EVALUATING BUILDING INTEGRATED PHOTOVOLTAIC PERFORMANCE MODELS

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ABSTRACT

Predictive performance tools could accelerate the implementation of building integrated photovoltaics (BIPV). The National Institute of Standards and Technology (NIST) seeks to improve and validate previously developed computer simulation tools with experimental data collected in a building integrated photovoltaic "test bed." Twelve months of performance data has been collected for BIPV panels using four different cell technologies: crystalline, polycrystalline, silicon film, and triple-junction amorphous. Two panels using each cell technology were present, one without any insulation attached to its rear surface and one with insulation attached to its rear surface. Two predictive performance tools were investigated: IV Curve Tracer, a photovoltaic model developed by Sandia National Laboratories (SNL), and PHANTASM, a BIPV predictive tool developed by the Solar Energy Laboratory at the University of Wisconsin. The performance data associated with the eight panels in the BIPV "test bed", along with meteorological data, was compared to the predictions of the SNL and PHANTASM models.

INTRODUCTION

Predictive performance tools are an important factor in the success of any technology. An effective performance model would accurately predict the annual energy production given the orientation of the proposed photovoltaic system, typical weather conditions for the geographic region, the nominal performance of the specified BIPV technology, and the proposed coverage area of the BIPV application. The predicted energy production would subsequently be used to compute the energy and cost savings for different cell technologies and system orientations.

The National Institute of Standards and Technology created a building integrated photovoltaic test facility to evaluate predictive performance tools [1]. The facility includes a "test bed" for side-by-side testing of BIPV products. During the calendar year 2000, four different cell technologies, crystalline, polycrystalline, silicon film, and triple-junction amorphous, were present in the "test bed." Two panels of each cell technology were installed, one panel without backside insulation and one with insulation attached to the rear surface of the panel. The 102 mm (4 in) thick extruded polystyrene insulation has a nominal R-value of 3.5 $m^2 \cdot K/W$ (R-20). Twelve months of performance data was recorded at five min. intervals, including peak power output, peak power voltage, peak power current, panel temperature, and meteorological data. A solar tracking facility is used to characterize the electrical performance of the panels used in the "test bed." A rooftop meteorological station measures the total horizontal, horizontal diffuse, and the direct beam irradiance; the outdoor ambient temperature; and the wind speed and direction. These facilities provide the measurements needed to evaluate BIPV predictive performance tools. The measured "test bed" performance [2,3] is compared to the performance predicted with two simulation programs: Sandia National Laboratories' IV Curve Tracer [4] and the University of Wisconsin's PHANTASM [5]. This paper describes the performance models and compares measured results to the model predictions.

SIMULATION MODELS

A number of publications have described the model developed by Sandia National Laboratories to predict the electrical output of photovoltaic panels [6,7,8,9]. The equations presented in this paper represent SNL's latest implementation of the model [10]. The premise of this performance model is that the I_{mp}, V_{oc}, and V_{mp} of a photovoltaic module can be described as functions of I_{sc} and the cell temperature. The short-circuit current is assumed to be dependant on the beam and diffuse irradiance, air mass, incident angle, and panel temperature. The effective irradiance compares the short-circuit current at any meteorological conditions with the short-circuit current at standard rating conditions. The remaining performance parameters (I_{mp}, V_{oc}, and V_{mp}) are predicted using the effective irradiance and several empirical coefficients, as well as the respective temperature coefficients.

A large number of performance parameters that are not provided by manufacturers are required. Temperature coefficients for the maximum power current and voltage, polynomials describing the effect of air mass and incident angle, and an empirical diode factor are a few of the less-common parameters that a system designer would need. The developers have provided these obscure values in a large database of parameters for a number of popular prefabricated panels. In the case of custom-fabricated BIPV panels, however, these parameters are not available. Once the parameters are acquired, the implementation of the model is simple, and several programs utilize the SNL model, including IV Curve Tracer [4] and PV-Design Pro [11].

