Energy Production and Performance of Polycrystalline Silicon Technology Photovoltaic Modules in the Field

Preprint

J.A. del Cueto

To be presented at the NCPV Program Review Meeting
Lakewood, Colorado
14-17 October 2001
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Energy Production and Performance of Polycrystalline Silicon Technology Photovoltaic Modules in the Field

J.A. del Cueto
National Renewable Energy Laboratory (NREL)
1617 Cole Blvd., Golden, CO 80401

ABSTRACT

Six polycrystalline silicon photovoltaic modules—two apiece from three manufacturers—were simultaneously deployed outdoors on the performance and energy ratings testbed at NREL’s Outdoor Test Facility (OTF) in June 2000. In situ electrical performance and energy production from these modules obtained under ambient conditions in the field between June 2000 and August 2001 are compared. The average effective efficiency—derived from module energy out divided by solar energy in calculations averaged on a weekly basis—is analyzed and compared with module current-voltage measurements performed at standard reporting conditions (SRC). The effective efficiencies exhibit seasonal variations correlated with average module temperatures—becoming larger at colder temperatures. The performance ratios (PRs) defined as the effective efficiency divided by the efficiency at SRC, range from 78% to 96%, depending on the module and time of the year. The PRs exhibit seasonal variations that range from 11% to 15%.

1. Introduction

Photovoltaic (PV) modules are rated by their current-voltage (I-V) characteristics measured at SRC. Yet, because operating conditions typically encountered in the field rarely emulate SRC, module performance in the field must be either explicitly modeled or measured. In this paper, the actual electrical performance data of polycrystalline-silicon (poly-c-Si) PV modules measured in situ are featured and compared. Module energy production, effective efficiency ($\eta_{\text{EFF}}$) and performance ratio (PR) are derived on a weekly basis. The $\eta_{\text{EFF}}$ is analyzed because it represents module energy output ($E_{\text{OUT}}$) divided by the incident solar insolation. The PR—defined as the $\eta_{\text{EFF}}$ divided by the efficiency measured at SRC ($\eta_{\text{SRC}}$)—denotes how much of the $\eta_{\text{SRC}}$ may be realized under typical field conditions. Temperature coefficients derived for the $E_{\text{OUT}}$ of the modules are also presented. They are likely to differ from canonical coefficients due to incorporation of varying light intensities and spectral content thereof in their derivation.

2. Experimental

Six poly-c-Si PV modules, each nominally rated as 40- to 50-watt (W) units, two apiece from three separate manufacturers, are studied—denoted X, Y, Z. Each module consists of 36 individual poly-c-Si cells interconnected in series, ranging between 0.32 m² and 0.43 m² in aperture areas. Prior to deployment, module I-V characteristics were measured at SRC both indoors and outdoors. For all six modules, the $\eta_{\text{SRC}}$ data ranged between 10.7% and 11.5%.

The six modules were deployed simultaneously in June of 2000 on the performance and energy ratings testbed (PERT), onto an open-air steel structure situated on the roof of the OTF. These are erected at fixed tilt—corresponding to the latitude for the site, 40° with respect to horizontal—facing due south ±2° and grouped closely together. These are electrically connected to data acquisition systems that monitor their I-V characteristics or otherwise actively keep them loaded constantly at their respective peak-power-point voltage and current. It is the peak-power-point tracking data that are featured in this paper. Measurements of module and ambient temperatures, and irradiance are also available from PERT data. More details concerning the PERT may be found in the literature [1, 2].

Basic module performance statistics were calculated on a weekly basis: daily average module $E_{\text{OUT}}$ and insolation, module and ambient temperatures, and effective efficiency. Module $E_{\text{OUT}}$ and insolation are derived, respectively, by integration of the average module power and irradiance versus time profiles. The $\eta_{\text{EFF}}$ is taken as the quotient of module $E_{\text{OUT}}$ divided by product of insolation times module area. All data taken between June 2000 and Aug. 2001 are analyzed with some exceptions: Aug.–Sep. 2000 due to PERT system downtime, and full or part snow days.

3. Results

Fig. 1 depicts daily $E_{\text{OUT}}$—average over both modules from each manufacturer—plotted against insolation, calculated weekly. At our locale in Golden, CO, the average insolation incident at latitude tilt, computed throughout the year is ~5.3 kilowatt-hours per square meter per diem (kW-hrs/m²/day), with a variance of ~43%. The corresponding daily average $E_{\text{OUT}}$ for module types X, Y, Z are 171.3, 207.8, 175.1 W-hr/day, respectively, throughout the year; percent-wise, the corresponding variances in the data scale 100% 120% 140% 160% 180% 200% 220% 240% 260% 280% 3.0 3.4 3.8 4.2 4.6 5.0 5.4 5.8 6.2 6.6 7.0

Fig. 1. Average poly-c-Si daily $E_{\text{OUT}}$ versus daily insolation
nearly identically to that of the insolation. Added variations of $E_{\text{OUT}}$ occur at similar values of insolation due primarily to temperature and spectral effects, amounting to ~10% (±5%).

