kWp) and $G_{h}$ is the STC irradiance (1000 W/m², AM1.5). $PR_{M}$ is more general than $Y_{M}$, because it normalizes $Y_{M}$ to the given location-specific $SE$ and thus becomes a more universal parameter for comparison of PV module field performance for different locations [5,6].

Instead of integration in Eq. (1), we can calculate $\eta_{eff}$ or $PR_{M}$ by summing averaged hourly contributions over a year:

\[ Y_{M} = \sum_{i=1}^{n} \eta_{eff,i} \cdot G_{h,i} \]

\[ PR_{M} = \frac{Y_{M}}{SE} \]

Fig. 1 Input data needed to assess the outdoor performance. Location specific data are time-dependent.
where the actual temperature variations are very well approximated by an average daylight ambient temperature \( T_{\text{amb AVG daylight}} \). The simplified approach neglects spectral changes and uses a single typical irradiance spectrum, which produces on a yearly basis a small error, which will be discussed later. The module specific data is represented with normalized conversion efficiency as a function of irradiance at the \( T_{\text{amb AVG daylight}} \) (normalized to the given STC conversion efficiency).

Normalized conversion efficiency vs. irradiance for a PV module at specific \( T_{\text{amb}} \) can be either measured or simulated by proper model with input parameters. Our model consists of serially connected solar cells based on a one-diode model with effective series resistance \( R_s \) and shunt conductance \( G_{sh} \). The input parameters were deduced from current-voltage characteristics of PV modules at different irradiances and temperatures published by manufacturers.

Figure 2 shows simulated normalized \( \eta \) vs. \( G \) curves at \( T_{\text{amb}} = 20 \) °C for modules from several manufacturers and technologies (monocrystalline silicon – Shell Solar SM110 [7] and multi/ribbon-crystalline silicon – RWE Schott Solar ASE-160 [8], CIGS – Wurth Solar WS75 [9], CdTe – First Solar FS55 [10], and amorphous silicon (a-Si) – Mitsubishi Heavy Ind. MA100 [11]) deduced from datasheets. In each case, the maximum of normalized efficiency is in the vicinity of one-half sun, but there are differences in how the efficiency falls off for high and low irradiance. Modules with larger series resistance had a more negative slope at higher irradiances, which lowers the one-sun efficiency compared to that near one-half sun. Those with larger leakage had a greater efficiency decrease at lower irradiance. The simulation of the a-Si and CdTe modules was slightly more complicated than the others, because the effective \( G_{sh} \) was significantly smaller at lower irradiances (modeled as \( G_{sh} \) increasing linearly with \( G \)). Among the modules, FS55 (CdTe) module exhibits the best normalized conversion efficiency regardless the irradiance up to 1 sun.

Figure 3 shows the profile of the annual irradiance histogram, based on hourly averaged irradiance, in Ljubljana (latitude = 46.07° N, longitude = 14.52° E) for an installation without tracking (tilt=30°, azimuth=180°) and for a 2-axis tracking installation. The vertical scale (ASE) is the contribution of solar irradiation each year at an irradiance interval between \( G \) and \( G+\Delta G \) (\( \Delta G = 25 \) W/m²), and the horizontal axis is the irradiance \( G \). Thus, the total annual solar energy per unit area (SE) for each location in kWh/m²/yr is the sum of the individual contributions. The profile on a 30°-tilted surface facing south for Ljubljana sums to 1296 kWh/m²/yr, while a 2-axis tracking installation yields 1620 kWh/m²/yr.

Figure 3. Distribution of annual solar energy in Ljubljana on a 30°-tilted surface facing south and a 2-axis sun-tracking surface. Irradiance is divided into 25 W/m² increments.

### 3 RESULTS

Table 1 shows annual performance ratios calculated by the simplified approach (Eq. 4) and Table 2 shows performance ratio calculated by hourly averages across the year (Eq. 3) for five PV modules (SM110, ASE-160, WS75, FS55 and MA100) for Ljubljana at different tilts and tracking schemes.

