A Comparison of Photovoltaic Module Performance Evaluation Methodologies for Energy Ratings

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A COMPARISON OF PHOTOVOLTAIC MODULE PERFORMANCE
EVALUATION METHODOLOGIES FOR ENERGY RATINGS

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ABSTRACT

The rating of photovoltaic (PV) modules has always been a controversial topic in the PV community. Currently, there is no industry standard methodology to evaluate PV modules for energy production. This issue must be discussed and resolved for the benefit of system planners, utilities, and other consumers. Several methodologies are available to rate a module's peak power, but do any accurately predict energy output for flat-plate modules? This paper analyzes the energy performance of PV modules using six different energy calculation techniques and compares the results to the measured amount of energy produced. The results indicate which methods are the most effective for predicting energy output in Golden, Colorado, under prevailing meteorological conditions.

INTRODUCTION

The rating of photovoltaic (PV) modules can be classified in two ways: as a power rating or as an energy rating. A power rating is an instantaneous measurement with respect to a fixed set of reference conditions or a value that is based on a statistical analysis (e.g., regression). An energy rating is based on the amount of energy a module produces over a certain amount of time under specific conditions. Both of these rating methods have good applications. A power rating is an excellent way to compare modules under specific reference conditions. An energy rating gives a good comparison of module performance under actual operating conditions. Currently, there is no industry standard methodology to evaluate PV modules for energy production. This issue must be discussed and resolved for the benefit of system planners, utilities, and consumers. This paper compares different methods that are used to predict the energy output of PV modules and presents a comparison of results based on measurements obtained on various PV modules in Golden, Colorado.

There are basically two methods of rating the amount of peak power that modules produce. One is by calculating the instantaneous peak power from I-V curves at specific conditions, such as Standard Reporting Conditions (SRC). The second method to rate power is to use regression analysis on long-term data of module power generation. These data can be used to form models of how the module operates at different meteorological and irradiance values. Rated power is then computed at a specific reference condition. PVUSA Test Conditions (PTC) and Nominal Terrestrial Environment (NTE) are examples of methods employing regression analysis. The reference criteria for these three methods are listed in Table 1.

Table 1. Reference criteria of module power rating test methods [1-4]

Method	Irradiance (W/m²)	Temperature (°C)	Spectrum	Wind Speed (m/s)
SRC	1000	25 (module)	AM1.5	-
PTC	1000	20 (ambient)	-	1
NTE	800	20 (ambient)	-	1

Once the amount of power a module produces at certain reference conditions is known, an energy rating can be determined. This is done by multiplying the instantaneous power by a selected period of time. For this paper, the time period is determined by the amount of peak sun-hours. One peak sun-hour is defined as the equivalent number of hours when the irradiance equals 1000 W/m² (i.e. 5 hours of irradiance at 200 W/m² equals 1 peak sun-hour). Multiplying the rated power (W) by the number of peak sun-hours (h) gives an approximate energy estimate in watt-hours (Wh). This method does not take into account changing temperature and spectral influences on the module, or the fact that the module may operate differently under different irradiance conditions.

Another method for determining a module energy rating is to use a "standard day" for the reference conditions and sum the energy generated over that standard day. This technique is used in the ENRA [4] and AM/PM [5] energy rating methods. This approach presents a standard method for comparing modules but may not give an accurate picture of the real operating conditions. Finally, the realistic reporting conditions (RRC) [6] method calculates the energy produced over a selected period of time usually monthly or annually, and takes into account actual or typical weather conditions. Typical weather conditions for a site can be found in typical meteorological year (TMY) data files, the Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors [7] developed by the National Renewable Energy Laboratory (NREL), or the Solar and Meteorological surface observation network 1961-1990, available from the National Climatic Data Center [8].

This paper analyzes the energy performance of a set of modules using six different energy calculation techniques and compares the results to the measured amount of energy produced. The different energy rating methods that will be compared are described below.

