Comparison of Predicted to Measured Photovoltaic Module Performance

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To accurately predict the electrical performance of photovoltaic modules computer simulation models are essential. Without such models, potential purchasers of photovoltaic systems have insufficient information to judge the relative merits and cost effectiveness of photovoltaic systems. The purpose of this paper is to compare the predictions of a simulation model, developed by Sandia National Laboratories, to measurements from photovoltaic modules installed in a vertical wall façade in Gaithersburg, MD. The photovoltaic modules were fabricated using monocrystalline, polycrystalline, tandem-junction amorphous, and copper-indium diselenide cells. Polycrystalline modules were constructed using three different glazing materials: 6 mm low-iron glass, 0.05 mm ethylene-tetrafluoroethylene copolymer, and 0.05 mm polyvinylidene fluoride. In order to only assess the simulation model's ability to predict photovoltaic module performance, measured solar radiation data in the plane of the modules is initially used. Additional comparisons are made using horizontal radiation measurements. The ability of the model to accurately predict the temperature of the photovoltaic cells is investigated by comparing predicted energy production using measured versus predicted photovoltaic cell temperatures. The model was able to predict the measured annual energy production of the photovoltaic modules, with the exception of the tandem-junction amorphous modules, to within 6% using vertical irradiance measurements. The model overpredicted the annual energy production by approximately 14% for the tandem-junction amorphous panels. Using measured horizontal irradiance as input to the simulation model, the agreement between measured and predicted annual energy predictions varied between 1% and 8%, again with the exception of the tandem-junction amorphous silicon modules. The large difference between measured and predicted results for the tandem-junction modules is attributed to performance degradation. Power measurements of the tandem-junction amorphous modules at standard reporting conditions prior to and after exposure revealed a 12% decline. Supplying post exposure module parameters to the model resulted in energy predictions within 5% of measured values. [DOI: 10.1115/1.3090826]

1 Introduction

In order to assess the economic feasibility of photovoltaic systems, computer simulation models are needed to predict the electrical energy production of photovoltaic systems. Ideally, the simulation models would be easy to use, accurate, capable of modeling photovoltaic modules using a variety of cell technologies, and suitable for all geographical locations and mounting orientations. A number of photovoltaic simulation tools are currently available with various levels of complexity, required inputs, and levels of accuracy. An excellent overview of current photovoltaic models is presented within PHOTON International [1].

Basic simulation models require limited information such as geographical location, the tilt and azimuth angles associated with the photovoltaic array, and the efficiency of the photovoltaic modules at a prescribed set of reference conditions. Other models require additional information such as power output, open-circuit voltage, and short-circuit current at standard reference conditions, as well as temperature coefficients that quantify the relationship between the module's operating temperature and conversion efficiency.

The model used in this study, developed by Sandia National Laboratories, is relatively complex, yet requires a manageable set of input parameters. It can be utilized in a variety of ways including sizing photovoltaic arrays, investigating the effect of various environmental conditions on module performance, and predicting the performance of photovoltaic systems. In addition to utilizing an expanded set of temperature coefficients, the model relies on empirical relationships to capture the influence of the angle of incidence, solar spectrum, and irradiance level on the module's electrical performance. The coefficients required for this model have been compiled into a database that contains over 200 commercially available modules [2]. The current implementation of the model [3] incorporates a number of features not utilized in this current study including meteorological data for a number of locations within the United States and the ability to incorporate inverters, electrical wiring, shading, and battery storage systems.

This study focused on comparing the measured to the predicted electrical performance of photovoltaic modules constructed using various cell technologies and glazing materials operated at their maximum-power point. This study differs from previous validation efforts in a number of ways. Unlike studies in which data are collected for a few days, this study utilized an entire year's data collected at 5 min intervals. In lieu of comparing the model to measured results for one type of cell technology, this study permitted comparisons to four different photovoltaic technologies—monocrystalline, polycrystalline, tandem-junction amorphous, and copper-indium diselenide—and three different glazing materials—6 mm low-iron glass, 0.05 mm (2 mils) ethylene-tetrafluoroethylene copolymer (ETFE), and 0.05 mm polyvinylidene fluoride (PVDF). Unlike many studies in which the photovoltaic modules are positioned at tilt angles that seek to

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Table 1 Building integrated photovoltaic module specifications

Cell technology	Monocrystalline (m-Si)	Polycrystalline (p-Si)	Tandem-junction amorphous (2-*a*-Si)	CIS
Panel dimensions, $W \times H$ (m^2)	1.38×1.18	1.38×1.18	1.33×1.18	1.32×1.29
Nominal cell dimensions (mm^2)	125×125	125×125	1160×9	1260×6.9
No. of cells (in series)	72	72	68	42
Glazing covered by PV cells (%)	63	70	94	85
Rated power (W)–NIST	133	143–155[a]	2×40.6 [b]	4×38.8
Total cell area (m^2)	1.020	1.134	1.487	1.451
Coverage area (m^2)	1.160	1.168	1.487	1.451
Aperture area (m^2)	1.682	1.682	1.682	1.935

[a]The first entry corresponds to the panel having the glass front; the second entry applies to the panel having the ETFE front cover. The power for the PVDF panel approached the ETFE value.
[b]This value was determined from testing conducted after 2-*a*-Si modules had been installed in the NIST south wall testbed for approximately 2 years. The value is the average of the measurements on two different modules, one from test cell E and one from test cell F.

maximize the annual energy collection, the photovoltaic modules in this study are integrated into a vertical building façade.

2 Experimental Apparatus

The apparatus used in this study includes the National Institute of Standards and Technology's (NIST) building integrated photovoltaic (BIPV) test facility [4], photovoltaic test specimens, meteorological instruments, and a multicurve tracer. Two separate meteorological stations were used to capture solar radiation data. A meteorological station located adjacent to the vertical south-facing photovoltaic modules included a vertically mounted precision spectral pyranometer to measure solar radiation, a radiation-shielded ambient temperature sensor, and an ultrasonic wind sensor. A more extensive meteorological station, located on the roof of NIST's Building Research Laboratory, incorporates redundant pyrheliometers and pyranometers to measure the beam component of solar radiation and total horizontal solar radiation, respectively. The diffuse solar radiation is either directly measured using a continuously shaded horizontal pyranometer or by subtracting the product of the measured direct normal irradiance and the cosine of the incident angle from the measured total horizontal irradiance. Wind speed (WS) and direction are monitored 3 m above the roof using a three-cup anemometer and wind direction sensor. Ambient temperature is measured using a sheathed type-T thermocouple sensor, enclosed in a naturally ventilated multiplate radiation shield.

The performance of each panel is monitored by a photovoltaic multicurve tracer. This instrument is configured to independently load and continuously operate each photovoltaic module at its peak power point. The multitracer records each panel's current and voltage outputs at the maximum-power point every 15 s and records average 5 min values. Current versus voltage measurements are also recorded every 5 min for each photovoltaic module.

The test specimens consisted of four custom-fabricated modules and two sets of commercially available photovoltaic modules (Table 1). The four custom-fabricated modules used 6 mm low-iron glass as the structural element. One of the custom-fabricated modules was fabricated using monocrystalline photovoltaic cells and the 6 mm glass as the front glazing. The remaining custom-fabricated photovoltaic modules were constructed using identical polycrystalline cells but with three different front covers: 6 mm low-iron glass, 0.05 mm ETFE, and 0.05 mm PVDF. The 6 mm glass served as the (rear) substrate for the two panels having the polymer front covers. All custom-fabricated modules were insulated on their rear surface using 100 mm of extruded polystyrene insulation.

