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Evaluation of the Performance of the PVUSA Rating Methodology Applied to DUAL Junction PV Technology

Preprint

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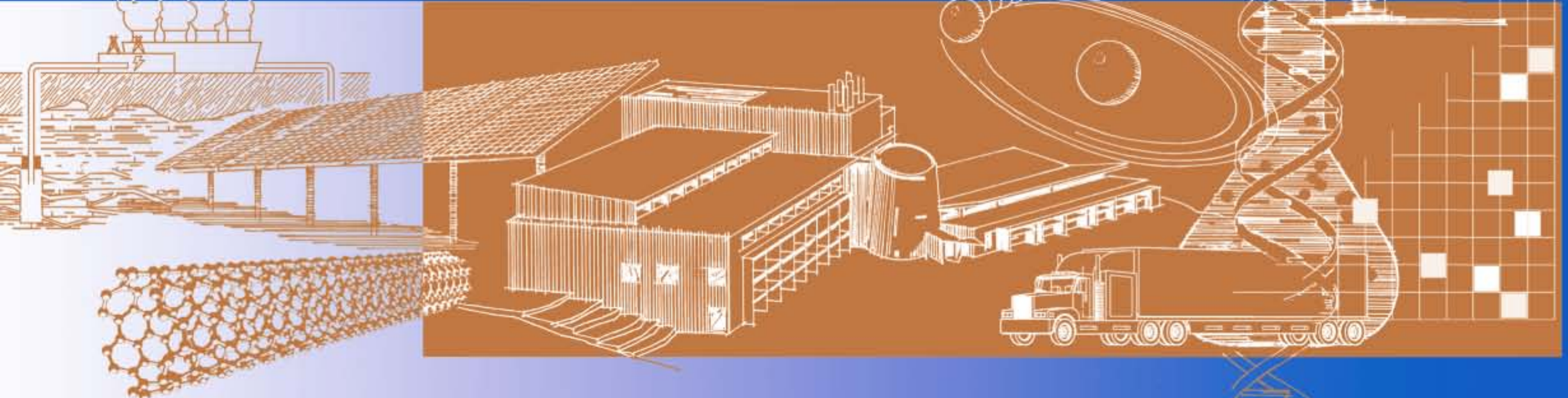

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The following corrections were made to this report/document:

A previous version of this paper, available until July 17, 2009, mistakenly referred to a triple junction roof mounted USSC system, which was incorrect. The Title, Abstract, Introduction paragraphs 1, 3, and 4, and Conclusion paragraph 1 were changed to reflect the correct setup, which was a rack-mounted dual-junction PV system.

EVALUATION OF THE PERFORMANCE OF THE PVUSA RATING METHODOLOGY APPLIED TO DUAL JUNCTION PV TECHNOLOGY

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NOTE: a previous version of this paper, available until July 17, 2009, mistakenly referred to a triple junction roof mounted USSC system, which was incorrect. The author is solely responsible for, and regrets, that error.

ABSTRACT

The PVUSA (Photovoltaics for Utility Scale Applications) project in the 1990's developed a rating methodology for PV performance evaluation which has become popular, and even incorporated into concentrating PV rating standards. The method is based on collecting solar, meteorological, and system power output data for a period of time, and regressing the system output against a combination of irradiance, wind speed, and ambient temperature. The selected irradiance, wind speed, and temperature rating conditions are I_s=1000 Wm^{-2}, W_s=1 ms^{-1}, and T_s=20 °C, respectively, for a flat plate collector. Here, we apply the method to a rack-mounted dual-junction PV system, and produce a system rating. We also describe in detail the uncertainties associated with the method, and mathematical issues associated with the technique.

1. INTRODUCTION

The PVUSA (Photovoltaics for Utility Scale Applications) project in the 1990's developed a rating methodology [1, 2] for PV performance evaluation which has become popular, and even incorporated into concentrating PV rating standards [3]. The method is based on collecting solar, meteorological, and system power output data for a period of time, and regressing the system output, P, against a combination of irradiance, I, wind speed, W, and ambient temperature, T, variables in the form of equation 1.

$$P = I * (a + b * I + c * W + d * T) \qquad (1)$$

The selected irradiance, wind speed, and temperature rating conditions are I_s=1000 Wm^{-2}, W_s=1 ms^{-1}, and T_s=20 °C, respectively, for a flat plate collector. For concentrating collectors (not addressed here, but our analysis is generally applicable) the only difference is that the rating condition (direct beam) irradiance is I_s=850 Wm^{-2}).