1. Energy at SRC (ESRC): The module's peak power is determined at SRC and then the power is multiplied by the number of sun-hours during a specified time period to determine energy output. The module is rated at 25°C; however, variations in temperature that the module may experience throughout the time period are not taken into account. This assumption will lead to significant discrepancies in energy output for modules that have relatively large

temperature coefficients. Energy calculated by this method will typically be higher than the measured value.

2. Energy at PTC (EPTC): This method determines a power rating based on a regression analysis over a 30-day period, at PTC. Data are collected for at least 30 days, with a cumulative total of at least 10 kWh/m² above 1000 W/m² of global plane-of-array irradiance. The rating is based on regression analysis of quality checked data using only irradiance of 500 W/m² or greater. The power is calculated using the following equation [4]:

$$P = A_1*E + A_2*E^2 + A_3*E*T_{amb} + A_4*E*WS \qquad (1)$$

where, P = output power, Wdc
E = irradiance, W/m²
T_{amb} = ambient air temperature, °C
WS = wind speed at 10 m above grade, m/s
A_n = regression coefficients

The PTC-rated power is then multiplied by the number of sun-hours during a specified time period to determine the energy rating. For this study, no wind speed restrictions were used.

3. Energy at NTE (ENTE): This method is similar to the EPTC except that the regression analysis is done at the Nominal Terrestrial Environment (NTE)[3]. The power rating is computed at 800 W/m², 20°C ambient temperature, and wind speed of 1 m/s using the PTC power model. Then the NTE-rated power is multiplied by the number of sun-hours during a specified time period to determine an energy rating.

4. ENRA (ENergy RAtings): This method also uses a regression analysis to determine the power output for each module using the following three parameter response function [5].

$$P = A_1*E + A_2*E^2 + A_3*E*\ln(E) \qquad (2)$$

where, P = output power, Wdc
E = irradiance, W/m²
A_n = regression coefficients

Only data above 500 W/m² are used in computing the regression coefficients. The response function is then integrated over a reference day. The reference day is defined by the following function:

$$E(t) = \sum_{n=0}^{4} B_n t^n [W / m^2] \qquad (3)$$

B_0 = 2.602676742e3
B_1 = -1.399250090e3
B_2 = 2.43511524e2
B_3 = -1.5395308e1
B_4 = 3.19483e-1
t = time in hours (from t=6 to t=18)

This function has a maximum of irradiance of 900 W/m² at 12:00, and its integral has a value of 6.82 kWh/m², or 6.82 sun-hours. This model does not take into account temperature or spectral changes over the reference time period.

5. AM/PM: A model of power is obtained using derived temperature and irradiance coefficients for each module. The power equation is defined below:

$$P = P_{irr}*(1 + 10^{-6}*T_{coef}*(T_{mod} - 25°C)) \qquad (4)$$

where, P = output power, Wdc
P_{irr} = calculated power based on irradiance
T_{coef} = max. power temp. coefficient in ppm/°C normalized at 25°C
T_{mod} = module temperature °C

Calculated power based on irradiance is derived from the following formula:

$$P_{irr} = m*I_{sc} + b = m * E_{tot}/(1000 * I_{src}) + b \qquad (5)$$

where, I_{sc} = short circuit current
E_{tot} = total irradiance, W/m²
I_{src} = I_{sc} at 25°C and 1000 W/m²

This function assumes that I_{sc} is linear with total irradiance and temperature. The module temperature is computed from the following equation [9]:

$$\Delta T = T_{mod} - T_{air} = 0.314*E_{tot}(1-\eta) / (1 + 0.4 * V^{\frac{1}{2}}) \qquad (6)$$

where, T_{air} = air temperature, °F
E_{tot} = total irradiance, W/ft²
η = efficiency = $P_{irr}/(Area*E_{tot})$
V = wind velocity, ft/sec

A better fit to the measured-versus-calculated module temperature was obtained when 0.15 was used instead of the 0.314 suggested by the reference. The energy over a standard day is then computed by multiplying the calculated power by the amount of time during a standard day. An "AM/PM" standard day is defined as a function of insolation, temperature, and air mass variations over a 24-hour period. For this experiment, only irradiance and temperature were defined. The equations below for the irradiance and temperature models were derived from a polynomial curve fit to the figures in the reference [5].

