Performance and Characterization of Building Integrated Photovoltaic Panels

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ABSTRACT

Buildings consume more than two-thirds of the electricity in the United States. The incorporation of photovoltaics into buildings, referred to as building integrated photovoltaics (BIPV), offers an aesthetically pleasing means of displacing centrally located utility generated power with distributed renewable energy. Building integrated photovoltaics replace conventional building elements such as roof tiles, asphalt shingles, facade elements, and shading devices with photovoltaic modules that perform the same functions but also provide electrical power.

A barrier to BIPV implementation is the lack of validated predictive tools to quantify the achievable energy savings. Building owners, architects, and designers need these predictive tools in order to make informed decisions about the economic viability of a proposed BIPV project. The Building and Fire Research Laboratory at the National Institute of Standards and Technology (NIST) is providing high quality experimental data for the development, validation, and improvement of computer simulation tools.

Among the computer simulation tools available for predicting the performance of photovoltaic (PV) systems are IV Curve Tracer, developed by Sandia National Laboratories [1], and PHANTASM, authored by the University of Wisconsin [2].

This paper describes NIST's BIPV "*test bed*", a facility that is used to measure the annual performance of different types of BIPV panels. Measurements are presented that compare the performance of four different cell technologies and document the effect of installing thermal insulation at the interior surface of BIPV panels. The annual performance of each BIPV panel is evaluated relative to its performance at standard rating conditions.

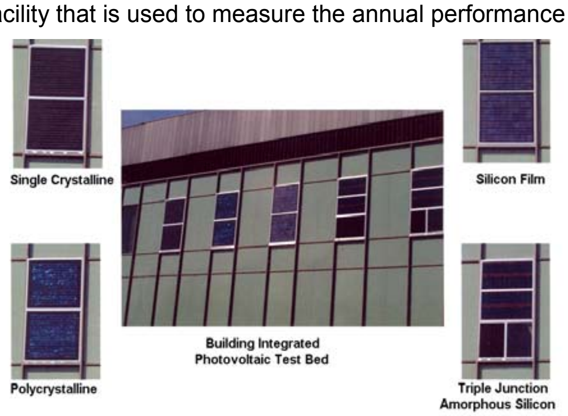

Figure 1 Photovoltaic BIPV *Test Bed*

EXPERIMENTAL FACILITIES

The BIPV *test bed* [3] is located on the south wall of NIST's Building Research Laboratory (see Fig. 1). Six custom fabricated BIPV panels and two BIPV panels constructed using commercially available triple-junction amorphous silicon modules were selected for the initial one-year study. The cell technologies used for the custom fabricated panels include single crystalline, polycrystalline, and silicon film. For each of the four cell technologies, two identical BIPV panels were installed: one insulated on its backside and one uninsulated. The backside insulation was extruded polystyrene having a thickness of 10 cm and a thermal resistance of 3.5 $m^2 \cdot K/W$ (R-20).

As shown in Fig. 1, each pair of custom fabricated panels were installed in test cells located one above the other. The amorphous silicon panels, each panel consisting of two modules connected in series, were installed in adjacent upper test cells. Specifications for each panel are given in Table 1. Meteorological instruments and a small BIPV panel equipped with a heat flux transducer were mounted in the remaining three test cells.

The electrical performance of each building integrated photovoltaic panel was measured every 15 s using a multi-curve tracer. This instrument continuously maintained each panel within 0.2% of its maximum power point. Every 5 min, the 15 s readings were averaged and saved. The multi-curve tracer also obtained a current versus voltage (IV) trace for each panel every five minutes.

Type-T thermocouples were installed on the rear of each panel and, if present, on the rear surface of the installed insulation. During fabrication of the custom-fabricated BIPV panels, thermocouples were embedded immediately behind two PV cells within each panel.

Table 1
Building Integrated Photovoltaic Panel Specifications

Cell Technology	Single Crystalline	Poly Crystalline	Silicon Film	Triple-Junction Amorphous
Panel Dimensions (m x m)	1.38 x 1.18	1.38 x 1.18	1.38 x 1.18	1.37 x 1.48
Front Cover	6 mm glass	6 mm glass	6 mm glass	*Tefzel
Encapsulant	EVA	EVA	EVA	
Backsheet/Color	*Tedlar/Charcoal	*Tedlar/Charcoal	*Tedlar/Charcoal	Stainless Steel
Cell dimensions (mm x mm)	125 x 125	125 x 125	150 x 150	119 x 340
Number of Cells (in series)	72	72	56	44
Adjacent Cell Spacing (mm)	2	2	2	
Vertical (Side) Border Width(mm)	100	100	51	8
Top Border Height(mm)	72	72	55	11
Bottom Border(mm)	70	70	29	5
Recessed Distance to PV Cell (mm)	12	12	12	9
Glazing Covered by PV Cells %	63	69	82	88
Total Cost ($)	1324	1123	995	578
Price/Watt($/W)	8.66	8.43	10.82	4.52
Rated Power (W)	153**	133**	92**	128***
Cell Area (m^2)	1.020	1.128	1.341	1.780
Aperture Area (m^2)	1.682	1.682	1.682	2.108
Coverage Area (m^2)	1.160	1.160	1.371	1.815

