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Comparison of Energy Production and Performance from Flat-Plate Photovoltaic Module Technologies Deployed at Fixed Tilt

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COMPARISON OF ENERGY PRODUCTION AND PERFORMANCE FROM FLAT-PLATE PHOTOVOLTAIC MODULE TECHNOLOGIES DEPLOYED AT FIXED TILT

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ABSTRACT

Performance data for 14 photovoltaic modules deployed at fixed latitude tilt in the field are presented and compared. Module performance is monitored continuously for optimum power characteristics. Flat-plate module technologies representative of crystalline, amorphous, and polycrystalline silicon, and cadmium telluride and copper indium diselenide, are scrutinized for energy production, effective efficiency and performance ratio (PR)—ratio of effective to reference efficiency. Most performance ratios exhibit seasonal fluctuations largely correlated to air or module temperatures, varying between 80% and 100%. These ratios tend toward larger values during winter and vise versa, except for amorphous silicon and cadmium telluride modules. In a-Si modules, the situation appears reversed: better PRs are obtained during late summer. The effective efficiency, PR, and average daily and yearly energy production are analyzed and quantified.

INTRODUCTION

Photovoltaic (PV) modules are currently rated using current-voltage (I-V) characteristics measured at standard reporting conditions (SRC). However, because operating conditions typically encountered in the field rarely emulate SRC, module energy production must be either explicitly modeled or measured. In this paper, the actual electrical performance data of PV modules measured in-situ, deployed at fixed tilt, are featured and compared for many of the currently viable flat-plate PV technologies. Module energy production (E_{OUT}), effective efficiency (η_{EFF}), and performance ratio (PR) are derived on a weekly basis. The η_{EFF} is derived as the quotient of daily E_{OUT} divided by the incident solar insolation times module area, calculated on a weekly basis. The η_{EFF} is analogous to the realistic reporting conditions (RRC) efficiency previously reported [1]: it represents a ratio of energy sums rather than power. PR is defined as the η_{EFF} divided by the efficiency measured at SRC (η_{SRC})—it denotes how much of the η_{SRC} may be realized under typical field conditions. Temperature coefficients derived for the PR of the modules are also presented. These are likely to differ from canonical coefficients due to incorporation of varying light intensities, and spectral content thereof, in their derivation.

EXPERIMENTAL

Fourteen PV modules are featured in this paper, grouped according to technology type. The details and labels used for each group are listed in Table 1. Most of the modules had been deployed outdoors between 1997 and 1999, except for the poly-c-Si modules that were deployed in June 2000. The areas listed represent aperture values, except for the CdTe module, in which aperture and total areas are synonymous. Both a-Si types consist of multijunction module technology. All modules are deployed on the performance and energy ratings testbed (PERT), on an open-air steel frame structure situated on the roof of the Outdoor Test Facility at NREL. These are erected at fixed latitude tilt—40° with respect to horizontal—facing due south ±2°. These are electrically connected to data acquisition systems (DAS) that monitor their I-V characteristics or otherwise actively keep them loaded constantly at their respective optimum-power-point (OPP) voltage and current. It is the OPP tracking data that are featured in this paper. Coincident module and ambient temperature data, and global irradiance measured in the same plane-of-array as the modules, were also obtained from the PERT DAS. More details concerning the PERT may be found in the literature [2].

Table 1. PV Module Technology Groups, Module Areas and Numbers of Modules Studied.

Technology	Label	No.	Area (m^2)
Crystalline silicon	c-Si 'A'	2	0.599
Crystalline silicon	c-Si 'B'	2	0.599
Crystalline silicon	c-Si 'C'	1	0.610
Polycrystalline silicon	poly-c-Si 'X'	2	0.320
Polycrystalline silicon	poly-c-Si 'Z'	2	0.355
Amorphous silicon	a-Si 'U'	1	0.452
Amorphous silicon	a-Si 'V'	1	0.357
Cadmium Telluride	CdTe	1	0.720
Copper indium diselenide	CIS	2	0.365, 0.400