$$E(t) = \sum_{n=0}^{4} B_n t^n [W / m^2] \qquad (7)$$

B_0 = 2.965956e3
B_1 = -1.484969e3
B_2 = 2.457535e2
B_3 = -1.532984e1
B_4 = 3.195195e-1
t = time in hours (from t=6 to t=18)

This function has an integral value of 5.35 kWh/m², or 5.35 sun-hours.

$$Air\_Temp(t) = \sum_{n=0}^{6} B_n t^n [W / m^2] \qquad (8)$$

B_0 = -1.276272e1
B_1 = 2.454010e1
B_2 = -7.683963
B_3 = 1.115173
B_4 = -8.009432e-2
B_5 = 2.801611e-3
B_6 = -3.848843e-5
t = time in hours (from t=6 to t=18)

6. RRC: A model for module power is obtained though laboratory characterization. The same power model that was

used for the AM/PM method was used for this methodology. The energy is then summed over a specific time period using realistic meteorological conditions. For this paper, hourly averages of actual measured meteorological data were used to calculate the amount of energy that each module produced. This should lead to accurate predictions of energy, if the power models for each module are valid.

EXPERIMENTAL

A set of modules at NREL has been deployed outdoors and loaded at the peak power point. The modules' voltage and current are measured every 5 s and averaged hourly. This provides the measured energy produced by each module in watt-hour(Wh). A set of seven modules has been selected to represent major types of terrestrial flat-plate PV modules. This set includes single-crystalline silicon (mono-Si); multicrystalline silicon (multi-Si); single-, dual-, and triple-junction amorphous silicon (a-Si, a-Si/a-Si); and a-Si/a-Si/a-Si); copper indium diselenide (CIS); and cadmium telluride (CdTe) modules. Each module's I-V curve is also taken every half hour and stored. These data are used, along with meteorological and radiometric data, to compute regression coefficients for various module performance evaluation models. The meteorological and radiometric data at the site are collected at the Reference Meteorological and Irradiance Station (RMIS). These data include ambient temperature, plane-of-array (POA) irradiance, direct normal irradiance, and wind speed. These data are used to compute power equations for each module using regression analysis over a period of 30 days. The 30-day period that was used for this study was the month of September, 1994.

Module temperature and irradiance coefficients for the AM/PM and RRC energy ratings methods were developed using a Spire 240 solar simulator. Irradiance measurements were taken between 0.1 and 1.2 suns, with the temperature held to 25±0.5°C. Temperature measurements were taken between 10°C and 50°C, with the irradiance held at 1000 W/m².

The modules' energy output is compared with the amount predicted by using six different energy rating methods over a clear day, a cloudy day, and a month. The clear day was September 8, 1994. This day had a total of sun-hours of 7.65 sun-hours and an average daily temperature of 22°C. The cloudy day was September 30, 1994. This day had a total of 2.21 sun-hours and an average daily temperature of 15°C. The month used was September, 1994, which had a total of 171 sun-hours and an average temperature of 18°C.

Table 2 lists the modules used in this study along with their manufacturers' rated power. Some modules do not contain manufacturer ratings because they are research modules. The table also includes the modules' rated power measured at SRC, and calculated power ratings at PTC and NTE. The table also contains the nominal operating cell temperature (NOCT) for each module for the month of September. The regression analysis for both the PTC and NTE consisted of the 30 days of the month of September. Only data with irradiance above 500 W/m² were used. All power ratings are normalized to 1000 W/m².