In this paper, we apply the method to a rack-mounted dual-junction PV system, and produce a system rating. We also describe in detail the uncertainties associated with the method, and mathematical issues associated with the technique. In particular, the relative contribution of each combination of variables is quantified, and it is argued that simpler regressions of PV power with respect to irradiance perform as well if not better.

This analysis is based upon one United Solar System Corp. (USSC) system of 96 dual-junction rack-mounted modules at a 40 degree (NREL latitude) tilt, facing due south. The array has a system Standard Test Condition (STC) direct current (DC) rating of 1800 Watts peak (Wpac) and an alternating current (AC) rating of 1600 Wpac. Recall that STC are 1000 Watt per square meter, Wm^{-2}, irradiance, 25° cell temperature, and under the American Society for Testing and Materials (ASTM) Air Mass 1.5 hemispherical tilt spectrum [4].

2. PV SYSTEM DATA COLLECTION

The PV system parameters listed in table 1 were measured with a Campbell Scientific CR 21X Data logger, with signal conditioning of the array electrical parameters including monitors for voltage, current, and module temperature. The data were sampled every 3 seconds and integrated over 1 minute. Fifteen minute averages of the data were reported.

In this subsection, we address the uncertainty associated with the measurement of performance parameters and input variables for the model. The combined CR21X data logger and sensor uncertainties are summarized and applied to the range of parameters applicable to this system.

Table 2 reports the measurement uncertainty in each parameter and combined overall measurement uncertainty for the NREL Photovoltaic Energy Rating Testbed (PERT) as reported in NREL technical report NREL/TP-520-26909 "Validation of a Photovoltaic Module Energy Ratings Procedure at NREL" [5].

TABLE 1: USSC 1.6 kW SYSTEM MEASUREMENTS.

Field	Parameter
SYS_ID	System Identification
YEAR	Year
DAY	Day of the year (1 to 365)
TIME	Mountain Standard Time HHMM
POA_IRR	Plane of Array solar irradiance Wm^{-2}
DC_POWER	Array Direct Current power output Watts (W)
AC_POWER	Array Alternating Current power output (W)
POS_VOLTS	Array Positive leg voltage, Volts (V)
POS_AMPS	Array Positive leg current, Amperes (I)
NEG_VOLTS	Array negative leg voltage, (V)
NEG_AMPS	Array negative leg current, (I)
AC_VOLTS	Array Alternating current volts (V)
AC_AMPS	Array Alternating current (I)
T_AMB	Ambient Temperature °C
T_MOD1	Module 1 Temperature °C
T_MOD2	Module 2 Temperature °C (not measured)
T_MOD3	Module 3 Temperature °C(not measured)
T_INV	Inverter Temperature °C
T_DAS	Data Acquisition System (DAS) Temperature °C
DAS_BATV	DAS battery Voltage (V)

2.1 System Monitoring Transducer Accuracy

The accuracy of the CR21X data logger with respect to the several electrical parameters measured (as derived from Campbell Scientific and Ohio Semitronics Incorporated (OSI) specifications) is summarized here.

CR21X current and voltage accuracy:

DC & AC Voltage**:** (range: 0 to 233 V DC, 0 -126 AC V)

Ohio Semitronics Inc (OSI) VT8-005B RMS Voltage Transducer, 0-150 V ac and/or dc input, 0-1 mA output, Temperature Coefficient. Tc = ± 1.0% of reading (-10ºC to +60ºC).
Accuracy = ± 0.25% F.S. (Full Scale)

Note 0.25% of system voltage of 150 V = 0.38 V Ac

DC & AC Current: (0- 3.8 DC amp, 0-12 AC amp)
OSI CTA-214 RMS Current Sensor Signal Conditioner
0-1 mA output proportional to RMS value of ac and/or dc input, Linearity: ± 0.1% F.S.
Tc = ± 0.005%/ºC (0º to +70ºC),
with OSI CTL-50 Hall-Effect Current Sensor
50 Ampere (A) rms input
30 mV output typical,
Tc = -0.15%/ºC (-40ºC to +65ºC).