Two different commercially available photovoltaic modules were installed in the BIPV test facility. One incorporated tandem-junction amorphous (2-*a*-Si) silicon cells, whereas the second module type utilized copper-indium diselenide (CIS) cells. Due to their smaller size, two tandem-junction amorphous and four copper-indium diselenide modules were required to fill the curtain wall openings created by removing existing fenestration units. In order to explore the effect of elevated operating temperature on performance, two identical sets of the tandem-junction and copper-indium diselenide modules were installed in the BIPV test facility. The rear surface of one set was not insulated while approximately 100 mm of extruded foam insulation was applied to the rear surface of the second set. Due to the limited number of aperture openings available, the custom-fabricated modules were only tested in one configuration: rear surface insulated. The performance of all modules was measured every 5 min over a twelve month interval. Short-term tests were conducted to determine temperature coefficients, the performance of the modules at standard reporting conditions, and the coefficients required to take into account the effects of air mass and angle of incidence. A detailed description of each test is described by Fanney et al. [5]. The resulting coefficients are given in Table 2.

3 Description of Model and Solar Radiation Data

The simulation model used to predict the performance of the various photovoltaic modules in this study was developed at Sandia National Laboratories [6]. The model can be used in a variety of ways including sizing photovoltaic arrays, "translating" the performance of a photovoltaic array from one set of operating conditions to a different set, and predicting the performance of photovoltaic systems. This empirically-based model (see Appendix) incorporates electrical, thermal, solar spectral, and optical effects. In an attempt to make SNL's photovoltaic model widely applicable to the photovoltaic industry, extensive outdoor performance tests have been conducted by SNL for over 200 commercially available photovoltaic modules to provide the input parameters required by the model. The results have been compiled into a database.[1] The solar resource and weather data required by the model can be obtained from the tabulated databases or from direct measurements.

The model utilizes four separate temperature coefficients, α_{ISC}, α_{IMP}, β_{VOC}, and β_{VMP}, to model the effects of cell temperature on module performance. Although two temperature coefficients α_{ISC} and β_{VOC} are traditionally used in modeling photovoltaic modules, the use of four is believed to be instrumental in making SNL's model versatile enough to apply equally well for all photovoltaic technologies over the full range of operating conditions. The model includes an algorithm for predicting the photovoltaic module's operating temperature given values of solar irradiance, ambient temperature, wind speed, and the manner in which the

[1]http://www.sandia.gov/pv.

Table 2 Summary of measured photovoltaic module parameters

Cell type		Monocrystalline	Polycrystalline			CIS	2-a-Si
Glazing material		Glass	Glass	ETFE	PVDF	Glass	Glass
Performance at standard reference condition							
P_{mpo} (W)		133.4	143.2	154.7	152.7	38.7	46.8
I_{sco} (A)		4.37	4.81	5.05	5.00	2.76	0.73
V_{oco} (V)		42.93	42.73	42.77	42.91	23.66	99.56
I_{mpo} (A)		3.96	4.19	4.63	4.45	2.40	0.61
V_{mpo} (V)		33.68	34.17	33.45	34.32	16.18	76.51
Module temperature coefficients							
α_{ISC} (A/°C)		1.75×10^{-3}	3.84×10^{-3}	3.60×10^{-3}	3.39×10^{-3}	-9.15×10^{-6}	6.05×10^{-4}
α_{ISC} (1/°C)		4.01×10^{-4}	7.98×10^{-4}	7.14×10^{-4}	6.78×10^{-4}	-3.32×10^{-6}	8.30×10^{-4}
α_{IMP} (A/°C)		-1.54×10^{-3}	1.03×10^{-3}	8.50×10^{-4}	1.14×10^{-3}	-1.28×10^{-3}	6.10×10^{-4}
α_{IMP} (1/°C)		-3.90×10^{-4}	2.46×10^{-4}	1.85×10^{-4}	2.56×10^{-4}	-5.33×10^{-4}	9.97×10^{-4}
β_{VOC} (V/°C)		-1.52×10^{-1}	-1.37×10^{-1}	-1.31×10^{-2}	-1.32×10^{-1}	-9.16×10^{-2}	-4.12×10^{-1}
β_{VOC} (1/°C)		-3.55×10^{-3}	-3.22×10^{-3}	-3.06×10^{-3}	-3.07×10^{-3}	-3.87×10^{-3}	-4.14×10^{-3}
β_{VMP} (V/°C)		-1.54×10^{-1}	-1.44×10^{-1}	-1.39×10^{-1}	-1.43×10^{-1}	-5.96×10^{-2}	-3.48×10^{-1}
β_{VMP} (1/°C)		-4.56×10^{-3}	-4.20×10^{-3}	-4.16×10^{-3}	-4.15×10^{-3}	-3.69×10^{-3}	-4.55×10^{-3}
Air mass coefficients							
$f(\mathrm{AM}_a)$	Cnst	9.36×10^{-1}	9.32×10^{-1}	9.28×10^{-1}	9.29×10^{-1}	9.38×10^{-1}	8.72×10^{-1}
	AM_a	5.43×10^{-2}	5.74×10^{-2}	6.00×10^{-2}	6.06×10^{-2}	5.27×10^{-2}	1.29×10^{-1}
	AM_a	-8.68×10^{-3}	-9.05×10^{-3}	-8.94×10^{-3}	-9.43×10^{-3}	-9.00×10^{-3}	-3.34×10^{-2}
	AM_a	5.27×10^{-4}	5.63×10^{-4}	4.74×10^{-4}	5.26×10^{-4}	6.35×10^{-4}	2.35×10^{-3}
	AM_a	-1.10×10^{-5}	-1.24×10^{-5}	-8.50×10^{-6}	-9.91×10^{-6}	-1.60×10^{-5}	-5.30×10^{-5}
Incident angle coefficients							
$f(\mathrm{AOI})$	Cnst	1	1	1	1	1	1
	AOI	-5.56×10^{-3}	-1.02×10^{-2}	-8.25×10^{-3}	-7.62×10^{-3}	-7.26×10^{-3}	-1.10×10^{-2}
	AOI	6.53×10^{-4}	1.22×10^{-4}	9.83×10^{-4}	9.04×10^{-4}	9.20×10^{-4}	1.30×10^{-3}
	AOI	-2.73×10^{-5}	-4.83×10^{-5}	-3.95×10^{-5}	-3.63×10^{-5}	-3.75×10^{-5}	-5.13×10^{-5}
	AOI	4.64×10^{-7}	7.77×10^{-7}	6.49×10^{-7}	5.97×10^{-7}	6.17×10^{-7}	8.25×10^{-7}
	AOI	-2.82×10^{-9}	-4.45×10^{-9}	-3.78×10^{-9}	-3.49×10^{-9}	-3.61×10^{-9}	-4.73×10^{-9}

The following values of uncertainty represent the expanded uncertainty using a coverage factor of 2: $P_{mpo} = \pm 2.2\%$, $V_{oco} = \pm 1.1\%$, $V_{mpo} = \pm 1.4\%$, $I_{sco} = \pm 1.7\%$, and $I_{mpo} = \pm 1.6\%$.

modules are mounted. SNL's photovoltaic model has been translated into practice through a commercially available program [3] as well as being considered for incorporation in building and system energy modeling programs, including DOE-2 [7], and a PV system analysis model (PV SunVisor) that is currently being developed at the National Renewable Energy Laboratory.