Basic module-performance statistics were calculated weekly, obtaining weekly averages of hourly data, including: average module power, current, voltage, irradiance, and temperatures obtained versus time. The integration of these data versus time profiles yields the average module E_{OUT}, insolation, plus module and ambient temperatures. The η_{EFF} is taken as the quotient of module E_{OUT} divided by the product of insolation times module area (E_{IN}=insolation*area). The normalized broad-spectrum photoresponse was derived from the integral of OPP current divided by the E_{IN}. This quantity is useful in helping to determine times of snow cover and/or system tracking glitches, since it is expected to vary only so much after allowing for spectral and angle-of-incidence effects. All the data taken between March 19, 2000, and April 12, 2002, are analyzed with some exceptions: PERT system downtime and full or part snow days as determined from log entries, or photoresponse values in excess of ±30% above or below average. In order to derive PRs that reflect actual to reference (SRC) performance, the I-V characteristics of all 14 modules were retested in April 2002 at SRC using three sets of I-V measurements taken on separate simulators using both pulsed and continuous illumination. This plus additional η_{SRC} data measured prior to either deployment or March 2000 were used to calculate an average η_{SRC}; this average was employed to mitigate potential changes of η_{SRC} over time. For c-Si and poly-c-Si, long-term changes in η_{SRC} were minimal, but this was not the case for thin-film modules.

RESULTS

Because daily insolation varies greatly from day to day, it is more useful to examine module E_{OUT} versus insolation as opposed to time or season. Moreover, to better compare amongst the different modules, E_{OUT} data normalized to unit module area are scrutinized. Figures 1 and 2 portray average daily normalized E_{OUT} plotted against average daily insolation derived weekly, for bulk (c-Si and poly-c-Si) and thin-film PV technology modules, respectively. These data represent daily averages obtained by integration for times when the irradiance is above 3 W/m^2. From Fig. 1, normalized E_{OUT} data for bulk modules vary between 300 and 860 watt-hours per square meter (W-hr/m^2), as the insolation ranges 3–8 kilowatt-hours per square meter (kW-hr/m^2). The data for bulk PV materials shown in Fig. 1 appear to segregate clearly into two distinct sets: one set consists of most c-Si and poly-c-Si modules in which normalized E_{OUT} ranges 300–750 W-hr/m^2; and the c-Si 'B' modules that obtain superior output, about 100 W-hr/m^2 larger at all corresponding values of insolation. For thin-film modules, normalized E_{OUT} data range 180–680 W-hr/m^2 across the span of insolation values of 3–7.8 kW-hr/m^2. In this group, the CIS modules exhibit the greater output, generating between 300 and 680 W-hr/m^2—rates comparable to some of the lower performing bulk PV modules at corresponding insolation. For both a-Si 'U' and CdTe thin-film technologies, energy production rates lie within a range of 220–510 W-hr/m^2. For the a-Si 'V' modules, normalized E_{OUT} spans 180 to 420 W-hr/m^2 across the daily insolation values displayed.

Salient features of the data shown in Figs. 1 and 2, include the linear relation between E_{OUT} and insolation, and variance of the data about this dependence. The linear relation between E_{OUT} and insolation arises from the linear dependence of the short-circuit current (I_{SC}) against irradiance. The variances differ among module types. About median insolation values (~5.6 kW-hr/m2), the sizes of one standard variance in E_{OUT} are: about 5%–6% for all the bulk PV modules; 6% for the CIS modules; 4% for the a-Si modules; and 3.5% for the CdTe module. These differences are not insignificant and may be ascribed to module technology effects, one of them being convolution of module thermal characteristics and the temperature dependence of the efficiency. Although at both extrema in insolation the E_{OUT} data appear to exhibit less scatter than at median, this is an artifact of the paucity of sampling conditions at these extrema. These assertions are better illustrated by plotting the η_{EFF} against average daily module temperature (T_{MOD}).

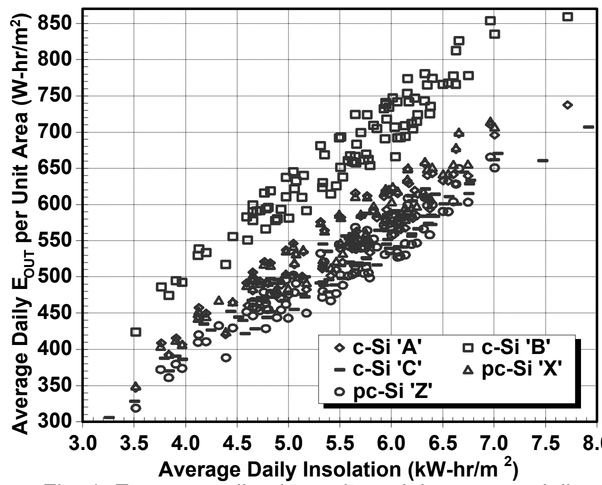

Fig. 1. E_{OUT} normalized to unit module area vs. daily insolation for 5 groups of c-Si and poly-c-Si modules.