0.1% of 50 Arms = 0.05 Amp out of 12 A ac = 0.42%

AC Power**:** (0-1900 Watts)
OSI PC8-003-01B Variable-Frequency Watt Transducer
0-150 V and 0-100 A input; ±1 mA output
Tc = ±1.0% of reading, ±0.1% F.S. output (0ºC to +40ºC).

Accuracy = ±1.0% F.S. (includes combined effects of voltage, current, load, & power factor),

We compute the total uncertainty in the AC power by root sum square of

$(1^2 + 1^2 + 0.1^2)^{1/2}$ = 1.45% of 1900 Wp = ±27.5 Watts AC

For power computed from AC Amps and AC Volts:

$(0.422 + 0.25^2)^{1/2}$ = 0.5% of 1900 Wp = ± 9.5 Watts.

TABLE 2: PERT UNCERTAINTY SUMMARY

PARAMETER	%Uncertainty
Voltage	0.1%
Current	0.1%
Irradiance	4.0%
ModuleTemp	0.5%
Module Power	N/A
RSS	4.0%

Excluding the irradiance component in table 2 (discussed below), the root-sum-square of the current, voltage, and power uncertainty measurements from table 2 is 0.22%.

3. PVUSA TEST CONDITION MODEL

3.1 PVUSA Model Structure

The PVUSA TC method is based on the regression of AC power output (P) in W (or kW) against a function of three variables: Plane of Array Irradiance (I) in Wm^{-2} (or kW m^{-2}), Wind speed (W) in meters per second (ms^{-1}), and ambient temperature (T) in °C. Recall the form of the PVUSA TC model, as in equation 1, is:

$P = I * (a + b* I + c * W + d * T)$

Note the model includes *four* irradiance terms (one of which is squared) and only one each of temperature and wind speed related terms. This fact leads to some interesting conclusions regarding the accuracy of the model. Only conditions where the irradiance data is greater than 500 Wm^{-2} (sometimes 700 Wm^{-2} is recommended) are used to determine the regression coefficients a, b, c, and d. We note the following:

- Uncertainty in the irradiance carries significantly more weight than uncertainty in the other variables.
- Ambient temperature is highly positively correlated with solar irradiance
- Rating condition is established for a wind speed of 1 ms^{-1}; a relatively infrequent condition

The selected values for irradiance, wind speed, and temperature to produce a rating for a flat plate collector are I_s=1000 Wm^{-2}, W_s=1 ms^{-1}, and T_s=20 °C, respectively.

3.2 <u>Meteorological Data</u>

In addition to the irradiance independent variable in eq. 1, wind speed and temperature are also required. Ambient temperature is monitored at the system, but for the wind speed, we utilized wind speed data from the Reference Meteorological and Irradiance System (RMIS) deployed at the OTF along the north side of the OTF test field boundary. RMIS data is collected and archived at 1 minute intervals. We downloaded the archived 2006 1 minute RMIS data, and averaged the wind speed data over 15 minute intervals to provide average wind speed data for the regression analysis.

3.3 <u>Model Sensitivity Coefficients</u>

Considering eq. 1, the uncertainty in the 'rating' at test conditions, Ps, is dependent upon the uncertainty in each of the independent variables. The uncertainty in each variable is propagated through sensitivity coefficients, which are the partial derivatives of the right hand side of eq. 1 with respect to each 'independent' variable [6, 7]:

$$\partial P/\partial I = a + 2* I *b + c*W + d*T \quad (2)$$

$$\partial P/\partial W = c*I \quad (3)$$

$$\partial P/\partial T = d*I \quad (4)$$

Given measurement errors, or uncertainties, e, in each of the independent variables, e_I, e_T, and e_W, the error in P, e_P is computed from:

$$e_P^2 = (\partial P/\partial I * e_I)^2 + (\partial P/\partial W * e_W)^2 + (\partial P/\partial T * e_T)^2 \quad (5)$$

$$e_p = [(\partial P/\partial I * e_I)^2 + (\partial P/\partial W * e_W)^2 + (\partial P/\partial T * e_T)^2]^{1/2}$$

Note that e_p is dependent upon the absolute magnitude of the irradiance, wind speed, and ambient temperature, as well as the measurement errors or uncertainties or e_I, e_W, and e_T, through equations 2, 3, and 4.