The PHANTASM model, developed by the University of Wisconsin, requires fewer parameters than the SNL model, and most of the parameters are commonly provided by panel manufacturers, such as the electrical performance at standard rating conditions and the short-circuit current and open-circuit voltage temperature coefficients. The PHANTASM model approximates the photovoltaic cell with an electrical circuit that includes a current generator, diode, shunt resistor, and series resistor. For very high shunt resistances, assuming an infinite shunt resistance results in a simpler four-parameter model, as compared to the standard five-parameter model. An equation is derived to calculate the output current with respect to voltage for the four or five-parameter model. An iterative routine is used to find the combination of current and voltage that result in the maximum power output.

PHANTASM requires the transmittance of the glazing, absorptance of the PV cells, series resistance, shunt resistance, and the electron bandgap, which are not as readily available from cell or panel manufacturers. However, the series resistance can be calculated by the program for any panel using the temperature coefficients and the rating conditions. The shunt resistance is assumed to be the absolute value of the inverse slope of the I-V curve, which is commonly supplied with the panel specifications, at the short-circuit condition. A slope of nearly zero corresponds to a high shunt resistance, which indicates that the use of the four-parameter model is reasonable. In general, the five-parameter model is only used with amorphous PV technologies. The electron bandgap is given for crystalline silicon (1.12 eV), but it is not provided for other materials. With these parameters and others describing the orientation of the application, the energy output for a building integrated photovoltaic module can be predicted using PHANTASM.

MODEL PARAMETERS

The parameters used to model the panels in the BIPV "test bed" for the SNL model and the four and five-parameter PHANTASM model are shown in Table 1. As mentioned previously, many of these parameters are not readily available from module specification sheets. For the purpose of evaluating the performance models, the remaining parameters were determined by contacting the PV technology's manufacturer or using measurement resources available at NIST.

The reference conditions, temperature coefficients, NOCT values, and the SNL model parameters (f(AMa), f(AOI), etc.) were measured using NIST's solar tracking test facility [12] for each PV technology. The slope of the I-V curve at short-circuit conditions was computed with measured I-V curves from each panel. The electron bandgap was assumed to be 1.12 eV unless the manufacturer specified another value. Rauschenbach described a method to determine the series resistance of a module using two I-V curves measured at differing irradiance values [13]. This method was used to calculate the series resistance for each module. The resulting values closely matched those measured using a dark I-V procedure by

Table 1. SNL and PHANTASM Model Parameters

		Single Crystalline	Poly-crystalline	Silicon Film	Triple Junction Amorphous
Reference Conditions					
P_{mpo}	(W)	103.96	133.40	125.78	57.04
I_{sco}	(A)	5.11	4.37	4.25	4.44
V_{oco}	(V)	29.61	42.93	41.50	23.16
I_{mpo}	(A)	4.49	3.96	3.82	3.61
V_{mpo}	(V)	23.17	33.68	32.94	16.04
NOCT	(°C)	316.2	316.9	316.5	311.1
NOCT (Ins)	(°C)	337.9	340.1	338.6	328.5
Temperature Coefficients					
α_{Isc}	(A/°C)	0.00468	0.00175	0.00238	0.00561
α_{Imp}	(A/°C)	0.00160	-0.00154	0.00018	0.00735
β_{Voc}	(V/°C)	-0.1300	-0.1524	-0.1528	-0.0931
β_{Vmp}	(V/°C)	-0.1304	-0.1536	-0.1591	-0.0477
SNL Model Parameters					
f(AMa)	Cnst	9.38E-01	9.36E-01	9.18E-01	1.10E+00
	Ama	6.22E-02	5.43E-02	8.63E-02	-6.14E-02
	AMa^2	-1.50E-02	-8.68E-03	-2.45E-02	-4.43E-03
	AMa^3	1.22E-03	5.27E-04	2.82E-03	6.32E-04
	AMa^4	-3.43E-05	-1.14E-05	-1.26E-04	-1.92E-05
f(AOI)	Cnst	9.99E-01	1.00E+00	9.99E-01	1.00E+00
	AOI	-6.10E-03	-5.56E-03	-1.21E-02	-5.65E-03
	AOI^2	8.12E-04	6.55E-04	1.44E-03	7.25E-04
	AOI^3	-3.38E-05	-2.73E-05	-5.58E-05	-2.92E-05
	AOI^4	5.65E-07	4.64E-07	8.78E-07	4.70E-07
	AOI^5	-3.37E-09	-2.81E-09	-4.92E-09	-2.74E-09
C0		0.96	1.00	1.01	1.07
C1		0.04	0.00	-0.01	-0.10
C2		0.23	-0.54	-0.32	-1.85
C3		-9.43	-21.41	-30.20	-5.18
n		1.36	1.03	1.03	3.09
PHANTASM Parameters					
IV Slope @ Isc	(A/V)	-0.008	-0.004	-0.003	-0.020
Rs	(Ohm)	0.57	0.52	0.52	0.41
Bandgap	(eV)	1.12	1.12	1.14	1.60
$\tau\alpha$ Product		0.748	0.779	0.755	0.763
SNL Temperature Model Parameters					
Panel Type		Mount	a	b	ΔT
Glass/Cell/Glass		Open	-3.473	-0.0595	2
Glass/Cell/Glass		Close Roof	-2.976	-0.0471	3
Glass/Cell/Tedlar*		Open	-3.562	-0.0786	3