The photovoltaic model was exercised using solar radiation data measured in the plane of the photovoltaic modules (vertical) as well as horizontal radiation data. When vertical radiation data is used, the diffuse irradiance on the vertical plane is determined by subtracting the product of the beam radiation and cosine of the incident angle from the measured total solar radiation incident on the panels. During times when the incident angle between the sun and the photovoltaic modules exceed 90 deg, the total solar radiation measured in the plane of the photovoltaic modules is considered to be all diffuse.

Measured solar radiation data in the plane of photovoltaic modules is not normally available for model validation. Thus, simulations were conducted using the measured horizontal surface solar radiation data. The diffuse component was determined using two different techniques: by using a precision spectral pyranometer with a shading disk and by subtracting the product of the beam irradiance measured using a normal incidence pyrheliometer and the cosine of the incident angle from the measured total horizontal (global) surface radiation. The resulting global and diffuse horizontal surface measurements are used with two anisotropic sky models HDKR [8,9] and Perez [10] to convert horizontal radiation measurements to predicted irradiance on the south-facing vertical photovoltaic modules. The photovoltaic modules are located approximately 7 m above an asphalt surface with an assumed ground reflectance of 0.1 [11]. A detailed description of the two models used in this study, HDKR and Perez, are described by Duffie and Beckman [12].

The photovoltaic simulation model used in this study allows the user to predict module operating temperature or use measured values. Measured values avoid the uncertainties associated with predicting module temperatures based on environmental parameters. However measured module temperatures for extended time intervals are rarely available. In this study the temperature of each photovoltaic module was measured every 5 min using calibrated thermocouples attached to each module's rear surface. For the modules that were insulated, the thermocouples were attached to the module's rear surface beneath the foam insulation. In the case of the custom-fabricated photovoltaic modules, additional calibrated thermocouples were attached to the rear surface of a centrally located photovoltaic cell. The predicted rear surface module temperatures are based on an empirical-based thermal model developed by King et al. [13] and described within the Appendix.

4 Comparison of Predicted to Measured Results

The measured performance of each of the photovoltaic modules used in this study (Table 1) is compared with their predicted performance. Performance predictions are made using both the vertical façade irradiance measurements and the horizontal irradiance measurements in conjunction with the anisotropic sky models. The photovoltaic modules parameters required by the SNL model are summarized in Table 2. Measured and predicted results are compared on a monthly basis.

Table 3 Measured versus predicted energy production based on vertical irradiance measurements and measured module temperature; also, measured versus predicted energy production based on vertical irradiance measurements and predicted module temperature

Module ID	A			B			C			D			E			F			G			H		
Cell type	Single crystalline			Polycrystalline			Polycrystalline			Polycrystalline			2-*a*-Si			2-*a*-Si			CIS			CIS		
Glazing	Glass			Glass			ETFE			PVDF			Glass			Glass			Glass			Glass		
Insulated	Yes			Yes			Yes			Yes			No			Yes			No			Yes		
Month	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.
January	10.62	10.40	2.05	12.10	12.17	−0.54	13.06	12.88	1.42	13.18	13.02	1.27	6.27	7.83	−24.87	6.24	7.65	−22.72	13.77	12.87	6.59	13.18	12.37	6.15
February	11.10	10.77	2.99	12.61	12.47	1.07	13.57	13.21	2.68	13.71	13.32	2.87	6.52	7.88	−20.87	6.52	7.74	−18.68	14.22	13.22	7.01	13.62	12.78	6.20
March	9.80	9.33	4.83	10.85	10.40	4.12	11.77	11.19	4.92	11.77	11.26	4.34	5.55	6.44	−16.09	5.60	6.35	−13.39	12.09	11.29	6.58	11.77	11.04	6.17
April	9.69	9.12	5.87	10.65	10.00	6.09	11.58	10.88	6.04	11.56	10.96	5.19	5.55	6.11	−10.04	5.58	5.98	−7.21	11.86	11.21	5.51	11.47	10.91	4.93
May	7.36	7.05	4.09	7.93	7.46	5.93	8.67	8.27	4.70	8.60	8.37	2.63	4.05	4.50	−11.12	4.11	4.44	−7.96	8.79	8.64	1.70	8.54	8.47	0.81
June	7.03	6.82	3.06	7.55	7.04	6.69	8.28	7.94	4.15	8.16	8.07	1.15	4.00	4.35	−8.81	4.01	4.25	−5.77	8.41	8.46	−0.62	8.10	8.23	−1.60
July	7.36	7.24	1.60	7.97	7.58	4.96	8.74	8.49	2.86	8.64	8.62	0.26	4.30	4.71	−9.63	4.28	4.58	−6.90	8.97	9.08	−1.18	8.60	8.77	−2.01
August	7.91	7.83	0.96	8.72	8.46	2.89	9.52	9.32	2.05	9.46	9.43	0.30	4.77	5.26	−10.21	4.73	5.10	−7.64	9.85	9.86	−0.14	9.35	9.02	3.55
September	9.68	9.48	2.01	10.96	10.70	2.43	11.86	11.54	2.77	11.91	11.65	2.18	6.00	6.72	−12.02	5.94	6.47	−8.95	12.45	12.05	3.24	11.67	11.46	1.80
October	6.98	6.72	3.78	7.93	7.63	3.80	8.54	8.19	4.09	8.58	8.31	3.25	4.22	4.87	−15.45	4.22	4.72	−11.92	8.94	8.48	5.15	8.43	8.10	3.90
November	7.89	7.70	2.34	8.96	8.85	1.30	9.67	9.43	2.44	9.72	9.50	2.25	4.56	5.65	−23.94	4.59	5.52	−20.18	10.14	9.49	6.37	9.69	9.16	5.53
December	9.20	9.01	2.08	10.58	10.52	0.58	11.35	11.13	1.94	11.49	11.25	2.05	5.22	6.73	−28.93	5.27	6.63	−25.86	11.90	11.04	7.18	11.41	10.70	6.19
Total	104.62	101.49	3.00	116.81	113.28	3.02	126.62	122.46	3.28	126.79	123.75	2.39	61.00	71.05	−16.47	61.09	69.42	−13.63	131.39	125.69	4.33	125.83	121.00	3.84