4. <u>USSC PTSC REGRESSION FITS</u>

AC power output for the USSC system was first filtered for:

- Daylight only data
- Removal of any record with missing data for any parameter
- Removal of any record with Irradiance < 500 Wm^{-2}
- Removal of any record where the AC power was less than 1.2 x Irradiance (indicating the array was shadowed, covered with snow, shut down for maintenance, or otherwise not in a standard operational mode).

The 'floor' value of P > 1.2 * Irradiance was chosen based on the nominal 1.6 kW rating of the system at 1.0 kWm^{-2} Standard Reporting Condition irradiance.

Figure 1 shows the data set as received, and figure 2 shows the filtered data set, from which the regression coefficients for the model were derived.

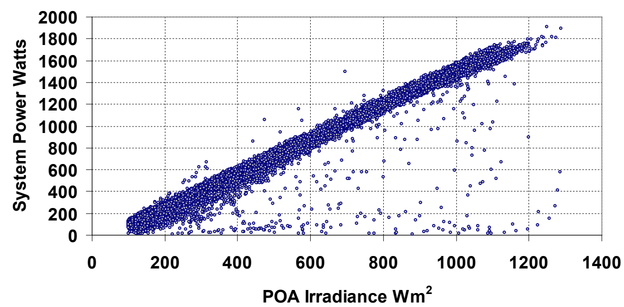

Fig 1. All raw USSC Array data versus plane of array irradiance for 2006

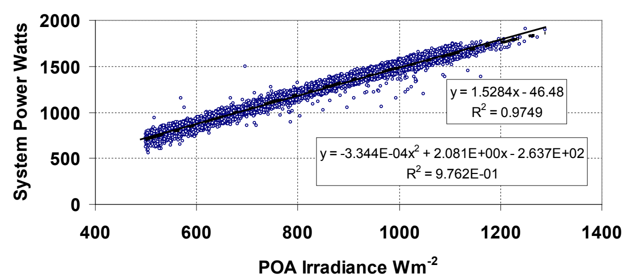

Fig 2. USSC Array data after filtering for non-standard operating conditions and for POA> 500 Wm^{-2}

The derived regression coefficients for this filtered data set were:

a= 1.4187, b= 5.0583 •10^{-5}, c= 2.2908•10^{-3},
d = 3.61332 •10^{-4}
It is instructive to examine the relative magnitude of the coefficients, since all are coefficients of I three times over , as well as the b coefficient of I^2. Using Watts as the units of power, at a rating condition of I = 1000 Wm^{-2}, the relative contribution of each term in the PVUSA model to the rating value is approximately (in the absence of any measurement error at all):

a: 96.4%, b: 2.9%, c: 0.4%, and d: 0.4%. (sums to 100.1% due to rounding).

Note that a and b (irradiance and irradiance square terms only) contribute 99.3% of the eventual rating value. This will be discussed further below. A linear fit (1.5284*I – 46.48, r^2 = 0.975, standard deviation of regression = 45.2 Wm^{-2}) of the array power to the irradiance (only) is shown by the line in fig 2. The quadratic fit is also shown.

5. PVUSA TC (PTC) RATING

Using the regression coefficients, a, b, c, and d, and the rating standard condition of I_s=1000 Wm^{-2}, W_s=1 ms^{-1}, and T_s=20 °C, in equation (1) we compute:

$$P_s = I_s * (a + b* I_s + c * W_s + d * T_s)= 1480.6 \text{ W.}$$

Table 3 shows the measured and modeled power data for the POA irradiance within ±0.5 Wm^{-2} of the 1000 Wm^{-2} PVUSA TC point.