Table 2. Power rating of modules and module NOCT

Module Type	Manf. (W)	SRC (W)	NTE (W)	PTC (W)	NOCT (°C)
a-Si	5	3.27	3.1	3.1	40.7
a-Si/a-Si	22	19.6	18.0	18.9	33.2
a-Si/a-Si/a-Si	-	25.1	23.6	24.7	31.7
mono-Si	75	67.2	60.7	60.8	30.9
multi-Si	60	53.9	49.0	49.2	29.6
CIS	-	31.4	24.6	25.8	33.1
CdTe	-	53.6	41.4	42.9	36.9

RESULTS AND DISCUSSION

Tables 3 and 4 show a comparison of measured energy output (Wh) versus different rating methods for September 8, 1994. This is considered a good solar day in Golden, Colorado.

Table 3. Measured energy (Wh) versus percent difference (%) for a clear day

Module Type	Meas.	ESRC	ENTE	EPTC
a-Si	23.6	5.6	5.2	0.4
a-Si/a-Si	141.1	5.8	1.7	2.4
a-Si/a-Si/a-Si	186.3	2.9	1.1	1.4
mono-Si	454.0	11.8	6.2	2.4
multi-Si	371.5	9.9	5.0	1.3
CIS	187.8	21.8	4.2	4.9
CdTe	329.3	19.7	0.2	-0.3

Table 3 shows that, for a clear day, the ESRC method over-predicts energy outputfor all module types. The ESRC values for a-Si are much closer to the measured values because these modules are not as temperature sensitive as crystalline silicon or other thin-films. The ENTE and EPTC methods predict module energy output within 6% for most technologies on clear days. The regression analysis works well because the models for the technologies are stable, and predict well, especially on clear days.

Table 4. Measured energy (Wh) versus percent difference (%) for a clear day

Module Type	Meas.	ENRA	AM/PM	RRC
a-Si	23.6	-11.3	-30.4	6.3
a-Si/a-Si	141.1	-11.9	-40.0	3.2
a-Si/a-Si/a-Si	186.3	-12.8	-46.6	0.7
mono-Si	454.0	7.4	-33.0	0.9
multi-Si	371.5	-1.0	-35.2	0.1
CIS	187.8	-7.3	-24.1	9.6
CdTe	329.3	-6.8	-15.1	14.4

Table 4 shows that, for a clear day, the ENRA and AM/PM methods under-predict the energy produced for all modules except one. This is because the ENRA and AM/PM method base their energy output on a standard day where the total irradiance was less than that of the clear day. The RRC method was extremely close to the measured value except for the a-Si, CIS and CdTe modules. This is because the models for these technologies may not be accurate (i.e., more scatter or bias in data).

Tables 5 and 6 show a comparison of measured energy output (Wh) versus different rating methods for September 8, 1994. This is considered a cloudy day for the month of September in Golden, Colorado.

Table 5. Measured energy (Wh) versus percent difference (%) for a cloudy day

Module Type	Meas.	ESRC	ENTE	EPTC
a-Si	7.1	1.4	1.4	-4.4
a-Si/a-Si	43.8	-1.4	-5.8	-5.0
a-Si/a-Si/a-Si	56.6	-2.2	-4.0	-3.9
mono-Si	141.6	4.6	-1.4	-5.4
multi-Si	115.2	3.3	-2.0	-6.0
CIS	56.7	18.2	-0.2	0.5
CdTe	101.7	14.1	-6.7	-7.3

Table 5 shows that, for a cloudy day, the ESRC method predicts energy within 3% for a-Si and within 5% for mono- and multi-Si modules. This is due to the lower operating temperatures under cloudy sky conditions. For CIS and CdTe modules, the SRC method overestimates energy output up to 18%. The ENTE and EPTC methods predicts module energy output within 8% for most technologies on cloudy days.

Table 6. Measured energy (Wh) versus percent difference (%) for a cloudy day

Module Type	Meas.	ENRA	AM/PM	RRC
a-Si	7.1	66.5	60.8	15.5
a-Si/a-Si	43.8	65.3	56.5	-12.9
a-Si/a-Si/a-Si	56.6	65.7	55.5	-21.7
mono-Si	141.6	71.1	58.5	-0.3
multi-Si	115.2	68.7	58.1	-3.6
CIS	56.7	67.6	62.5	-0.2
CdTe	101.7	67.0	64.4	18.5

Table 6 shows that, for a cloudy day, the ENRA and AM/PM methods over-predict the energy produced for all modules by at least 55%. This is because the ENRA and AM/PM method base their energy output on a standard day where the total irradiance was more than that of the cloudy day. The RRC method had a lot of variation in predicting energy output. This method's estimation is very close for mono-Si and CIS. This is because the models for these technologies are accurate at low irradiance levels.