* Certain trade names and company products are mentioned in the test or identified in an illustration in order to adequately specify the experimental procedure and equipment used. In no case does such an identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.
** Reported by the manufacturer of the custom fabricated BIPV panels.
*** Reported by the manufacturer of the photovoltaic modules.

Two meteorological stations, a complete rooftop station and a *test-bed* station, are used to capture the meteorological data needed as inputs to the simulation tools. The rooftop station incorporates instruments to measure beam, diffuse, and total horizontal solar radiation, ambient temperature, and wind conditions. The *test-bed* meteorological station is located adjacent to and in the same vertical, south-facing plane as the BIPV panels. Infrared radiation, wind conditions, and redundant measurements of total solar radiation and outdoor ambient temperature are provided. Indoor ambient temperature and infrared radiation are also recorded. Wind conditions are measured using with a 3-cup anemometer and vane for the rooftop and using an ultrasonic wind sensor for the *test-bed*. The two meteorological stations provide a means for evaluating the impact of having truly local measurements versus data from a more typical, more remote weather station.

EXPERIMENTAL RESULTS

The BIPV panels were monitored to determine if performance differences existed between the two panels of each cell technology prior to installing thermal insulation to one of each set. During this baseline monitoring period, the differences in delivered energy between the two panels of each technology were 0.7%, 1.3%, 0.3% and 1.8% for the single-crystalline, polycrystalline, silicon-film, and amorphous silicon panel sets, respectively. The performance differences observed during this initial comparison period were assumed to exist throughout the year and were used to normalize the results for the uninsulated panels.

The conversion efficiency of the building integrated photovoltaic panels in converting the incident solar radiation into electrical energy is calculated using,

$$\eta_c = \frac{\int_o^\tau P_o d\tau}{A\int_o^\tau H_T d\tau} \qquad (1)$$

where A is a representative area, m^2,
P_o is the panel's electrical power output, W,
H_T is the incident solar radiation, W/m^2,
and τ is the monitoring time interval, h.

Two representative areas, cell and coverage, were used in this study to compute conversion efficiencies. Cell area is defined as the sum of the individual cell areas within a panel. Coverage area is defined as the cell area plus any areas that may exist between cells.

The monthly and annual energy production and conversion efficiencies of the BIPV panels are given in Table 2. The effect of thermal insulation on the annual coverage area conversion efficiencies is shown in Fig. 2. The highest overall conversion efficiency, 10.3%, was achieved by the uninsulated panel using single-crystalline cells. The insulated single-crystalline panel efficiency was 3.8% lower, 9.9% versus 10.3%. The polycrystalline panels differed by 3.1%: 9.7% for the uninsulated panel compared to 9.4% for the insulated panel. The uninsulated and insulated silicon film panels converted 6.0% and 5.8% of the incident solar radiation, a 3.3% difference. The addition of insulation to the amorphous silicon panel improved its efficiency from 5.9% to 6.0%. Figures 3 and 4 show the variation in operating temperature and resulting power output for insulated and uninsulated BIPV panels using single-crystalline cells and triple junction amorphous silicon cells, respectively, for a selected day.

The cost of photovoltaics is most often quoted in terms of dollars per watt at standard rating conditions (SRC). However standard rating conditions H_T=1000 W/m^2, T_c = 25°C, angle of incidence = 0°, and AM_a=1.5, are rarely, if ever, encountered in an actual installation. Building practitioners are generally more interested in the amount of energy that photovoltaics can generate over a given time interval than power output at an arbitrary set of rating conditions. A figure of merit — the ratio of energy produced by each BIPV panel over a specified interval of time to the power output of the panel at standard rating conditions — would be beneficial to the building community. This figure of merit is referred to as Specific Yield [4].