Module ID	A			B			C			D			E			F			G			H		
Cell type	Single crystalline			Polycrystalline			Polycrystalline			Polycrystalline			2-*a*-Si			2-*a*-Si			CIS			CIS		
Glazing	Glass			Glass			ETFE			PVDF			Glass			Glass			Glass			Glass		
Insulated	Yes			Yes			Yes			Yes			No			Yes			No			Yes		
Month	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.
January	10.62	10.62	−0.05	12.10	12.09	0.08	13.06	12.74	2.44	13.18	12.70	3.67	6.27	7.69	−22.62	6.24	7.51	−20.50	13.77	12.71	7.75	13.18	12.41	5.87
February	11.10	10.98	1.12	12.61	12.41	1.58	13.57	13.10	3.50	13.71	13.04	4.91	6.52	7.78	−19.34	6.52	7.62	−16.78	14.22	13.12	7.72	13.62	12.83	5.80
March	9.80	9.40	4.14	10.85	10.34	4.65	11.77	11.07	5.96	11.77	11.06	6.00	5.55	6.37	−14.94	5.60	6.27	−11.96	12.09	11.24	6.96	11.77	11.05	6.11
April	9.69	9.17	5.38	10.65	9.94	6.67	11.58	10.78	6.90	11.56	10.81	6.54	5.55	6.00	−8.15	5.58	5.92	−6.01	11.86	11.05	6.81	11.47	10.90	5.04
May	7.36	7.08	3.75	7.93	7.42	6.45	8.67	8.21	5.33	8.60	8.28	3.66	4.05	4.45	−9.68	4.11	4.40	−7.12	8.79	8.55	2.80	8.54	8.45	0.95
June	7.03	6.82	3.10	7.55	6.99	7.36	8.28	7.87	4.97	8.16	7.98	2.23	4.00	4.25	−6.25	4.01	4.21	−4.87	8.41	8.27	1.63	8.10	8.19	−1.18
July	7.36	7.25	1.52	7.97	7.52	5.64	8.74	8.42	3.64	8.64	8.52	1.39	4.30	4.58	−6.59	4.28	4.53	−5.90	8.97	8.82	1.68	8.60	8.73	−1.59
August	7.91	7.88	0.34	8.72	8.42	3.38	9.52	9.27	2.62	9.46	9.32	1.44	4.77	5.11	−7.02	4.73	5.04	−6.56	9.85	9.60	2.53	9.35	9.48	−1.40
September	9.68	9.65	0.33	10.96	10.67	2.68	11.86	11.51	3.02	11.91	11.50	3.42	6.00	6.52	−8.74	5.94	6.41	−7.97	12.45	11.71	5.97	11.67	11.52	1.34
October	6.98	6.90	1.18	7.93	7.64	3.66	8.54	8.20	3.96	8.58	8.21	4.41	4.22	4.77	−13.19	4.22	4.69	−11.01	8.94	8.34	6.77	8.43	8.19	2.93
November	7.89	7.84	0.60	8.96	8.82	1.61	9.67	9.34	3.32	9.72	9.32	4.14	4.56	5.56	−22.01	4.59	5.45	−18.70	10.14	9.39	7.35	9.69	9.20	5.12
December	9.20	9.26	−0.64	10.58	10.50	0.75	11.35	11.06	2.49	11.49	11.03	4.00	5.22	6.69	−28.08	5.27	6.54	−24.17	11.90	11.04	7.16	11.41	10.79	5.43
Total	104.62	102.84	1.70	116.81	112.77	3.46	126.62	121.58	3.98	126.79	121.77	3.96	61.00	69.77	−14.38	61.09	68.59	−12.27	131.39	123.84	5.74	125.83	121.73	3.26

Table 4 Measured versus predicted energy production based on horizontal irradiance measurements and HDKR radiation model using the shaded pyranomenter diffuse radiation; second part shows measured versus predicted energy production based on horizontal irradiance measurements and HDKR radiation model using the total horizontal minus the product of the beam radiation and cosine of the incident angle measurement

Module ID	A			B			C			D			E			F			G			H		
Cell type	Single crystalline			Polycrystalline			Polycrystalline			Polycrystalline			2-*a*-Si			2-*a*-Si			CIS			CIS		
Glazing	Glass			Glass			ETFE			PVDF			Glass			Glass			Glass			Glass		
Insulated	Yes			Yes			Yes			Yes			No			Yes			No			Yes		
Month	Meas. (k Wh)	Pred. (k Wh)	% diff.	Meas. (k Wh)	Pred. (k Wh)	% diff.	Meas. (k Wh)	Pred. (k Wh)	% diff.	Meas. (k Wh)	Pred. (k Wh)	% diff	Meas. (k Wh)	Pred. (k Wh)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.
January	10.62	10.33	2.68	12.10	11.78	2.63	13.06	12.41	4.97	13.18	12.38	6.11	6.27	7.54	−20.13	6.24	7.36	−17.96	13.77	12.36	10.28	13.18	12.06	8.53
February	11.10	11.51	−3.62	12.61	13.06	−3.60	13.57	13.77	−1.49	13.71	13.72	−0.08	6.52	8.29	−27.13	6.52	8.10	−24.19	14.22	13.74	3.37	13.62	13.41	1.53
March	9.80	10.23	−4.36	10.85	11.32	−4.37	11.77	12.09	−2.69	11.77	12.08	−2.63	5.55	7.04	−26.87	5.60	6.91	−23.40	12.09	12.23	−1.18	11.77	12.00	−1.93
April	9.69	9.75	−0.60	10.65	10.67	−0.18	11.58	11.51	0.59	11.56	11.52	0.33	5.55	6.48	−16.82	5.58	6.38	−14.33	11.86	11.74	1.06	11.47	11.55	−0.65
May	7.36	7.12	3.21	7.93	7.53	5.02	8.67	8.29	4.42	8.60	8.35	2.88	4.05	4.52	−11.44	4.11	4.47	−8.72	8.79	8.59	2.35	8.54	8.48	0.60
June	7.03	6.54	6.95	7.55	6.75	10.61	8.28	7.58	8.52	8.16	7.90	3.19	4.00	4.11	−2.72	4.01	4.07	−1.29	8.41	7.94	5.58	8.10	7.86	2.96
July	7.36	7.02	4.71	7.97	7.35	7.86	8.74	8.18	6.44	8.64	8.26	4.39	4.30	4.48	−4.30	4.28	4.43	−3.53	8.97	8.53	4.92	8.60	8.44	1.86
August	7.91	6.61	16.44	8.72	7.03	19.32	9.52	7.78	18.31	9.46	7.84	17.06	4.77	4.29	10.04	4.73	4.24	10.46	9.85	8.05	18.21	9.35	7.95	14.94
September	9.68	8.75	9.59	10.96	9.67	11.83	11.86	10.43	12.09	11.91	10.43	12.42	6.00	5.89	1.69	5.94	5.80	2.34	12.45	10.62	14.70	11.67	10.45	10.46
October	6.98	6.18	11.44	7.93	6.86	13.45	8.54	7.36	13.81	8.58	7.37	14.20	4.22	4.30	−1.90	4.22	4.22	0.09	8.94	7.47	16.45	8.43	7.33	13.04
November	7.89	7.40	6.25	8.96	8.31	7.28	9.67	8.81	8.88	9.72	8.78	9.66	4.56	5.24	−14.91	4.59	5.13	−11.81	10.14	8.86	12.63	9.69	8.67	10.51
December	9.20	8.71	5.36	10.58	9.90	6.40	11.35	10.43	8.11	11.49	10.39	9.50	5.22	6.35	−21.55	5.27	6.20	−17.74	11.90	10.38	12.73	11.41	10.13	11.18
Total	104.62	100.14	4.28	116.81	110.23	5.63	126.62	118.63	6.31	126.79	119.04	6.11	61.00	68.52	−12.32	61.09	67.30	−10.16	131.39	120.50	8.29	125.83	118.34	5.95