TABLE 3: MEASURED AND MODELED P
(I=1 kW ± 0.5 W)

AC Power W	POA Irradiance Wm^{-2}	Wind Speed m/s	Temp °C	PTC Model AC W
1506.4	999.9	7.4	9.0	1489.28
1467.4	999.8	2.8	19.5	1482.39
1506.8	1000.0	2.3	16.6	1480.50
1504.0	999.6	2.3	16.2	1479.74
1454.4	1000.1	2.0	26.6	1483.58
1468.4	999.7	2.2	25.1	1482.08
1481.9	999.9	2.8	26.6	1485.11
1528.8	999.9	2.0	16.4	1479.49
1558.7	999.9	2.2	17.9	1480.59
1545.3	1000.4	1.7	1.1	1474.13
1565.1	1000.2	3.8	16.9	1484.35
1513.3	1000.0	0.5	11.4	1474.50
1493.0	1000.4	1.4	4.0	1474.50
1516.7	1000.1	1.3	0.4	1472.51
PTCRATE	**1000.0**	**1.0**	**25.0**	**1480.56**

Note this one watt per meter square window is somewhat unrealistic, since typical pyranometer calibration error for a well characterized pyranometer is ±0.5% at 1000 Wm^{-2}, or ± 5 Wm^{-2}, ten times our specified window here.

There is measurement uncertainty associated with the array power, as well. An estimate of this measurement uncertainty is ±1%, or 15 Watts. Note the standard deviation, sigma, of the measured AC power in table 3 is ±36 Watts, (2.4% of the 1480 W rating) and 2-sigma would be ±72 Watts.

The mean measured AC power for the table 3 data points is 1507.8 ± 36.6 Wm^{-2}; the mean PTC modeled AC power is 1480.3 ± 4.8 Wm^{-2} (a 1.8% difference). Mean Wind speed and temperatures are 2.4 ± 1.6 ms^{-1} and 14.5 ± 8.7 °C, respectively. This difference is about the measurement uncertainty in the power from V and A transducer measurement (1.2%, 2 sigma) derived in section 2.1.

Figure 3 shows the residuals (measured – modeled) between measured and modeled array power (for prevailing temperature and wind speeds) over a twenty watt irradiance 'window' centered on the PVUSA TC rating point of 1000 Wm^{-2}. With the exception of one residual of -307 Wm^{-2} (where T = 0.6 °C and W = 1.7 ms^{-1}; possible frost or snow on the array) the range of residuals is -124 Wm^{-2} to + 100 Wm^{-2} in this irradiance regime. This range represents –0.8% to +0.7% of the rating at PVUSA TC. Thus, an uncertainty component due to the model fit can be assumed as ~ ± 1.0%. This same scatter is apparent in figure 2, about the linear fit line in that plot.

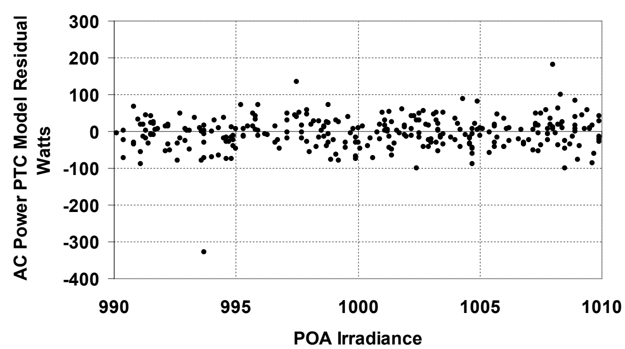

Fig. 3. Residuals (measured – modeled) of measured data from the PVUSA TC model line for irradiance levels from 990 Wm^{-2} to 1000 Wm^{-2}. Note this includes temperature range from -32.5 °C to 36 °C and wind speeds from 0.4 to 9.1 ms^{-1}.

6. CORRELATIONS OF POWER WITH MODEL VARIABLES

Since the PVUSA TC model is based on an assumed correlation of array power with the three independent variables, expressed as four terms in the model equation 1, it is interesting to look at the correlation of the array power with each model term, as in figure 5. Here we plot the array power versus the corresponding term of the model, e.g. a times Irradiance, a * I, b times Irradiance squared, $b*I^2$, c times Irradiance times wind speed, c*I*W, and d * I * T. The strong correlation of the array power with the irradiance terms is immediately obvious. There is a great deal of noise and virtually zero correlation between array power and the wind and temperature terms, except for the extremely cold days (Feb 16, 2006, March 27, 28 2006 where the reported temperature was less than -5 °C).