SNL for all four PV technologies except the triple-junction amorphous [14]. The product of glazing transmission measurements and bare cell absorptance measurements, each as a function of wavelength, were weighted according to the quantum efficiency of each module. The resulting value yields a transmittance-absorptance ($\tau\alpha$) product weighted according to its performance across the range of wavelengths that each module responds. The SNL temperature model parameters are used to predict the module temperature necessary for electrical performance predictions. The model developers provide values for three mounting scenarios. The "Glass/Cell/Tedlar*" panel with an "open" mount was used to model the uninsulated panels, and the "Glass/Cell/Glass" panel with a "Close Roof" mount was used to model the insulated panels.

MODEL IMPLEMENTATION

In order to compare the measurements made by the BIPV "test bed" with those predicted by the SNL and PHANTASM models on an annual basis, both models are applied at five min. intervals over one year for eight different panels. IV Curve Tracer, which houses the SNL photovoltaic performance model, is used to trace a single I-V curve at specified input conditions. To simplify the use of the BIPV "test bed" meteorological data [2,3], the SNL model was implemented in a FORTRAN subroutine for use in the TRNSYS [15] frontend. The predicted electrical output using the FORTRAN subroutine was compared to the predicted output using IV Curve Tracer. As expected, results from the TRNSYS subroutine matched those of IV Curve Tracer. The PHANTASM model is an extension of an existing TRNSYS subroutine for predicting the performance of photovoltaics. Therefore, the TRNSYS subroutine was used to calculate the predicted energy output for the eight BIPV panels in the "test bed."

RESULTS

All three models (SNL, PHANTASM four-parameter, and PHANTASM five-parameter) were applied to the eight panels present in the BIPV "test bed" over the course of a year. The electrical output of the models are compared to the measured electrical output of each panel. The measured accumulated energy is compared to the predicted energy output directly, which is expressed as a positive

Table 2. Monthly Comparisons of Predicted and Measured Energy Outputs for Eight BIPV Panels

	Uninsulated Single Crystalline						Insulated Single Crystalline					
	PHANTASM-4		PHANTASM-5		SNL		PHANTASM-4		PHANTASM-5		SNL	
Month	Diff (%)	R^2	Diff (%)	R^2	Diff (%)	R^2	Diff (%)	R^2	Diff (%)	R^2	Diff (%)	R^2
January	-0.1	0.914	-1.6	0.906	0.7	0.916	-3.7	0.928	-5.0	0.918	-3.0	0.932
February	-1.1	0.955	-4.9	0.948	0.6	0.959	-3.3	0.963	-6.5	0.955	-1.8	0.967
March	-3.7	0.968	-8.9	0.959	-1.4	0.971	-5.3	0.968	-10.0	0.958	-3.1	0.972
April	-8.4	0.968	-16.8	0.950	-5.0	0.973	-9.4	0.967	-17.4	0.948	-6.2	0.973
May	-9.5	0.957	-20.8	0.925	-6.3	0.964	-8.9	0.959	-19.9	0.929	-5.9	0.966
June	-8.2	0.956	-20.6	0.918	-5.3	0.962	-7.2	0.959	-19.4	0.923	-4.5	0.964
July	-8.5	0.933	-20.2	0.897	-5.7	0.939	-7.5	0.936	-19.0	0.902	-4.9	0.942
August	-7.0	0.944	-16.4	0.921	-2.8	0.948	-6.3	0.946	-15.4	0.925	-2.3	0.950
September	-4.5	0.937	-10.2	0.925	-1.4	0.940	-4.6	0.939	-9.8	0.926	-1.6	0.942
October	-1.3	0.973	-4.3	0.968	0.4	0.976	-1.2	0.977	-3.6	0.972	0.4	0.980
November	-1.7	0.937	-5.3	0.929	0.8	0.938	-3.1	0.946	-6.1	0.937	-0.7	0.949
December	1.2	0.933	-3.3	0.928	2.8	0.933	-2.1	0.945	-5.9	0.939	-0.8	0.948
Total	**-3.4**	**0.945**	**-9.2**	**0.935**	**-1.1**	**0.947**	**-4.6**	**0.952**	**-9.9**	**0.941**	**-2.5**	**0.956**