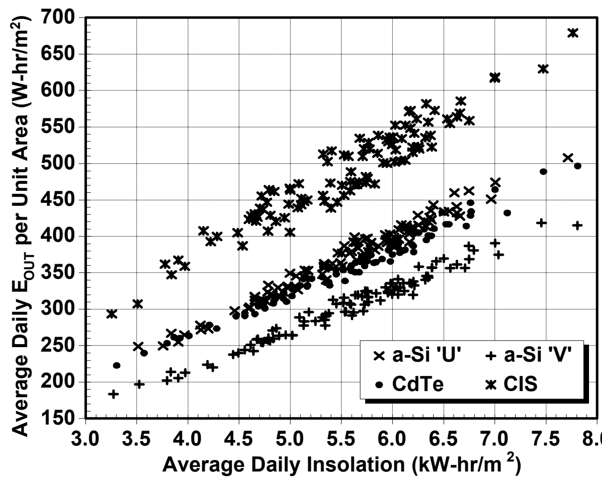

Fig. 2. E_{OUT} normalized to unit module area vs. daily insolation for thin-film modules: CIS, a-Si and CdTe.

Module η_{EFF} data are plotted against average daily T_{MOD} in Fig. 3. These data were derived weekly for coincident times as for the data shown in the previous figures. Fig. 3 largely illustrates the temperature behavior of the η_{EFF} and differences in temperature dependence amongst the various module types. For all the c-Si,

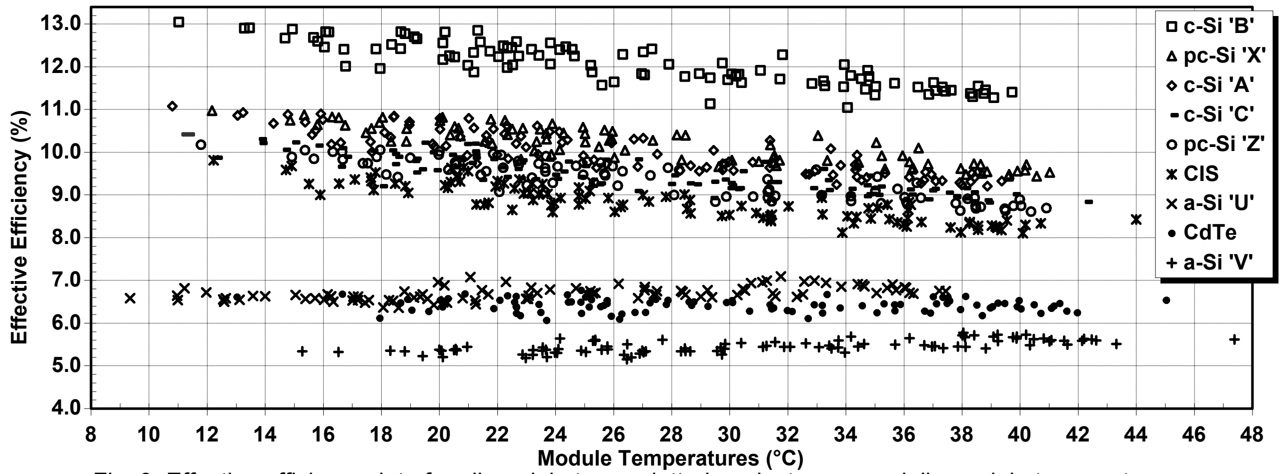

Fig. 3. Effective efficiency data for all module types plotted against average daily module temperatures.

poly-c-Si, and CIS modules groups, temperature-dependent changes in η_{EFF} appear to range 1% to 2% absolute, across the span of 30°C changes in T_{MOD}. However, for the a-Si and CdTe module types, the temperature dependence of η_{EFF} is much weaker, appearing to be slightly positive for both the a-Si modules and slightly negative for the CdTe module. Other mechanisms that impact module performance are also buried in this figure, including: spectral effects, low-light level behavior and any long-term variations in efficiency.

For a-Si, the seemingly retrograde behavior of η_{EFF} with T_{MOD} can occur after this material has undergone initial degradation and then largely stabilized after initial onset. It is due to the steady-state generation of light-induced defects and thermal annealing thereof [3] occurring at lower and higher operating T_{MOD}, respectively, incurred during winter and summer seasons. In actuality, the temperature dependence of η_{EFF} in a-Si is negative at any given moment of the year, largely because of the temperature dependence of the open-circuit voltage (V_{OC}). However, module power is given by the product of OPP voltage times current, and each of these values is proportional to the fill factor (FF) times V_{OC} and I_{SC}, respectively. In a-Si modules, light-induced defects and thermal annealing thereof drives the FF to significantly higher values in summer and lower in winter. This effect on OPP voltage generally opposes and can overwhelm the negative temperature dependence of V_{OC}.