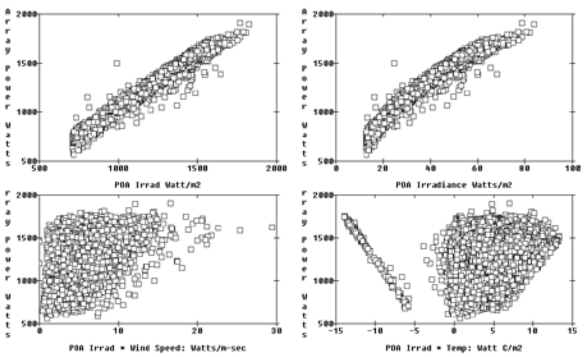

Fig. 5. Correlations of array power with each independent term of the PVUSA TC model. Top left to bottom right: array power versus a*I, $b*I^2$, c*I*w, d*I*T. The values of a, b, c, and d developed from the model are used. Note the lack of strong correlation between wind speed and temperature components of the model and the array output, except for very cold (T<-5 °C) day [135 data points] in the bottom right graph.

7. UNCERTAINTY IN THE PTC RATING

The uncertainty in the PTC rating value depends on the magnitude of the measurement errors in the independent variables, the magnitudes of the fixed reporting conditions, and the sensitivity coefficients, equation 5.

7.1 NREL USSC 1.6 kW System Rating Uncertainty

An Excel spreadsheet was constructed which permits one to compute the absolute uncertainty in P at various combinations of I, W, and T, with assumed values of e_I, e_W, and e_T, of course incorporating equation 6.

Table 4 displays a typical result, with error terms (assumed for measurements) of e_I=25 Wm^{-2}, e_W = 1 ms^{-1}, and e_T= 1° C for the USSC 1.6 kW system at NREL at each of the indicated plane of a array (POA) irradiance levels in column 1. The Ps 'error' result is computed from eq. 5 and the values in the columns to the left.

The results of these computations need to be combined with the measurement uncertainty in the array power, the dependent variable of the model, to achieve an overall uncertainty for the entire method. If instrumentation similar to that described in table 2 above (used in the PV Energy Rating Testbed experiments) then the combined current, voltage, and power measurement uncertainty is 0.22%. Note the magnitude of the uncertainty in Ps (gray cell), 42 Watts, or about 2.8% of the rating. Compare this with the fact that 0.7% of the rating value, or 10.3 W, is contributed by the combined wind speed and temperature terms in the model equation. These latter two elements contribute to the rating value an amount that is 4 times smaller than the uncertainty contributed by the irradiance uncertainty. The 25 Wm^{-2} irradiance uncertainty is 2.5% of the rating irradiance value of 1000 Wm^{-2}. Such accuracy is representative of an exceptionally well

TABLE 4: UNCERTAINTY IN P AS FUNCTION OF UNCERTIANTY IN VARIABLES (USSC 1.6 kW)

POA kWm^{-2}	Note: e_I=25 Wm^{-2}, e_W = 1 ms^{-1}, and e_T= 1° C. PTC Rating = 1480 W. (ei*∂/∂i)^2	(ew*∂/∂w)^2	(∂/∂t)^2	Ps RSS ERROR	% error wrt 1480
0.5	781.39	1.3	0.033	28.0	1.9%
0.6	942.90	1.9	0.047	30.7	2.1%
0.7	1119.57	2.6	0.064	33.5	2.3%
0.8	1311.41	3.4	0.084	36.3	2.5%
0.9	1518.40	4.3	0.106	39.0	2.6%
1.0	1740.56	5.2	0.131	41.8	2.8%
1.1	1977.87	6.3	0.158	44.5	3.0%

Mean residual when 990 Wm^{-2}<POA<1010 Wm^{-2} is 2.5 W

calibrated and maintained pyranometer. This irradiance uncertainty in table 1 is typical. Combining the 2.8% combined uncertainty contributions from the independent variables with the 0.22% uncertainty in measured power, the overall uncertainty in the PVUSA TC approach for the USSC system tested is 2.8%.