	Uninsulated Polycrystalline						Insulated Polycrystalline					
	PHANTASM-4		PHANTASM-5		SNL		PHANTASM-4		PHANTASM-5		SNL	
Month	Diff (%)	R^2	Diff (%)	R^2	Diff (%)	R^2	Diff (%)	R^2	Diff (%)	R^2	Diff (%)	R^2
January	0.3	0.926	-2.9	0.921	0.6	0.919	-4.8	0.942	-7.5	0.936	-4.8	0.938
February	-5.0	0.961	-2.9	0.957	0.2	0.958	-8.7	0.969	-6.4	0.964	-4.1	0.967
March	-1.6	0.970	-5.9	0.966	-1.7	0.969	-5.4	0.969	-9.2	0.963	-5.8	0.969
April	-4.0	0.971	-11.1	0.963	-4.5	0.972	-8.1	0.967	-14.7	0.956	-9.0	0.968
May	-3.6	0.960	-13.1	0.948	-6.8	0.961	-6.7	0.959	-15.7	0.942	-10.4	0.957
June	-1.3	0.960	-11.8	0.946	-6.6	0.957	-4.4	0.960	-14.3	0.941	-10.2	0.952
July	-2.3	0.935	-12.1	0.921	-7.1	0.932	-5.1	0.936	-14.4	0.918	-10.4	0.930
August	-2.3	0.945	-10.1	0.936	-3.6	0.945	-5.0	0.946	-12.3	0.934	-6.8	0.945
September	-2.4	0.938	-7.1	0.932	-2.2	0.937	-5.0	0.940	-9.2	0.932	-5.3	0.939
October	-0.8	0.977	-3.3	0.974	-0.3	0.976	-2.6	0.981	-4.7	0.978	-2.4	0.981
November	-0.3	0.947	-3.4	0.943	1.1	0.943	-3.7	0.958	-6.3	0.953	-2.6	0.958
December	2.8	0.944	-1.1	0.942	3.0	0.939	-2.3	0.959	-5.6	0.955	-2.5	0.958
Total	**-1.4**	**0.951**	**-5.8**	**0.947**	**-1.4**	**0.948**	**-5.0**	**0.959**	**-9.0**	**0.953**	**-5.4**	**0.958**

	Uninsulated Silicon Film						Insulated Silicon Film					
	PHANTASM-4		PHANTASM-5		SNL		PHANTASM-4		PHANTASM-5		SNL	
Month	Diff (%)	R^2	Diff (%)	R^2	Diff (%)	R^2	Diff (%)	R^2	Diff (%)	R^2	Diff (%)	R^2
January	13.4	0.905	7.3	0.909	7.9	0.918	9.3	0.938	4.0	0.936	3.1	0.948
February	14.0	0.935	7.6	0.942	6.7	0.954	11.2	0.951	5.6	0.954	3.1	0.965
March	14.0	0.944	5.3	0.955	4.6	0.965	11.3	0.954	3.4	0.960	1.2	0.969
April	15.5	0.949	1.4	0.965	3.6	0.970	12.6	0.957	-0.7	0.967	0.1	0.972
May	22.0	0.915	2.1	0.954	4.1	0.956	20.2	0.922	1.1	0.955	1.5	0.959
June	27.6	0.874	5.1	0.941	6.4	0.947	25.7	0.884	4.1	0.942	3.8	0.952
July	25.1	0.858	4.1	0.910	4.8	0.923	23.4	0.867	3.3	0.912	2.4	0.929
August	21.1	0.894	4.9	0.925	6.0	0.937	19.8	0.901	4.3	0.927	3.8	0.943
September	14.9	0.905	5.3	0.915	4.0	0.930	13.7	0.912	4.7	0.918	1.8	0.936
October	12.4	0.956	7.2	0.962	4.5	0.974	12.4	0.961	7.9	0.964	3.4	0.979
November	13.2	0.927	7.2	0.931	7.5	0.941	11.3	0.948	6.0	0.948	4.7	0.960
December	16.6	0.921	9.4	0.930	10.0	0.937	12.5	0.951	6.1	0.954	5.1	0.964
Total	**16.2**	**0.925**	**6.2**	**0.935**	**6.2**	**0.945**	**14.0**	**0.943**	**4.6**	**0.949**	**3.0**	**0.960**