The PR data of PV modules composed of c-Si and poly-c-Si types are depicted, respectively, in the upper and lower portions of Fig. 4, plotted against time. The highest and lowest values depicted on the abscissas are 102% and 80%, respectively. These data exhibit clear seasonal variation arising largely from the temperature dependence of η_{EFF} in these materials. In c-Si modules, the PRs fluctuate from 84%–88% in summertime and up to 95%–101% in the winter, with module types A and B obtaining very similar values, and the type C exhibiting PR values about ~2% lower. For poly-c-Si, the PR data range from 80%–85% in summer and up to 92%–97% in winter, with the type X modules outperforming the type Z modules by about 2%–3% at all comparable times.

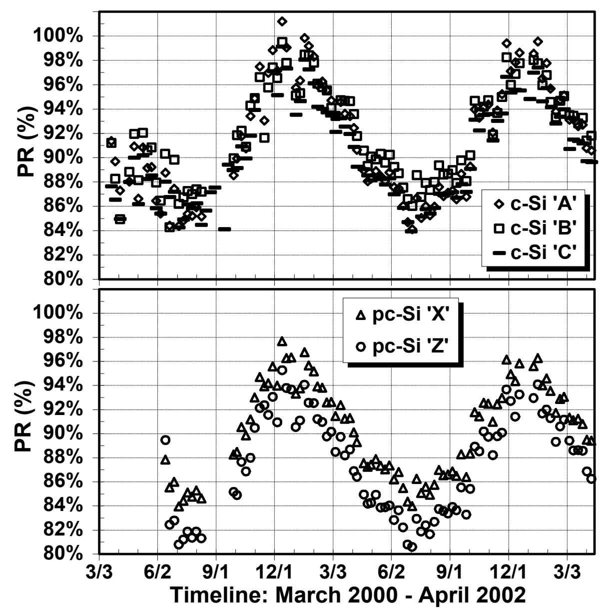

Fig. 4. Performance ratio data of bulk-material PV modules: of 3 c-Si (upper portion) module types and 2 poly-c-Si (lower part) module types plotted vs. time.

The PR data for thin-film modules are portrayed in Fig. 5 for polycrystalline CIS and CdTe, plus two a-Si types, respectively, in upper and lower portions of the graph, plotted against time. There exist non-negligible changes in performance over time for all the thin-film modules, with the least alterable module being CdTe: hence, the use of average η_{SRC} data—taken prior to March 2000 and on April 2002—to mitigate obfuscation with long-term performance variation. Fig. 5 shows that for a-Si modules, the PR peak in late summer, stand at 98%–99% for type U, around 94% for type V, and diminish to 89%–90% and 84%–86%, respectively, for types U and V in winter. Conversely, for CIS, the PR reach zenith in winter at ~97%–101%, and sink to lows of 84%–85% at the height of summer. Whereas the behavior of the PR for CIS and a-Si can be either largely or partly ascribed to temperature effects, that of CdTe cannot be characterized so simply. In CdTe, the PR data show complex behavior, climaxing in the fall and declining to lows in spring.

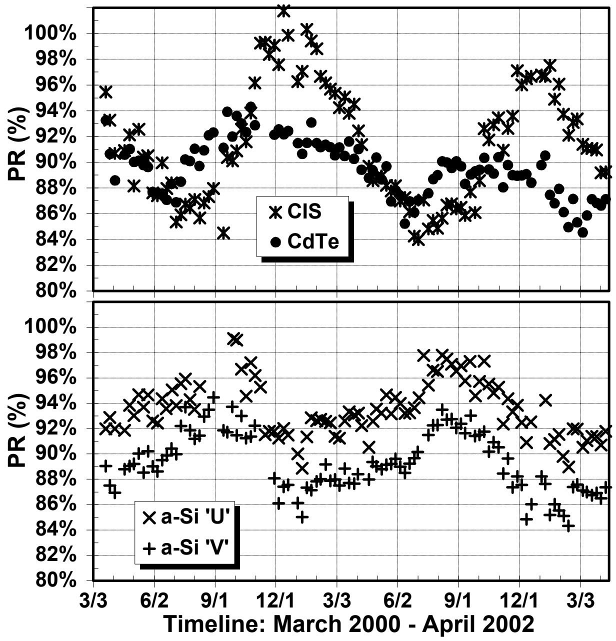

Fig. 5. Performance ratio data for thin-film PV modules: polycrystalline CIS and CdTe types (upper portion) and 2 a-Si types (lower part) plotted vs. time.