7.2 Uncertainty in PVUSA Ratings for Other Systems

From PVUSA TC model coefficients for several large (~ 200 kW or larger) PV systems in a 1993 PVUSA project progress report [8]. IPC US-1, at Davis, CA and SSI-US-2 at Kerman systems were selected (page 3-9). We replicated the above calculations for these systems. The systems in tables 5 and 6 are much larger than the NREL, rated at ~ 190 kW and 500 kW, respectively. The units of power for the systems and the input irradiance in these cases are kW and kWm^{-2}.

Results in tables 4, 5 and 6, for assumed measurement uncertainty in irradiance, temperature, and wind speed of ±25 Wm^{-2}, ±1 °C and ±1 ms^{-1}, respectively, show that the derived uncertainty in the PVUSA TC results is between 2% and 3% at the rating condition. This uncertainty is primarily driven by the uncertainty in irradiance measurement (25 Wm^{-2} at 1000 Wm^{-2} = 2.0%). Factors of 10 increases in the measurement errors for the temperature and wind speed hardly influence the resultant uncertainty at all. In these two cases, PVUSA quoted an uncertainty in their rating at

TABLE 5: UNCERTAINTY IN P AS FUNCTION OF UNCERTAINTY IN VARIABLES IPC US-1 DAVIS

POA kWm^{-2}	Note: e_I=25 Wm^{-2}, e_W = 1 ms^{-1}, and e_T= 1° C PVUSA* rating 192.25 kW ± 3 kW =1.6%. a=282.14 b=-70.152 c=1.5824 d=-0.8998			RSS Power Uncert (kW)	% error wrt 190 kW
	$(ei*\partial/\partial i)^2$	$(ew*\partial/\partial w)^2$	$(\partial/\partial t)^2$		
0.5	28.17	0.6	0.198	5.4	2.7%
0.6	24.59	0.8	0.285	5.1	2.6%
0.7	21.26	1.1	0.388	4.8	2.4%
0.8	18.17	1.4	0.506	4.5	2.3%
0.9	15.32	1.8	0.641	4.2	2.2%
1.0	12.71	2.3	0.792	4.0	2.0%
1.1	10.35	2.7	0.958	3.7	1.9%

*Quoted uncertainty by PVUSA; no documentation of derivation. Presumably model standard error

TABLE 6: UNCERTAINTY IN P AS FUNCTION OF UNCERTAINTY IN VARIABLES KERMAN

POA kWm^{-2}	Note: e_I=25 Wm^{-2}, e_W = 1 ms^{-1}, and e_T= 1° C PVUSA* Rating: 498.4 ± 6 kW =1.2%. a=701.1 b=-142.2 c=6.412 D=-3.384			Power RSS Uncert	% error wrt 498 kw
	$(ei*\partial/\partial i)^2$	$(ew*\partial/\partial w)^2$	$(\partial/\partial t)^2$		
0.5	196.35	10.2	2.89	14.5	2.9%
0.6	177.16	14.7	4.16	14.0	2.8%
0.7	158.95	20.1	5.66	13.6	2.7%
0.8	141.73	26.2	7.39	13.2	2.7%
0.9	125.50	33.2	9.36	13.0	2.6%
1.0	110.25	41.0	11.56	12.8	2.6%
1.1	95.99	49.6	13.98	12.6	2.5%

*Quoted uncertainty by PVUSA; no documentation of derivation. Presumably model standard error

about ½ that of the analysis here; however there is no report of how the uncertainty was calculated.

7.3 Residual Analysis for the USSC PVUSA Model.

The residuals for the PVUSA TC (eq. 1) fit, and a linear and quadratic fit of the AC power as a function of irradiance alone (see figure 2) for the NREL USSC 1.6 kW system are shown in figure 6.