Module ID	A			B			C			D			E			F			G			H		
Cell type	Single crystalline			Polycrystalline			Polycrystalline			Polycrystalline			2-*a*-Si			2-*a*-Si			CIS			CIS		
Glazing	Glass			Glass			ETFE			PVDF			Glass			Glass			Glass			Glass		
Insulated	Yes			Yes			Yes			Yes			No			Yes			No			Yes		
Month	Meas. (kW h)	Pred. (k Wh)	% diff.	Meas. (k Wh)	Pred. (k Wh)	% diff.	Meas. (k Wh)	Pred. (k Wh)	% diff.	Meas. (k Wh)	Pred. (k Wh)	% diff.	Meas. (k Wh)	Pred. (k Wh)	% diff.	Meas. (KW h)	Pred. (KW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.
January	10.62	10.27	3.22	12.10	11.74	3.02	13.06	12.36	5.35	13.18	12.33	6.48	6.27	7.51	−19.77	6.24	7.33	−17.55	13.77	12.29	10.75	13.18	11.99	9.04
February	11.10	11.40	−2.65	12.61	12.95	−2.72	13.57	13.65	−0.60	13.71	13.60	0.79	6.52	8.23	−26.13	6.52	8.04	−23.19	14.22	13.61	4.27	13.62	13.29	2.46
March	9.80	9.92	−1.18	10.85	11.01	−1.46	11.77	11.74	0.30	11.77	11.72	0.39	5.55	6.85	−23.45	5.60	6.72	−20.03	12.09	11.85	1.92	11.77	11.63	1.23
April	9.69	9.58	1.17	10.65	10.49	1.46	11.58	11.32	2.27	11.56	11.33	2.02	5.55	6.38	−14.99	5.58	6.28	−12.51	11.86	11.53	2.80	11.47	11.34	1.15
May	7.36	7.13	3.11	7.93	7.54	4.88	8.67	8.30	4.31	8.60	8.36	2.78	4.05	4.53	−11.66	4.11	4.47	−8.92	8.79	8.59	2.26	8.54	8.49	0.52
June	7.03	6.72	4.45	7.55	6.93	8.18	8.28	7.78	6.08	8.16	7.89	3.42	4.00	4.22	−5.45	4.01	4.17	−3.99	8.41	8.15	3.05	8.10	8.07	0.35
July	7.36	6.81	7.47	7.97	7.08	11.15	8.74	7.92	9.31	8.64	8.02	7.13	4.30	4.33	−0.67	4.28	4.28	0.03	8.97	8.29	7.64	8.60	8.20	4.62
August	7.91	6.84	13.45	8.72	7.29	16.42	9.52	8.05	15.43	9.46	8.12	14.19	4.77	4.43	7.07	4.73	4.38	7.48	9.85	8.34	15.29	9.35	8.24	11.88
September	9.68	8.86	8.47	10.96	9.79	10.73	11.86	10.56	10.97	11.91	10.56	11.32	6.00	5.96	0.66	5.94	5.86	1.31	12.45	10.75	13.63	11.67	10.58	9.33
October	6.98	6.59	5.56	7.93	7.30	7.93	8.54	7.84	8.24	8.58	7.84	8.66	4.22	4.55	−7.94	4.22	4.47	−5.88	8.94	7.97	10.89	8.43	7.83	7.21
November	7.89	7.56	4.13	8.96	8.52	5.00	9.67	9.02	6.68	9.72	9.00	7.48	4.56	5.36	−17.61	4.59	5.25	−14.39	10.14	9.06	10.61	9.69	8.87	8.48
December	9.20	9.10	1.12	10.58	10.35	2.17	11.35	10.90	3.94	11.49	10.87	5.36	5.22	6.63	−26.92	5.27	6.47	−22.91	11.90	10.85	8.77	11.41	10.59	7.16
Total	104.62	100.78	3.67	116.81	110.98	4.99	126.62	119.45	5.67	126.79	119.64	5.64	61.00	68.96	−13.05	61.09	67.73	−10.86	131.39	121.30	7.68	125.83	119.11	5.34

Table 5 Measured versus predicted energy production based on horizontal irradiance measurements and Perez radiation model using the shaded pyranomenter diffuse radiation me; second part shows the measured versus predicted energy production based on horizontal irradiance measurements—Perez radiation model total horizontal minus the product of the beam radiation and cosine of the incident angle measurements

Module ID	A			B			C			D			E			F			G			H		
Cell type	Single crystalline			Polycrystalline			Polycrystalline			Polycrystalline			2-*a*-Si			2-*a*-Si			CIS			CIS		
Glazing	Glass			Glass			ETFE			PVDF			Glass			Glass			Glass			Glass		
Insulated	Yes			Yes			Yes			Yes			No			Yes			No			Yes		
Month	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.
January	10.62	10.56	0.53	12.10	12.00	0.81	13.06	12.66	3.08	13.18	12.62	4.29	6.27	7.64	−21.81	6.24	7.47	−19.71	13.77	12.63	8.30	13.18	12.33	6.43
February	11.10	11.63	−4.77	12.61	13.19	−4.60	13.57	13.91	−2.52	13.71	13.86	−1.08	6.52	8.36	−28.12	6.52	8.17	−25.20	14.22	13.89	2.30	13.62	13.57	0.40
March	9.80	10.36	−5.62	10.85	11.45	−5.55	11.77	12.23	−3.91	11.77	12.22	−3.88	5.55	7.12	−28.47	5.60	6.99	−24.95	12.09	12.38	−2.42	11.77	12.14	−3.18
April	9.69	10.07	−3.96	10.65	11.01	−3.35	11.58	11.89	−2.66	11.56	11.90	−2.96	5.55	6.70	−20.78	5.58	6.60	−18.19	11.86	12.13	−2.25	11.47	11.94	−4.02
May	7.36	7.39	−0.45	7.93	7.78	1.90	8.67	8.58	1.02	8.60	8.65	−0.63	4.05	4.67	−15.22	4.11	4.62	−12.44	8.79	8.91	−1.38	8.54	8.81	−3.25
June	7.03	6.64	5.57	7.55	6.79	10.01	8.28	7.67	7.44	8.16	7.79	4.62	4.00	4.15	−3.68	4.01	4.11	−2.31	8.41	8.06	4.11	8.10	7.99	1.37
July	7.36	6.95	5.62	7.97	7.18	9.98	8.74	8.06	7.79	8.64	8.16	5.50	4.30	4.39	−2.27	4.28	4.35	−1.65	8.97	8.46	5.73	8.60	8.38	2.57
August	7.91	7.39	6.49	8.72	7.85	9.96	9.52	8.68	8.83	9.46	8.74	7.53	4.77	4.78	−0.10	4.73	4.72	0.29	9.85	9.01	8.50	9.35	8.90	4.77
September	9.68	9.31	3.79	10.96	10.26	6.43	11.86	11.08	6.60	11.91	11.08	6.95	6.00	6.26	−4.36	5.94	6.16	−3.70	12.45	11.30	9.23	11.67	11.13	4.69
October	6.98	6.87	1.59	7.93	7.57	4.51	8.54	8.15	4.64	8.58	8.15	5.04	4.22	4.73	−12.17	4.22	4.65	−10.08	8.94	8.30	7.19	8.43	8.15	3.31
November	7.89	7.74	1.94	8.96	8.66	3.36	9.67	9.19	4.90	9.72	9.17	5.71	4.56	5.45	−19.47	4.59	5.34	−16.31	10.14	9.27	8.62	9.69	9.08	6.34
December	9.20	9.16	0.42	10.58	10.36	2.06	11.35	10.93	3.69	11.49	10.89	5.17	5.22	6.60	−26.38	5.27	6.45	−22.56	11.90	10.92	8.18	11.41	10.67	6.44
Total	104.62	104.08	0.52	116.81	114.10	2.32	126.62	123.03	2.84	126.79	123.25	2.79	61.00	70.84	−16.13	61.09	69.62	−13.96	131.39	125.26	4.66	125.83	123.09	2.18
Module ID	A			B			C			D			E			F			G			H		
Cell type	Single crystalline			Polycrystalline			Polycrystalline			Polycrystalline			2-*a*-Si			2-*a*-Si			CIS			CIS		
Glazing	Glass			Glass			ETFE			PVDF			Glass			Glass			Glass			Glass		
Insulated	Yes			Yes			Yes			Yes			No			Yes			No			Yes		
Month	Meas. (kW h)	Pred. (kW h)	% diff	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.	Meas. (kW h)	Pred. (kW h)	% diff.
January	10.62	10.69	−0.69	12.10	12.16	−0.50	13.06	12.83	1.80	13.18	12.79	3.02	6.27	7.74	−23.44	6.24	7.56	−21.28	13.77	12.79	7.14	13.18	12.49	5.26
February	11.10	11.62	−4.63	12.61	13.17	−4.47	13.57	13.90	−2.40	13.71	13.85	−0.97	6.52	8.35	−28.00	6.52	8.16	−25.08	14.22	13.87	2.43	13.62	13.55	0.54
March	9.80	10.33	−5.32	10.85	11.41	−5.23	11.77	12.20	−3.60	11.77	12.19	−3.56	5.55	7.10	−28.12	5.60	6.98	−24.61	12.09	12.34	−2.12	11.77	12.11	−2.88
April	9.69	10.08	−4.01	10.65	11.01	−3.39	11.58	11.89	−2.70	11.56	11.91	−2.99	5.55	6.71	−20.86	5.58	6.60	−18.28	11.86	12.13	−2.30	11.47	11.94	−4.07
May	7.36	7.39	−0.51	7.93	7.79	1.82	8.67	8.59	0.95	8.60	8.66	−0.68	4.05	4.68	−15.35	4.11	4.62	−12.57	8.79	8.92	−1.44	8.54	8.82	−3.31
June	7.03	6.61	5.98	7.55	6.76	10.42	8.28	7.63	7.84	8.16	7.75	5.03	4.00	4.13	−3.24	4.01	4.09	−1.88	8.41	8.03	4.53	8.10	7.95	1.81
July	7.36	6.71	8.79	7.97	6.90	13.39	8.74	7.78	10.95	8.64	7.90	8.57	4.30	4.23	1.47	4.28	4.19	2.07	8.97	8.18	8.87	8.60	8.10	5.82
August	7.91	7.33	7.32	8.72	7.78	10.79	9.52	8.60	9.62	9.46	8.67	8.31	4.77	4.73	0.85	4.73	4.68	1.24	9.85	8.93	9.30	9.35	8.82	5.60
September	9.68	9.27	4.26	10.96	10.21	6.88	11.86	11.03	7.01	11.91	11.04	7.33	6.00	6.22	−3.78	5.94	6.12	−3.12	12.45	11.25	9.65	11.67	11.07	5.13
October	6.98	6.96	0.39	7.93	7.67	3.23	8.54	8.25	3.38	8.58	8.26	3.78	4.22	4.79	−13.56	4.22	4.70	−11.42	8.94	8.40	6.03	8.43	8.25	2.11
November	7.89	7.91	−0.23	8.96	8.87	1.01	9.67	9.41	2.64	9.72	9.39	3.44	4.56	5.58	−22.32	4.59	5.46	−19.03	10.14	9.48	6.55	9.69	9.28	4.27
December	9.20	9.39	−2.09	10.58	10.65	−0.66	11.35	11.23	1.07	11.49	11.19	2.56	5.22	6.79	−30.01	5.27	6.64	−26.00	11.90	11.20	5.82	11.41	10.94	4.07
Total	104.62	104.28	0.33	116.81	114.39	2.07	126.62	123.35	2.59	126.79	123.59	2.53	61.00	71.04	−16.46	61.09	69.81	−14.27	131.39	125.52	4.46	125.83	123.32	1.99