	Uninsulated Triple-Junction Amorphous						Insulated Triple-Junction Amorphous					
	PHANTASM-4		PHANTASM-5		SNL		PHANTASM-4		PHANTASM-5		SNL	
Month	Diff (%)	R^2	Diff (%)	R^2	Diff (%)	R^2	Diff (%)	R^2	Diff (%)	R^2	Diff (%)	R^2
January	-6.0	0.943	-10.4	0.933	-6.1	0.958	-5.6	0.939	-9.3	0.930	-6.1	0.953
February	-9.1	0.960	-13.9	0.946	-3.8	0.971	-9.4	0.959	-13.5	0.947	-4.3	0.971
March	-16.0	0.947	-22.6	0.919	-3.4	0.973	-16.9	0.943	-22.8	0.917	-4.5	0.973
April	-24.1	0.918	-33.9	0.863	-2.0	0.975	-25.1	0.913	-34.2	0.860	-3.0	0.976
May	-30.1	0.866	-42.8	0.766	0.5	0.968	-30.3	0.865	-42.6	0.769	0.5	0.968
June	-31.7	0.841	-45.8	0.707	2.7	0.961	-31.8	0.840	-45.6	0.710	2.9	0.962
July	-31.7	0.824	-45.1	0.702	0.8	0.943	-31.7	0.824	-44.7	0.706	1.1	0.943
August	-26.8	0.874	-38.0	0.795	3.0	0.949	-26.9	0.873	-37.7	0.798	3.0	0.950
September	-19.4	0.903	-26.6	0.868	-0.7	0.943	-19.5	0.904	-26.1	0.870	-0.9	0.944
October	-8.4	0.974	-12.6	0.963	-0.6	0.984	-8.5	0.973	-12.0	0.963	-1.1	0.983
November	-4.6	0.955	-9.2	0.946	0.2	0.967	-5.5	0.955	-9.3	0.945	-1.1	0.968
December	1.1	0.956	-4.4	0.951	1.2	0.970	0.1	0.954	-4.6	0.948	-0.2	0.968
Total	**-14.8**	**0.938**	**-22.2**	**0.912**	**-1.0**	**0.967**	**-15.2**	**0.937**	**-22.0**	**0.911**	**-1.5**	**0.966**

percent difference from the measured value if the predicted value is higher, Table 2. The expanded uncertainty of the measurements is ±1.2 %. A second method of comparison is the statistical correlation coefficient, R^2. Unlike the comparison of accumulated energy, the correlation coefficient compares the predicted output at each five min. data point. This provides a clearer picture of the precision of the model.

It is clear from Table 2 that the SNL model outperforms the two PHANTASM models overall with respect to percent difference and R-squared. This is to be expected considering the number of parameters that are required for the SNL model. The greatest yearly percent difference is 6.2 % for the uninsulated silicon film panel, and the greatest monthly percent difference is -10.4 % for the insulated polycrystalline panel in May and July. The four-parameter PHANTASM model performed well (less than 5 % difference) for the single crystalline and polycrystalline panels, but large differences were observed during the months of April through September for the silicon film and triple-junction amorphous panels. Likewise, large differences were found using the five-parameter PHANTASM model for the single crystalline and triple-junction amorphous during these same months. The large differences tended to occur during months in which high incident angles (approximately 75° at solar noon in June) were accompanied by low values of incident irradiance. The magnitude of the differences varied between models for each panel. For example, the low irradiance values and high incident angles did not seem to affect the five-parameter model on the silicon film panel, but the exact same meteorological conditions produced large differences between the predicted and measured energy output for silicon film panels using the four-parameter PHANTASM model. The opposite trend occurred for the polycrystalline panel.