Note that the PVUSA TC model produces the widest range of residuals (Squares), due mainly to the additional wide dispersion of the correlation of the AC power with respect to the wind and temperature components of the model shown in figure 5. The range of residuals for the linear (+) and quadratic (circles) fits are somewhat smaller. The mean residual for the PVUSA model is -0.56 W, however the mean residuals for the linear and quadratic fits are 10 orders of magnitude smaller and near very near zero (1.6• 10^{-12} W and 6.2 •10^{-12} W, respectively).

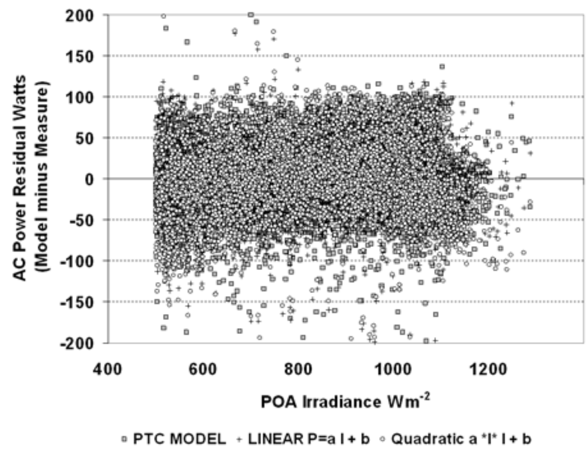

Fig. 6. Residuals between measured and modeled PTC (gray squares), and quadratic (open circle) and linear (+) fits of AC power versus irradiance alone for the USSC system.

This suggests that the addition of the wind speed and temperature terms in the PVUSA model *results in additional noise being introduces into the mode*l, and not improvement in the model performance.

Multicollinearity [9] between the ambient temperature and the irradiance, and the 'weighting' of the wind and temperature data by the irradiance term increases the multiple correlation coefficient of the PVUSA TC model, *but* increases the residuals to the fit, and results in a lower performance model than a simple linear or quadratic for of AC power versus irradiance.

The uncertainty in the irradiance measurements is the largest contributor to the uncertainty in the model results. To achieve a rating uncertainty of 1.0%, the uncertainty in the irradiance must be reduced to this level (better than ± 1% accuracy). The only way to achieve this level or uncertainty is to apply incidence angle modifiers to the pyranometer data used to collect the irradiance data.

8. CONCLUSION

We applied the PVUSA rating system to a thin film dual junction 1.6 kW (nominal) PV system at NREL. Our analysis of the uncertainties associated with the measurement instrumentation, and propagation of errors through sensitivity coefficients for the variables in the model equation demonstrated an uncertainty in the rating using the PVUSA PTC model of about 2.8 % for a rating of 1.480 kW, or ±41 watts. Analogous results were obtained for two other larger PV systems reported by PVUSA. We have shown a lack of strong correlation between system output and two variables (wind speed, ambient temperature) in the PTC rating model. The lack of true independence in the 'independent' variable terms, or multicollinearity, engendered by multiplying these variables by irradiance, artificially inflates the correlation coefficient for the model, and may be adding noise to the model. Simple linear and quadratic regressions of AC power versus plane of array irradiance produce within 3% of the PVUSA TC results; with essentially same uncertainties (3%), the error bars about the simple and PVUSA TC results would overlap, and the results would be considered comparable. Residuals from the three fits essentially overlay one another, however the spread in the residuals from the PTC model have a somewhat larger spread. Measured AC power with POA irradiance within ±0.5 watts of 1 kWm^{-2}, over several days produced a rating within 1.8% of the PTC rating, or within the PTC uncertainty.

From these results, we conclude that the PTC, simple linear and quadratic regression of AC power versus POA irradiance, and measured AC power near STC irradiance conditions all produce results ('ratings') within about 3% of each other, with similar uncertainties. The results from all four techniques are comparable, and have uncertainties on the order of 3%, mainly due to measurement system (particularly radiometer) uncertainties.

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The PVUSA (Photovoltaics for Utility Scale Applications) project in the 1990's developed a rating methodology for PV performance evaluation which has become popular, and even incorporated into concentrating PV rating standards This report apply that method to rack-mounted dual-junction PV system, and produces a system rating.

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PFUSA; performance; concentrating solar; CSP, dual junction

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