This added 10% scatter is better examined by removing variations in light intensity from the data and analyzing $\eta_{\text{EFF}}$, which exhibit strong dependence with module temperature ($T_M$). Fig. 2 portrays $\eta_{\text{EFF}}$ plotted against $T_M$—daily averages computed weekly over both modules of each three types. The $\eta_{\text{EFF}}$ of module types Y and Z vary between 8.5% and 10.1%, while those of type X fluctuate between 9.4% and 11%, as the mean $T_M$ change, respectively, from 40°C down to 12°C. This temperature dependence may be quantified by least-squares fitting of the $\eta_{\text{EFF}}$ data against $T_M$. Although the specifics vary between the three module types, the slopes resulting from this analysis yield similar temperature coefficients varying between −0.046 and −0.049 absolute-% per °C. The squares of the linear correlation coefficients of the regression reveal that 77% to 79% of the variations in $\eta_{\text{EFF}}$ are correlated with variations in $T_M$.

The output for each module type may be expressed by the product of insolation times a linear expression in $T_M$, as per Eq. 1: $E_{\text{OUT}} = \eta_{\text{EFF}}/\varepsilon_{\text{SRC}}$ for the three module types. Using our locale as example, in the course of a year, at fixed latitude tilt, we get 5.3 kW-hr/m²/day insolation, and all three module types obtain 26.5°±0.5°C average temperature. The yearly $E_{\text{OUT}}$ anticipated from types X, Y, and Z is, respectively, 62.4, 75.3, and 63.7 kW-hrs apiece—standard variance of ±2% for all types. Expressing the output energy as per Eq. 1 has reduced the variance from about ±5% to ±2% by accounting for temperature effects. Spectral effects may account for the remaining variance.

$$E_{\text{OUT}} \left( \text{W-hrs} \right) = \left( \varepsilon_0 + \varepsilon_1 \cdot T_M \right) \cdot E \left( \text{kW-hr/m}^2 \right)$$  

![Fig. 2. Average poly-c-Si $\eta_{\text{EFF}}$ against module temperature](image)

Fig. 2. Average poly-c-Si $\eta_{\text{EFF}}$ against module temperature

![Fig. 3. Average poly-c-Si PRs and air temperatures vs. time](image)

Fig. 3. Average poly-c-Si PRs and air temperatures vs. time

### Table I. Coefficients and standard errors relating module $E_{\text{OUT}}$ to incident insolation and average module temperature

<table>
<thead>
<tr>
<th>Module Type</th>
<th>$\varepsilon_0$ (W-hr per kW-hr/m²)</th>
<th>Error</th>
<th>$\varepsilon_1$ (W-hr/°C per kW-hr/m²)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>36.41</td>
<td>0.31</td>
<td>-0.16</td>
<td>0.01</td>
</tr>
<tr>
<td>Y</td>
<td>44.14</td>
<td>0.41</td>
<td>-0.20</td>
<td>0.01</td>
</tr>
<tr>
<td>Z</td>
<td>37.60</td>
<td>0.36</td>
<td>-0.18</td>
<td>0.01</td>
</tr>
</tbody>
</table>

### 4. Analysis and Conclusions

The energy production capacities of six poly-c-Si PV modules from three manufacturers were measured under actual ambient conditions over the course of a year. Energy production was formulated by the product of the incident insolation times an expression characterized by a constant plus a linear temperature-dependent term. Values for the coefficients were derived and tabulated for all three module types. Using our locale as example, in the course of a year, at fixed latitude tilt, we get 5.3 kW-hr/m²/day insolation, and all three module types obtain 26.5°±0.5°C average temperature. The yearly $E_{\text{OUT}}$ anticipated from types X, Y, and Z is, respectively, 62.4, 75.3, and 63.7 kW-hrs apiece—standard variance of ±2% for all three types. Expressing the output energy as per Eq. 1 has reduced the variance from about ±5% to ±2% by accounting for temperature effects. Spectral effects may account for the remaining variance.

### 5. Acknowledgements

This work was funded by U.S. Dept. of Energy, contract no. DE-AC36-99GO10337.

### REFERENCES