4.1 Measured Versus Predicted Performance Using Vertical Irradiance Measurements. For this comparison, the meteorological data supplied to the model consisted of the total vertical solar irradiance measurements measured adjacent to the photovoltaic modules. The vertical solar irradiance measurement represents an average 5 min value based on 15 s measurements. The diffuse component is computed as previously noted by subtracting the product of the incident beam irradiance and the cosine of the incident angle from the total vertical solar irradiance. Instantaneous values of ambient temperature and wind velocity are supplied by a nearby meteorological station [4].

The electrical output of each photovoltaic module at its maximum-power point is measured every 15 s and subsequently averaged and recorded every 5 min. Data were excluded from the analysis during time intervals that shading occurred on any module [14]. Predicted energy production values using the *measured* module temperature are compared with the measured energy values in Table 3; predicted energy production using the *predicted* module temperature are compared with the measured monthly and annual energies in Table 3.

With the exception of the tandem-junction amorphous panels, modules E and F, the annual energy predicted by the model when using the irradiance measured in the vertical plane is within 5.7%, with the agreement being 4.0% or better for five of the six modules. The predicted annual energy production values were as much as 13.6% and 16.5% greater than those measured for the insulated and uninsulated tandem-junction modules, respectively. It was anticipated that using the measured module temperature (Table 3), in lieu of the temperature predicted by the model (Table 3), would result in the predicted monthly energy values closer to the measured values. This expectation was found to be the case for only five of the eight modules. The tandem-junction amorphous panels constituted two of three cases where the model did better using the predicted module temperature.

Excluding the tandem-junction amorphous modules, the SNL monthly energy predictions were within 8% of measured values. Differences exceeding 28% between predicted and measured monthly energy production values were observed for the tandem-junction amorphous modules. The model underpredicted the monthly energy production for the crystalline and polycrystalline modules while consistently overpredicting the monthly energy production for the tandem-junction amorphous modules. With the exception of June, July, and August for some modeling cases, the SNL model underpredicted the monthly energy production of the copper-indium diselenide modules.

For all subsequent comparisons, predictions were made using the model's algorithms to predict module temperature. This decision was made because the results using predicted module temperature were in relatively close agreement to those using measured module temperatures, and, more importantly, measured module temperatures are normally not available.

4.2 Measured Versus Predicted Performance Using Horizontal Irradiance Measurements. Measurements of solar irradiance on a surface of arbitrary tilt and azimuth are not generally available. Horizontal irradiance measurements from nearby meteorological stations are typically the only solar radiation data available. In this section, the performance of each photovoltaic module is predicted using measurements of horizontal irradiance and two anisotropic sky models commonly referred to as the HDKR [8,9] and Perez [10] models.

As previously noted, the horizontal diffuse component was determined two ways: via measuring the output from a shaded disk precision spectral pyranometer and via calculation using the measured beam irradiance and total horizontal surface radiation. The resulting predictions using the HDKR radiation model and the two different approaches for quantifying the diffuse component are compared with the measured energy production values in Table 4 The annual differences between measured and predicted values range from 4.3% for panel A to 12.3% for panel E (Table 4), using the shaded pyranometer as the source of horizontal diffuse irradiance measurements. The results in Table 4 were produced by setting the horizontal diffuse irradiance equal to the difference between the measured total horizontal irradiance and the product of the beam irradiance and the cosine of the incident angle. The annual differences between measured and predicted energy production range from 3.7% for panel A to 13.1% for panel E. A comparison of Table 4 reveals that the technique used to quantify the horizontal diffuse component had an insignificant effect, less than 1%, on the predicted annual energy values.

The Perez anisotropic sky model was used to generate the results in Table 5 by using the two techniques previously described for determining the diffuse solar radiation component. With the exception of the tandem-junction amorphous panels, modules E and F, the annual energy production for the modules was within 5% of the measured values. Further exclusion of panel G, the uninsulated CIS panels, results in the predicted and measured values being within 3%. Consistent with the HDKR modeling results (Table 4), the techniques used to determine the horizontal diffuse component had an insignificant effect on the final results.