Despite some differences among modules, there is only weak dependency of \( PR_M \) over a broad range of tilt angles for fixed position, which was already calculated.

### Table 1. Calculated annual performance ratio for several modules by simplified approach (Eq. 4).

<table>
<thead>
<tr>
<th>PV module</th>
<th>( PR_M )</th>
<th>( SE ) (kWh/m²/yr)</th>
<th>( PR_M )</th>
<th>( SE ) (kWh/m²/yr)</th>
<th>( PR_M )</th>
<th>( SE ) (kWh/m²/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM110</td>
<td>0.94</td>
<td>0.94</td>
<td>0.94</td>
<td>0.94</td>
<td>0.94</td>
<td>0.94</td>
</tr>
<tr>
<td>ASE-160</td>
<td>0.90</td>
<td>0.91</td>
<td>0.90</td>
<td>0.91</td>
<td>0.90</td>
<td>0.91</td>
</tr>
<tr>
<td>WS75</td>
<td>0.92</td>
<td>0.93</td>
<td>0.92</td>
<td>0.93</td>
<td>0.92</td>
<td>0.93</td>
</tr>
<tr>
<td>FS55</td>
<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td>MA100</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
</tr>
</tbody>
</table>
by the simplified approach and reported in [5,6], is confirmed with results of a more thorough approach (Table 2), which takes into account actual spectral changes and ambient temperatures. Larger differences in calculated PRs values by both approaches occur in thin-film PV modules, where the FS55 (CdTe) module is the most sensitive to spectral changes (9% relative increase).

Despite a significant difference in irradiance conditions, however, the values of PRs for each module show little variation between different tilts and tracking schemes. Both, FS55 (CdTe) and MA100 (a-Si) module suffer more evident decrease of PRs by increasing the share of higher irradiance (e.g., 2-axis tracking in Fig. 3). A decrease of PRs originates from lower normalized efficiency at higher irradiance (Fig. 2) due to effective series resistance.

Dependence of calculated modules’ PRs (detailed approach) on tilt for fixed or 1-axis tracking installation is shown in Fig. 4. FS55 exhibits the highest PRs irrespective the tilt or tracking scheme. The ASE160 module exhibits lowest PRs for all fixed tilts due to the worst performance at low irradiances (Fig. 2), but it improves with 1-axis tracking scheme regardless the tilt. On the other hand, all other modules exhibit a decrease in PRs when 1-axis tracking is included (most strongly for MA100), since series resistance reduces the performance at higher irradiances.

To improve the modules’ performance ratio, their four parameters: dI/dG, δ, Rs, and Gsh should be as small as possible. There is little potential, however, to improve dI/dG, where values for all modules under consideration are close to 0.03 °C/(W/m²), since all flat-plate modules are good absorbers and sealed with glass and/or a back sheet. Similarly, δ is determined by the technology employed, predominately by the band-gap of absorber layer. They both are considered more appropriately in PTC efficiency than in STC efficiency. However, the module parameters that affect the overall field performance are the effective series resistance Rs and the effective leakage conductance Gsh [5].

### 4 DISCUSSION

To predict PV module field performance with precision requires an hourly average over the illumination, temperature, and solar-angle distributions at the installation site and a detailed model of PV module. We have shown that the detailed approach does not vary much from the simplified approach, especially for crystalline Si PV modules. For thin-film PV modules, a detailed approach is more realistic and reveals the advantage of thin-film modules. PRs is relatively insensitive to the details of these distributions as long as the distribution of annual solar energy remains the same shape regardless the total irradiation. Therefore evaluation at one site gives a reasonable effective efficiency for many other locations. The question remains whether there is a simple protocol that predicts with sufficient accuracy the effective module efficiency averaged over a typical year of operation.

The STC module rating or PTC module rating at one sun and different module temperatures implicitly assumes that all module efficiencies have the same relative irradiance dependence. In Fig. 5 we show that irradiance dependence is quite strong and such rating approaches are thus not accurate enough. The impact of series resistance will lower the rating at one-sun of some modules more than others. An additional factor in outdoor energy rating is the effective leakage of a module, which affects the module efficiency at lower illumination. Although cell temperature tends to increase with illumination intensity at approximately the same rate for all modules [14], the fractional decrease of efficiency with temperature can vary significantly among modules.

