October 2001 • NREL/CP-520-30822

Conference Paper

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

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle • Bechtel

Contract No. DE-AC36-99-GO10337

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

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 (η_{EFF}) and performance ratio (PR) are derived on a weekly basis. The η_{EFF} is analyzed because it represents module energy output (E_{OUT}) divided by the incident solar insolation. The PR—defined as the η_{EFF} divided by the efficiency measured at SRC (η_{SRC})—denotes how much of the η_{SRC} may be realized under typical field conditions. Temperature coefficients derived for the E_{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 m^2 and 0.43 m^2 in aperture areas. Prior to deployment, module I-V characteristics were measured at SRC both indoors and outdoors. For all six modules, the η_{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_{OUT} and insolation, module and ambient temperatures, and effective efficiency. Module E_{OUT} and insolation are derived, respectively, by integration of the average module power and irradiance versus time profiles. The η_{EFF} is taken as the quotient of module E_{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_{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/m^2/day), with a variance of ~43%. The corresponding daily average E_{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

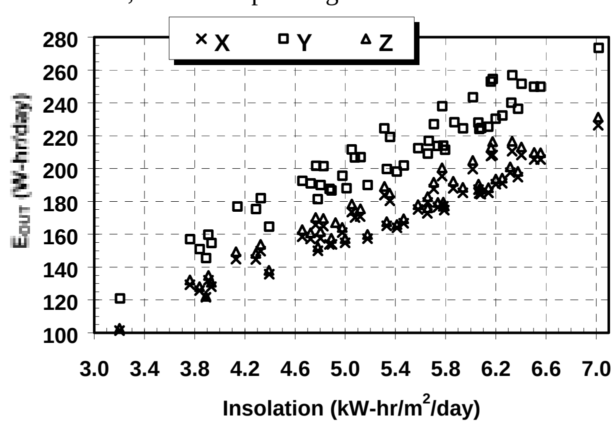

Fig. 1. Average poly-c-Si daily E_{OUT} versus daily insolation

nearly identically to that of the insolation. Added variations of E_{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 η_{EFF}, which exhibit strong dependence with module temperature (T_M). Fig. 2 portrays η_{EFF} plotted against T_M—daily averages computed weekly over both modules of each three types. The η_{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 η_{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 η_{EFF} are correlated with variations in T_M.

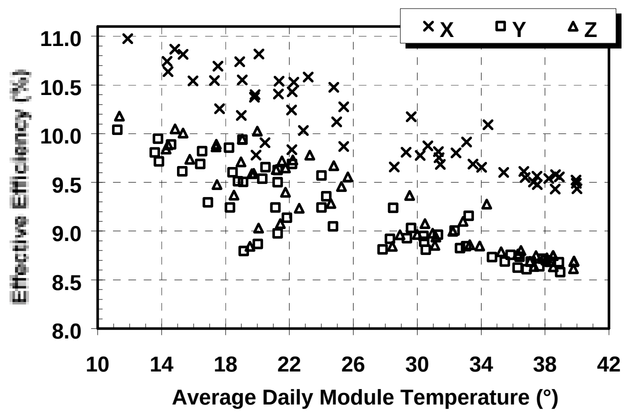

Fig. 2. Average poly-c-Si η_{EFF} against module temperature

Fig. 3 depicts the average PRs (η_{EFF}/η_{SRC}) for the three module types along the left-hand abscissa plotted against time along the ordinate. Also plotted and read along the right-hand abscissa are the concurrent average daytime air temperatures. The vertical gridlines and tick-marks along the ordinate axis correspond to the first days of each month. The PRs achieve their highest values in winter and vice versa—exposing largely seasonal temperature effects—fluctuating between 78% and 93% for module types Y and Z, and ranging 82%–96% for module type X. Seasonal variations in performance range between 11% and 15%.

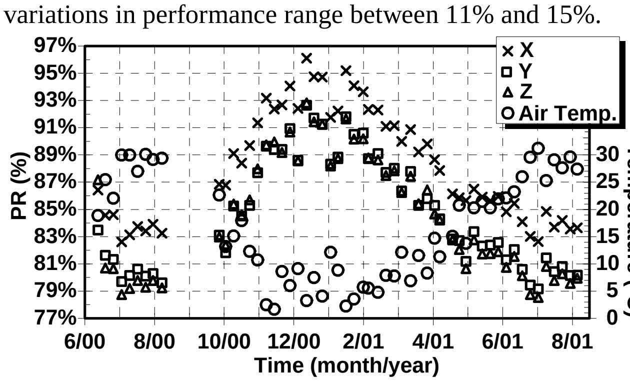

Fig. 3. Average poly-c-Si PRs and air temperatures vs. time

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: where E is the insolation in kW-hrs/m^2; E_{OUT} units are in W-hrs; and the coefficients ε_0 and ε_1 represent, respectively, the intercept and linear temperature-dependent terms. A synopsis of the coefficients for E_{OUT} for each module type is summarized in Table I. These coefficients are derived from the product of the regression of η_{EFF} versus T_M data shown in Fig. 2, times respective module areas. For example, module type X at average T_M = 0°C and for every 1 kW-hr/m^2 of insolation: one obtains ~36.4 W-hrs output energy, regardless of whether that insolation accumulates during the course of a day or in several hours; and for every 10°C temperature rise above 0°C, this output declines by 1.6 W-hrs. Both the example output and temperature derating are proportional to the actual insolation incident on module surface, regardless of the specific angle of tilt chosen for deployment. The values tabulated under the columns labeled "Error" represent one standard deviation in their respective derived coefficients.

$$E_{OUT}\ \{\mathrm{W-hrs}\} = \left(\varepsilon_0 + \varepsilon_1 \cdot T_M\right) \cdot E\ \{\mathrm{kW-hrs/m^2}\} \quad (1)$$

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

Module Type	ε_0 (W-hr per kW-hr/m^2)		ε_1 (W-hr/°C per kW-hr/m^2)	
	Coefficient	Error	Coefficient	Error
X	36.41	0.31	-0.16	0.01
Y	44.14	0.41	-0.20	0.01
Z	37.60	0.36	-0.18	0.01

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/m^2/day insolation, and all three module types obtain 26.5°±0.5°C average temperature. The yearly E_{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

[1] B. Marion, B. Kroposki, K. Emery, J. del Cueto, D. Myers, C. Osterwald, NREL/TP520-26909, 1999.

[2] J.A. del Cueto, Prog. Photovolt., Res. & Appl. 1998; 6 (6): 443–446.