Table 6 summarizes the modeling results by comparing the measured annual energy production to the predicted values using the vertical and horizontal irradiance measurements and the two anisotropic sky modules. Excluding the tandem-junction amorphous panels, the predicted performance using the vertical irradiance measurements and the horizontal irradiance measurements in conjunction with the Perez anisotropic sky model were in excellent agreement with the measured data. For these six modules, the annual energy production predicted by the models agreed to within 5% of the measured values. For five of these six modules, the agreement was within 3.5%. It is somewhat surprising that the use of the Perez model and the horizontal irradiance data resulted in energy production numbers that were in better agreement than

Table 6 Comparison of predicted annual energy production using HDKR and Perez radiation models to measured results

Radiation source				Horizontal—HDKR model				Horizontal—Perez model			
Diffuse source		Vertical irradiance		Shaded pyranometer		Total minus beam		Shaded pyranometer		Total minus beam	
Module ID	Meas. (kW h)	Pred. (kW h)	% diff.	Pred. (kW h)	% diff.	Pred. (kW h)	% diff.	Pred. (kW h)	% diff.	Pred. (kW h)	% diff.
A	104.6	102.8	1.7	100.1	4.3	100.8	3.7	104.1	0.5	104.3	0.3
B	116.8	112.8	3.5	110.2	5.6	111.0	5.0	114.1	2.3	114.4	2.1
C	126.6	121.6	4.0	118.6	6.3	119.5	5.7	123.0	2.8	123.4	2.6
D	126.8	121.8	4.0	119.0	6.1	119.6	5.6	123.3	2.8	123.6	2.5
E	61.0	69.8	−14.4	68.5	−12.3	69.0	−13.1	70.8	−16.1	71.0	−16.5
F	61.1	68.6	−12.3	67.3	−10.2	67.7	−10.9	69.6	−14.0	69.8	−14.3
G	131.4	123.8	5.7	120.5	8.3	121.3	7.7	125.3	4.7	125.5	4.5
H	125.8	121.7	3.3	118.3	6.0	119.1	5.3	123.1	2.2	123.3	2.0

Table 7 Performance of tandem-junction amorphous silicon modules at standard reporting conditions

Exposure duration	Module initially tested to obtain characterization parameters: 124 h	344 h	Modules removed after exposure in BIPV facility: Insulated module 14 months	Noninsulated module 14 months
I_{sc}(A)	0.73	0.71	0.69	0.68
I_{mp}(A)	0.61	0.59	0.56	0.55
V_{oc}(V)	99.6	97.7	95.6	96.5
V_{mp}(V)	76.5	74.2	73.0	73.5
P_{mp}(W)	46.8	43.8	40.9	40.4

those predicted using the measured vertical irradiance and were considered fortuitous. The use of the HDKR sky model also resulted in generally good agreement with the measured results ranging from 3.7% to 7.7%. The predicted performance of the two tandem-junction amorphous modules agreed poorly with the measured results throughout this study with differences between measured and predicted results ranging from 11% to 17%. Due to these large observed differences, additional research was conducted in an attempt to identify possible explanations.

4.3 Tandem-Junction Amorphous Results. The tandem-junction amorphous panels exhibited the greatest difference between measured and predicted energy production. Without exception, the measured values were significantly lower than the

Table 8 Tandem-junction amorphous module predicted energy production using initial and post exposure characterization data—panels E and F

		Initial characterization				Post exposure characterization			
		Vertical irradiance		Horizontal irradiance		Vertical irradiance		Horizontal irradiance	
Module ID		E		E		E		E	
Cell Type		2-*a*-Si		2-*a*-Si		2-*a*-Si		2-*a*-Si	
Glazing		Glass		Glass		Glass		Glass	
Insulated		No		No		No		No	
Month	Meas. (kW h)	Pred. (kW h)	% diff.	Pred. (kW h)	% diff.	Pred. (kW h)	% diff.	Pred. (kW h)	% diff.
January	6.27	7.83	−24.87	7.64	−21.81	6.67	−6.41	6.63	−5.71
February	6.52	7.88	−20.87	8.36	−28.12	6.76	−3.63	7.25	−11.22
March	5.55	6.44	−16.09	7.12	−28.47	5.54	0.16	6.19	−11.57
April	5.55	6.11	−10.04	6.70	−20.78	5.20	6.22	5.81	−4.71
May	4.05	4.50	−11.12	4.67	−15.22	3.73	8.02	4.05	0.13
June	4.00	4.35	−8.81	4.15	−3.68	3.67	8.10	3.59	10.34
July	4.30	4.71	−9.63	4.39	−2.27	3.96	7.89	3.80	11.61
August	4.77	5.26	−10.21	4.78	−0.10	4.41	7.53	4.13	13.51
September	6.00	6.72	−12.02	6.26	−4.36	5.64	5.98	5.41	9.75
October	4.22	4.87	−15.45	4.73	−12.17	4.13	1.99	4.10	2.85
November	4.56	5.65	−23.94	5.45	−19.47	4.83	−5.88	4.73	−3.70
December	5.22	6.73	−28.98	6.60	−26.38	5.81	−11.28	5.73	−9.80
Total	61.00	71.05	−16.47	70.84	−16.13	60.35	1.06	61.41	−0.67
Module ID		F		F		F		F	
Cell Type		2-*a*-Si		2-*a*-Si		2-*a*-Si		2-*a*-Si	
Glazing		Glass		Glass		Glass		Glass	
Insulated		Yes		Yes		Yes		Yes	
Month	Meas. (kW h)	Pred. (kW h)	% diff.	Pred. (kW h)	% diff.	Pred. (kW h)	% diff.	Pred. (kW h)	% diff.
January	6.24	7.65	−22.72	7.47	−19.71	6.41	−2.26	6.37	−2.17
February	6.52	7.74	−18.68	8.17	−25.20	6.51	0.19	6.98	−6.91
March	5.60	6.35	−13.39	6.99	−24.95	5.36	3.37	5.98	−6.78
April	5.58	5.98	−7.21	6.60	−18.19	5.05	8.97	5.63	−0.83
May	4.11	4.44	−7.96	4.62	−12.44	3.63	10.33	3.94	4.04
June	4.01	4.25	−5.77	4.11	−2.31	3.58	10.38	3.50	12.90
July	4.28	4.58	−6.90	4.35	−1.65	3.86	10.25	3.70	13.54
August	4.73	5.10	−7.64	4.72	0.29	4.29	10.12	4.01	15.22
September	5.94	6.47	−8.95	6.16	−3.70	5.45	9.03	5.24	11.77
October	4.22	4.72	−11.92	4.65	−10.08	3.99	5.32	3.96	6.21
November	4.59	5.52	−20.18	5.34	−16.31	4.65	−2.04	4.56	0.66
December	5.27	6.63	−25.86	6.45	−22.56	5.59	−7.02	5.52	−4.76
Total	61.09	69.42	−13.63	69.62	−13.96	58.38	4.29	59.38	2.80

predicted values. It was postulated that the electrical performance characteristics of the tandem-junction amorphous module supplied to the SNL's computer simulation model were significantly different than those associated with the modules within the BIPV test facility. To verify this hypothesis, two tandem-junction amorphous modules were removed from the BIPV test facility and their performance at standard reporting conditions were determined. The panel used to originally obtain the parameters required for the SNL model was placed beside the two modules removed from the BIPV test facility and recharacterized simultaneously. The results are given in Table 7.