The normal-operating-condition (NOC) rating, based on ambient temperature (20 °C), compensates for variations in the module temperature coefficient as PTC and evaluates the efficiency at 0.8 sun (Fig. 5), closer to the average operational irradiance. This only partially addresses the series-resistance issue. In addition, the distribution of annual solar irradiation in Ljubljana and many other European locations tends to peak closer to 0.5 sun for fixed installations, while for 2-axis tracking it is around 0.8 sun.

The solution we recommend regardless of the installation scheme applied is to measure efficiency at multiple illuminations (0.1- or 0.2-sun intervals) under constant ambient temperature. An average of these values, weighted by a solar-radiation distribution based on hourly average values (Fig. 3), should give an effective efficiency consistent with operation of the module in the field. More exact results can be rendered by simulation of the module’s performance over a year.

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**Table 2. Calculated annual performance ratio for several modules by detailed approach (Eq. 3).**

<table>
<thead>
<tr>
<th>PV module</th>
<th>SE (kWh/m²/yr)</th>
<th>Ljubljana (ϕ = 30°)</th>
<th>Ljubljana (ϕ = 30°, 1-axis)</th>
<th>Ljubljana (2-axis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM110</td>
<td>0.94</td>
<td>0.93</td>
<td>0.93</td>
<td>0.93</td>
</tr>
<tr>
<td>ASE-160</td>
<td>0.92</td>
<td>0.93</td>
<td>0.93</td>
<td>0.93</td>
</tr>
<tr>
<td>WS75</td>
<td>0.94</td>
<td>0.93</td>
<td>0.93</td>
<td>0.93</td>
</tr>
<tr>
<td>FS55</td>
<td>1.07</td>
<td>1.05</td>
<td>1.04</td>
<td>1.04</td>
</tr>
<tr>
<td>MA100</td>
<td>0.98</td>
<td>0.94</td>
<td>0.93</td>
<td>0.93</td>
</tr>
</tbody>
</table>

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**Figure 4. Calculated PRs of different modules (by detailed approach) at different tilts without or with 1-axis tracking (lines as guide to the eyes).**
Figure 5. Normalized conversion efficiency of SM110 and its reported data (performance at STC, PTC, NOCT and low irradiance).

using serially connected solar cells with one-diode model and hourly averaged irradiances and temperatures.

We have demonstrated that PV modules with higher $R_s$ exhibit poorer performance at higher irradiation (e.g. in tracking schemes). On the other hand, PV modules with higher $G_{sh}$ may perform less well at low irradiation (e.g. fixed tilt installations in northern locations).

5 CONCLUSIONS

PV module performance assessment can be expressed by the annual effective efficiency and the module performance ratio, which both weight the module specific data by location specific data. Two approaches were presented: (i) a more accurate one with hourly averaged data over a year and a model of PV module and (ii) a simplified approach with annual hourly averaged irradiance histogram and the module specific data represented by normalized conversion efficiency as a function of irradiance at the average daylight ambient temperature. We demonstrated how to calculate the annual outdoor performance ratio of five PV modules in Ljubljana for different tilts and tracking schemes.

Differences arise in distribution of annual solar energy as a function of irradiance for a specific scheme, but performance ratio results are only weakly dependent on the specific location, the tilt angle of the module or tracking scheme. Normal variations in the spectral distribution do not affect crystalline Si modules significantly, but affect thin-film PV modules much more, in particular CdTe modules. An accurate approach proved that the performance of all PV modules in all schemes is nearly independent of actual temperature fluctuations, but it depends on the average annual daylight ambient temperature. We have shown that PV modules with higher $R_s$ exhibit poorer performance at higher irradiation (e.g. in tracking schemes). On the other hand, PV modules with higher $G_{sh}$ may perform less well at low irradiation (e.g. fixed installations).

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7 REFERENCES