Duplicates of each BIPV panel were tested using NIST's Solar Tracking Facility to obtain each panel's power output at SRC conditions [3,5]. Specific Yields (SY) calculated using the NIST-measured power outputs at SRC (Case A) and using the manufacturer's reported rated power outputs (Case B) are provided in Table 3. Although the amorphous silicon panels have conversion efficiencies significantly lower than those of the single crystalline and polycrystalline panels (see Table 2), the Specific Yields based on the NIST-measured power output at SRC (Case A) is highest for the amorphous silicon panels. The Case A results suggest that if each of the eight panels had the same rated power at SRC (e.g., 100 W_p) then the insulated amorphous silicon panel would provide the most energy over a typical day.

As shown in Table 3, the rank ordering of the eight panels based on SY changes significantly between Case A versus Case B. Because the Case A data were all collected using the same apparatus, the authors judge the Case A rank ordering to be more representative. The combined Case A and Case B results, although different, do support that a rank ordering based on rated performance at one set of operating conditions does not translate into the same rank ordering for annual energy production.

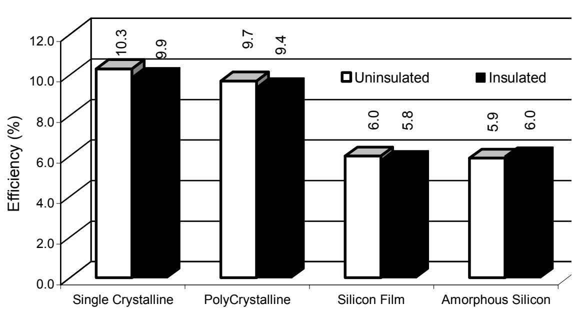

Figure 2 Overall BIPV Conversion Efficiency January 4 - December 31, 2000

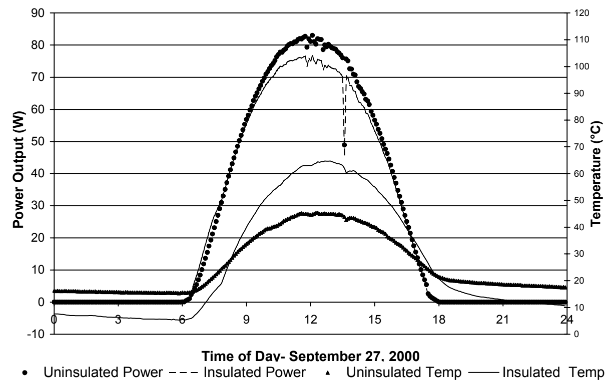

Figure 3 Single Crystalline Power Output and Temperature: Uninsulated Versus Insulated

SUMMARY

Among the barriers to the widespread proliferation of building integrated photovoltaics is the lack of performance data and validated computer simulation tools. A building integrated photovoltaic *test-bed* has been constructed to help address these barriers. The facility is capable of providing side-by-side performance comparisons of BIPV panels.

The performance of eight BIPV panels has been measured for 12 months. The panels included custom fabricated single-crystalline, polycrystalline, and silicon film panels as well as commercially available amorphous silicon modules. An insulated and un-insulated panel of each cell technology was evaluated.

The data summarized in this paper should be of interest to building owners, photovoltaic cell manufacturers, and fabricators of BIPV panels. In subsequent publications [6], the hourly data will be compared to the computer predictions.

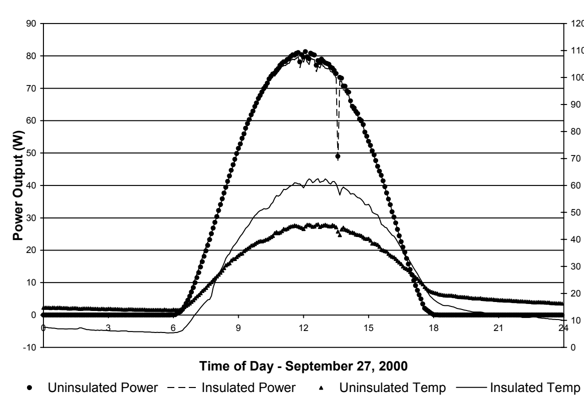

Figure 4 Amorphous Silicon Power Output and Temperature: Uninsulated Versus Insulated