Tables 7 and 8 show a comparison of measured energy output (kWh) versus different rating methods for September, 1994.

Table 7. Measured energy (kWh) versus percent difference (%) for the month of September 1994

Module Type	Meas.	ESRC	ENTE	EPTC
a-Si	0.53	4.7	4.1	-0.6
a-Si/a-Si	3.15	5.7	1.6	2.4
a-Si/a-Si/a-Si	4.13	3.5	1.8	2.1
mono-Si	10.25	10.7	5.0	1.2
multi-Si	8.41	8.6	3.7	-0.1
CIS	4.22	21.2	3.5	4.2
CdTe	7.34	19.7	0.3	-0.2

Table 7 shows that, for the month of September, the ESRC method predicts energy within 6% for a-Si and within 11% for mono- and multi-Si modules. For CIS and CdTe modules, the ESRC method overestimates energy output by 22%. The ENTE and EPTC methods can predict module energy output within 5% for all technologies for the month of September.

Table 8. Measured energy (kWh) versus percent difference (%) for the month of September 1994

Module Type	Meas.	ENRA	AM/PM	RRC
a-Si	0.53	16.5	0.4	7.5
a-Si/a-Si	3.15	16.7	-4.2	2.1
a-Si/a-Si/a-Si	4.13	16.7	-8.4	-1.2
mono-Si	10.25	30.3	-0.1	3.4
multi-Si	8.41	23.8	-2.0	1.7
CIS	4.22	19.7	7.0	10.5
CdTe	7.34	20.6	14.4	17.7

Table 8 shows that, for the month of September 1994, the ENRA method over-estimates the energy produced for all module types. This is because the standard day that this method uses is considered a clear day, and this method applies no corrections for temperature. The AM/PM method come considerably closer to predicting a monthly energy output because its standard day is a well-defined average day, and it incorporates temperature effects on modules. The RRC method predicts energy very well for technologies that have a well-defined model for performance, but did not predict as well for technologies where the models for their performance are not well known.

CONCLUSIONS

The ESRC methodology does not accurately predict module energy output for modules that are temperature-sensitive when the modules operate at elevated temperatures. This is because there are no temperature corrections in the power or energy ratings. The ESRC method is a good predictor of energy only when the modules' operating conditions are close to the standard reporting conditions.

Methodologies that use regression analyses like EPTC and ENTE can accurately predict energy output if the regression and prediction are computed for the same time periods. The equations that are developed with regression analyses may not be valid if the module's response changes over conditions that were not used in the regression. An example would be using models developed from summer data, which might not accurately predict winter energy output. Scatter in the data used to derive the models will lead to less-accurate predictions.

Standard day techniques, such as the ENRA and AM/PM, work well for long-term averages if the standard day is representative of an average day in a particular area. These methods do not do well in predicting energy for days or periods when the conditions are not close to the standard day. The energy totals for these methods would be closer to the actual values if they were corrected back to the actual amount of irradiance on a daily basis.

The RRC method works well at predicting energy for modules if the power models for the technology are accurate and stable. This paper showed that the RRC method works well when using actual meteorological and irradiance data, but these results will vary if one were to use typical monthly or yearly data.

FUTURE WORK

The Photovoltaic Module and Systems Performance and Engineering Project at NREL will continue to study the issue of module energy ratings. Work needs to be conducted on

developing better models that predict how modules perform under a variety of meteorological conditions. This will lead to more accurate energy predictions. Also, a decision must be made regarding calculating energy based on standard or typical conditions or actual conditions.

ACKNOWLEDGEMENTS

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