The five-Parameter PHANTASM model should perform the same or better than the four-parameter PHANTASM model, which is a simplification of the five-parameter model, for each panel. More importantly, the five-parameter model, which is intended for use on amorphous panels (steeper I-V slopes), should outperform the four-parameter PHANTASM model for the triple-junction amorphous panel. Six of the eight panels were more closely modeled using the four-parameter model than the five-parameter model, including the triple-junction amorphous. However, the silicon film panel, which has the second steepest slope at short-circuit conditions, was more closely modeled by the five-parameter PHANTASM model than the four-parameter.

CONCLUSION

The SNL model closely models the measured performance of all eight panels in the NIST BIPV "test bed." The PHANTASM model does not produce results consistent with its basic premise, which indicates that the complete five-parameter model should better predict PV performance than the simplified four-parameter model. Only two of the eight panels were better modeled by the five-parameter PHANTASM model than the four-parameter. Future work will investigate the abnormalities found in the PHANTASM models.

REFERENCES

[1] Fanney, A.H., and Dougherty, B.P., 2001, "Building Integrated Photovoltaic Test Facility," ASME J. Solar Energy Engineering, **123**, pp. 194-199.

[2] Fanney, A.H., Dougherty, B.P., and Davis, M.W. 2001, "Performance and Characterization of Building Integrated Photovoltaic Panels," Proc. IEEE PVSC May 2002.

[3] Fanney, A.H., Dougherty, B.P., and Davis, M.W. 2001, "The Measured Performance of Building Integrated Photovoltaic Panels," ASME J. Solar Energy Engineering, **123**, pp. 187-193.

[4] 2000, Sandia Photovoltaic Performance Model I-V Curve Tracer, Maui Solar Energy Software Corp., Haiku, HI.

[5] 1999, PHANTASM, Solar Energy Laboratory, University of Wisconsin, Madison, WI.

[6] King, D.L., Kratochvil, J.A., and Boyson, W.E, 1997, "Temperature Coefficients for PV Modules and Arrays: Measurement Methods, Difficulties, and Results", Proc. 26th IEEE Photovoltaic Specialists Conference, Anaheim, CA, pp. 1183-1186.

[7] King, D.L., 1996, "Photovoltaic Module and Array Performance Characterization Methods for all System Operating Conditions", Proc. NREL/SNL Photovoltaics Program Review, AIP Press, Lakewood, CO, 347-368.

[8] King, D.L., Kratochvil, J.A., and Boyson, W.E, 1997, Measuring Solar Spectral and Angle-of-Incidence Effects on Photovoltaic Modules and Solar Irradiance Sensors", Proc. 26th IEEE Photovoltaic Specialists Conference, Anaheim, CA, pp. 1113-1116.

[9] King, D.L., Kratochvil, J.A., and Boyson, W.E, 1998, "Field Experience with a New Performance Characterization Procedure for Photovoltaic Arrays", Proc. 2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion, Vienna, Austria.

[10] King, David L., "Sandia's PV Module Electrical Performance Model (Version, 2000)," Sandia National Laboratories, Albuquerque, NM

[11] 2000, PV-Design Pro, Solar Design Studio, v4.0, Maui Solar Energy Software Corp., Haiku, HI.

[12] Fanney, A. H., Davis, M.W., and Dougherty, B.P., 2002 "Short-Term Characterization of Building Integrated Photovoltaic Panels", Proc. Solar Forum 2002, Reno, NV

[13] Rauschenbach, H.S., 1980, *Solar Cell Array Design Handbook*, Van Nostrand Reinhold Co., New York, pp 390-391.

[14] King, D.L., et al, "Dark Current-Voltage Measurements of Photovoltaic Modules as a Diagnostic or Manufacturing Tool", Proc. 26th IEEE Photovoltaic Specialists Conference, Anaheim, CA

[15] 2000, TRNSYS, v15, Solar Energy Laboratory, University of Wisconsin, Madison, WI

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