The panels that were subjected to the 14 months of exposure showed significant degradation in electrical performance in comparison to the module that was initially tested to provide the parameters for the SNL model. The originally tested panel's performance also degraded as a result of the exposure time (244 h versus 124 h). Table 8 compares the predicted performance of the tandem-junction amorphous modules (E and F) using the original characterization data and data obtained from the BIPV modules after 14 months of exposure. Using post exposure characterization, the SNL model was able to predict the performance of the tandem-junction amorphous modules to within 5% compared with differences that exceeded 16% using characteristics obtained from an identical module with limited exposure.

5 Conclusions

The SNL model did an excellent job of predicting the monthly and annual performances of the monocrystalline and polycrystalline modules. Large differences between predicted and measured energy productions for the tandem-junction amorphous modules are attributed to significant degradation during the 14 months of exposure. The use of characterization parameters obtained after exposure resulted in the model predicting monthly energy production values in close agreement with measured values for the tandem-junction amorphous modules. The use of measured, as opposed to predicted, module temperatures in conjunction with the simulation model did not result in significant improvements between measured and predicted energy production values. Additionally, the technique used to determine the diffuse component of incident solar radiation had an insignificant effect on predicted energy production.

Using horizontal radiation data and the Perez anisotropic sky model, the SNL model was able to predict monthly and annual energy production values to the same level of agreement as obtained using the measured irradiance on the vertical plane adjacent to the modules. A comparison of results obtained using the HDKR and the Perez anisotropic sky models reveals that the results obtained using the Perez model consistently came closer to the measured values. The slightly better agreement between the predicted results using the horizontal radiation in conjunction with the Perez model compared with using the radiation measurements from parameters located adjacent to the modules is deemed fortuitous.

Finally, it is important to note that accurate predictions of energy production require accurate input parameters to the simulation model being utilized. For photovoltaic technologies that change significantly as a result of exposure, it may be necessary to obtain the model's input parameters by measuring the characteristics of an identical panel subjected to exposure conditions typical to those that will be experienced or, alternatively, for the model to incorporate projections of performance degradation. In this study, failure to do so resulted in disagreements between measured and predicted results approaching 18%.

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Nomenclature

C_0, C_1 = empirically determined coefficients relating I_{mp} to effective irradiance E_e
C_2, C_3 = empirically determined coefficients relating V_{mp} to effective irradiance (C_2 is dimensionless and C_3 has units of 1/V)
C_4, C_5 = empirically determined coefficients relating the current (I_x) to effective irradiance E_e
C_6, C_7 = empirically determined coefficients relating the current (I_{xx}) to effective irradiance E_e
E_e = "effective" solar irradiance defined as the ratio of the short-circuit current to the short-circuit current at standard rating conditions (dimensionless)
E_b = E_{dni} cos (AOI), beam component of solar irradiance incident on the module surface (W/m^2)
E_{diff} = diffuse component of solar radiance indecent on the solar module (W/m^2)
E_o = reference solar spectrum, 1000 W/m^2 in this study
f_d = fraction of diffuse irradiance used by module, assumed to be 1 for flat-plate modules
FF = fill factor (dimensionless)
I_{sc} = short-circuit current (A)
I_{mp} = current at the maximum-power point (A)
I_{mpo} = current at the maximum-power point at standard reference test conditions (A)
I_{sco} = short-circuit current when the module is subjected to standard reference test conditions (A)
k = Boltzmann's constant, 1.38066×10^{-23} (J/K)
n = empirically determined "diode factor" associated with individual cells in the module
N_s = number of cells in series in a module's cell-string
N_p = number of cell-strings in parallel in module
P_{mp} = power at maximum-power point (W)
q = elementary charge, 1.60218×10^{-19} (C)
T_a = ambient temperature (°C)
T_c = cell temperature inside module (°C)
T_o = reference cell temperature, 25°C
T_m = back-surface module temperature (°C)
V_{oc} = open-circuit voltage (V)
V_{mp} = voltage at maximum-power point (V)
V_{mpo} = voltage at maximum-power output (V)
V_{oco} = open-circuit voltage when the module is subjected to standard reference conditions (A)
WS = wind speed (m/s)
α_{Imp} = normalize maximum-power current temperature coefficients (V/°C)
α_{Isc} = normalized short-circuit temperature coefficient (V/°C)
β_{vmp} = maximum-power voltage temperature coefficient (V/°C)
β_{voc} = open-circuit voltage temperature coefficient (V/°C)
$\delta(T_c)$ = thermal voltage per cell at temperature T_c

Appendix

The model used to predict the electrical performance of photovoltaic modules [6] is described by the following. The short-circuit current I_{sc}, is described by

$$I_{sc} = I_{sco} \cdot f_1(AM_a) \cdot \{(E_b \cdot f_2(AOI) + f_d \cdot E_{diff})/E_o\} \cdot \{l + \alpha_{Isc} \cdot (T_c - T_o)\} \quad (A1)$$

The air mass function of f_1 (AM_a) (Eq. (A1)) is an attempt to take into account variations in electrical performance due to changes in the solar spectrum. The angle of incidence function f_2 (AOI) takes into account the influence of optical losses due to reflections from the glazing system. The procedures used to determine the coefficients associated with these empirically-based functions are described by King et al. [13].

The current produced by the photovoltaic module at its maximum-power point is based on an empirical data fit relating the maximum-power point current at standard rating conditions to the effective irradiance E_e and the module's operating temperature

$$I_{mp} = I_{mpo} \cdot \{C_0 \cdot E_e + C_1 \cdot E_e^2\}\{1 + \alpha_{Imp} \cdot (T_c - T_o)\} \quad (A2)$$

where the effective irradiance is determined using

$$E_e = I_{sc}/[I_{sco} \cdot \{1 + \alpha_{Isc} \cdot (T_c - T_o)\}] \quad (A3)$$

The open-circuit voltage V_{oc} at a given irradiance level is computed using the measured open-circuit voltage at rating conditions V_{oco}, the effective irradiance E_e, and the open-circuit voltage temperature coefficient $\beta_{V_{oc}}$

$$V_{oc} = V_{oco} + N_s \cdot \delta(T_c) \cdot \ln(E_e) + \beta_{V_{oc}}(E_e) \cdot (T_c - T_o) \quad (A4)$$

where the function $\delta(T_c)$ is completed using

$$\delta(T_c) = n \cdot k \cdot (T_c + 273.15)/q \quad (A5)$$

Similar to the maximum-power output, the voltage associated with the maximum-power output V_{mp} is based on an empirical fit to the effective irradiance

$$V_{mp} = V_{mpo} + C_2 \cdot N_s \cdot \delta(T_c) \cdot \ln(E_e) + C_3 \cdot N_s \cdot \{\delta(T_c) \cdot \ln(E_e)\}^2 + \beta_{V_{mp}}(E_e) \cdot (T_c - T_o) \quad (A6)$$

The effect of temperature on the voltage at maximum-power is taken into account through the use of maximum-power voltage temperature coefficient $\beta_{V_{mp}}$.

The rear surface temperature of the photovoltaic modules is predicted using

$$T_m = E \cdot e^{a+b\cdot WS} + T_a \quad (A7)$$

where the empirical coefficients a and b have been established by the Sandia National Laboratories for a wide range of module types and mounting configurations. Having determined the measured back-surface temperature, the cell temperature is computed using the following relationship

$$T_c = T_m + \frac{E}{E_0}\Delta T \quad (A8)$$

where the temperature difference ΔT has been determined for various types of module constructions. For photovoltaic modules with a thermally insulated rear surface, the temperature differential is assumed to be zero. For the other modules in this study, the temperature difference was set to 1°C.

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