In the course of a year, PR data vary by 14%–16% in c-Si, poly-c-Si, and CIS modules; whereas for a-Si and CdTe, the PR change less than 10%. Except for CdTe, a significant portion of this variation and that in E_{OUT} are accounted for by temperature. It turns out that both η_{EFF} and PR exhibit slightly greater correlation against average daytime air temperature (T_{AIR}) than T_{MOD}. The regression analysis of PR data represented by a constant plus linear term in T_{AIR} are summarized in Table 2 (by module type listed in the first column). The second and third columns are, respectively, the constant and linear terms of the fit; the fourth and sixth columns represent the square of the correlation coefficient and one standard deviation of the fit, respectively. For c-Si, poly-c-Si, and CIS, 80%–87% of the variance in PR, η_{EFF} and E_{OUT} data is accounted for by linear regression against air temperature. For a-Si, only ~33%–51% of the variance is accounted for in this way; and in CdTe, almost none of the variance (~2%) may be simply ascribed to temperature.

The average yearly E_{OUT} normalized to unit module area for each module type was derived from the average daily E_{OUT} calculated weekly, evenly weighing the data by week, based on a 365-day year, without any missing days. These data are listed by module type in Table 3, in units of kW-hr/m^2. These production quotas are based on average daily, global insolation obtained at latitude tilt for our site: 5.53 ±0.08 kW-hr/m^2. These will also depend on the average daytime T_{AIR} obtained: for all data sets, T_{AIR} is 16.6°±0.8°C. Table 3 data show that the better c-Si and poly-c-Si type 'X' modules will typically generate in excess of 200 kW-hr of energy output per square meter yearly.

Table 2. Linear Regression Analysis of Module PR as a Function of Average Daily, Daytime Air Temperature.

Module Type	Constant	Slope	R^2	Average PR	σ_{FIT}
	(%)	(% / °C)		(%)	(%)
c-Si 'A'	99.6	-0.496	0.849	91.5	1.81
c-Si 'B'	98.4	-0.388	0.797	92.0	1.69
c-Si 'C'	97.5	-0.427	0.812	90.3	1.71
pc-Si 'X'	96.7	-0.401	0.872	90.3	1.38
pc-Si 'Z'	94.4	-0.431	0.874	87.5	1.47
CIS	99.5	-0.484	0.855	91.4	1.71
a-Si 'U'	91.1	+0.147	0.327	93.6	1.82
a-Si 'V'	85.8	+0.202	0.510	89.3	1.66
CdTe	90.1	-0.035	0.019	89.5	2.12

Table 3. Yearly Energy Output per Unit Area (kW-hr/m^2).

c-Si 'A'	c-Si 'B'	c-Si 'C'	poly-c Si 'X'	poly-c Si 'Z'	CIS	a-Si 'U'	a-Si 'V'	CdTe
202	243	192	203	187	177	136	111	131

CONCLUSION

Module energy output E_{OUT} normalized to unit area was analyzed as a function of insolation and categorized by the ratio: $\eta_{EFF} = E_{OUT}/E_{IN}$. The η_{EFF} was shown to be strongly temperature-dependent and negative for c-Si, poly-c-Si, and CIS module types. Conversely, for a-Si, its temperature dependence is much weaker, and positive. For CdTe, the η_{EFF} is not a simple function of temperature, and more likely a complicated function that includes spectral and low-light level effects in conjunction with temperature. The performance ratios and their seasonal variations were presented and adequately formulated as functions of air temperature for c-Si, poly-c-Si and CIS. Yearly average energy production quotas per unit module area were calculated and presented for all modules types, based on average insolation and daytime air temperatures obtained at our locale.

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REFERENCES

[1] K. Bucher, G. Kleiss, D. Batzner, "RRC Module Energy Rating: A Module Survey", *Proc. 26th IEEE PVSC*, 1997, pp. 1187–1191.

[2] J.A. del Cueto, "Review of the Field Performance of One Cadmium Telluride Module", *Prog. Photovolt., Res. & Appl.* **6** (6): 443–446, 1998.

[3] J.A. del Cueto, B. von Roedern, "Temperature-Induced Changes in the Performance of Amorphous Silicon Multi-Junction Modules in Controlled Light Soaking", *Prog. Photovolt., Res. & Appl.* **7**: 443–446, 1999.

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