Table 2 Monthly and Cumulative BIPV Panel Performance

		Jan 2000	Feb 2000	Mar 2000	Apr 2000	May 2000	Jun 2000	Jul 2000	Aug 2000	Sep 2000	Oct 2000	Nov 2000	Dec 2000	Total
Panel Energy Production Sunrise to Sunset (Wh)	Single Crystalline - U	11795	12197	12289	6628	6745	6520	7185	7626	10119	14243	10036	11985	117368
	Single Crystalline - I	11556	11833	11925	6491	6552	6332	6967	7367	9694	13463	9644	11725	113551
	Poly Crystalline - U	11332	11662	11624	6130	6124	5859	6509	7029	9596	13668	9653	11546	110733
	Poly Crystalline - I	11116	11349	11341	6084	6075	5833	6452	6904	9262	12956	9317	11327	108015
	Silicon Film – U	8538	8711	8541	4390	4217	3947	4443	4938	7024	10186	7235	8698	80868
	Silicon Film - I	8334	8399	8273	4318	4146	3904	4372	4810	6718	9543	6928	8487	78232
	Amorphous - U	10117	10734	11064	5995	6345	6272	6954	7295	9548	12822	8613	9681	105438
	Amorphous - I	10252	10894	11287	6130	6431	6353	7029	7381	9647	12954	8832	9977	107168
Conversion Efficiency Based On Cell Area (%) Sunrise To Sunset	Single Crystalline - U	12.5	12.3	12.0	11.9	11.0	10.5	10.5	11.1	11.2	11.6	12.1	12.4	11.7
	Single Crystalline - I	12.2	11.9	11.6	11.6	10.7	10.2	10.2	10.7	10.7	10.9	11.6	12.2	11.3
	Poly Crystalline - U	10.9	10.6	10.3	9.9	9.0	8.6	8.6	9.3	9.6	10.1	10.5	10.8	10.0
	Poly Crystalline - I	10.7	10.3	10.0	9.8	8.9	8.5	8.5	9.1	9.3	9.5	10.1	10.6	9.7
	Silicon Film – U	6.9	6.7	6.3	6.0	5.2	4.8	4.9	5.5	5.9	6.3	6.6	6.9	6.1
	Silicon Film - I	6.7	6.4	6.1	5.9	5.1	4.8	4.9	5.3	5.6	5.9	6.3	6.7	5.9
	Amorphous - U	6.1	6.2	6.2	6.1	5.9	5.8	5.8	6.1	6.0	6.0	5.9	5.8	6.0
	Amorphous - I	6.2	6.3	6.3	6.3	6.0	5.9	5.9	6.2	6.1	6.0	6.1	5.9	6.1
Conversion Efficiency Based On Coverage Area (%) Sunrise To Sunset	Single Crystalline - U	11.0	10.8	10.5	10.4	9.6	9.3	9.2	9.8	9.8	10.2	10.6	10.9	10.3
	Single Crystalline - I	10.8	10.5	10.2	10.2	9.4	9.0	8.9	9.4	9.4	9.6	10.2	10.7	9.9
	Poly Crystalline - U	10.6	10.3	10.0	9.6	8.8	8.3	8.4	9.0	9.3	9.8	10.2	10.5	9.7
	Poly Crystalline - I	10.4	10.1	9.7	9.6	8.7	8.3	8.3	8.9	9.0	9.3	9.8	10.3	9.4
	Silicon Film – U	6.7	6.5	6.2	5.8	5.1	4.7	4.8	5.4	5.8	6.2	6.5	6.7	6.0
	Silicon Film - I	6.6	6.3	6.0	5.7	5.0	4.7	4.7	5.2	5.5	5.8	6.2	6.6	5.8
	Amorphous - U	6.0	6.1	6.1	6.0	5.8	5.7	5.7	6.0	5.9	5.9	5.8	5.6	5.9
	Amorphous - I	6.1	6.2	6.2	6.2	5.9	5.8	5.8	6.0	6.0	5.9	6.0	5.8	6.0

Note: The expanded uncertainties associated with the reported energy measurements and efficiency results are ± 1.2% and ± 2.4%, respectively. These uncertainties were calculated using a coverage factor of 2 (i.e., level of confidence is approximately 95%).

Table 3. Specific Yields

Panel Type		Annual Energy Output* (Wh)	CASE A: NIST Measured Power Output at SRC (W)	CASE A: Specific Yield (Wh/W_p/day)	CASE A: Rank	CASE B: Rated Power Output (W)	CASE B: Specific Yield (Wh/W_p/day)	CASE B: Rank
Single Crystalline	Uninsulated	117368	133.4	2.558	4	153	2.230	7
	Insulated	113551		2.474	6		2.157	8
Poly Crystalline	Uninsulated	110733	125.8	2.559	3	133	2.420	4
	Insulated	108015		2.498	5		2.363	6
Silicon Film	Uninsulated	80868	104.0	2.260	7	92	2.555	1
	Insulated	78232		2.187	8		2.472	2
Amorphous Silicon	Uninsulated	105438	114.0	2.689	2	128	2.395	5
	Insulated	107168		2.733	1		2.434	3

*Based on data from 344 days.

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