March 1999 • NREL/CP-520-25851

Conference Paper

Performance and Modeling of Amorphous Silicon Photovoltaics for Building-Integrated Applications

Preprint prepared for Solar 99

B. Kroposki and R. Hansen

To be Presented at Solar 99: Growing the Market
Portland, Maine
June 12-17, 1999

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393

NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle • Bechtel

Contract No. DE-AC36-98-GO10337

NOTICE

Available to DOE and DOE contractors from:
Office of Scientific and Technical Information (OSTI)
P.O. Box 62
Oak Ridge, TN 37831
Prices available by calling 423-576-8401

Available to the public from:
National Technical Information Service (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
703-605-6000 or 800-553-6847
or
DOE Information Bridge
http://www.doe.gov/bridge/home.html

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

PERFORMANCE AND MODELING OF AMORPHOUS SILICON PHOTOVOLTAICS FOR BUILDING-INTEGRATED APPLICATIONS

Benjamin Kroposki and Robert Hansen
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401

ABSTRACT

Amorphous silicon photovoltaic (PV) modules offer several advantages for building-integrated applications. The material can be deposited on glass or flexible substrates, which allows for products like roofing shingles and integrated PV/building glass. The material also has a uniform surface, which is ideal for many architectural applications. Amorphous silicon modules perform well in warm weather and have a small temperature coefficient for power. Depending on the building load, this may be beneficial when compared to crystalline systems. At the National Renewable Energy Laboratory, we are monitoring the performance of a triple-junction a-Si system. The system consists of 72 roofing shingles mounted directly to simulated roofing structures. This paper examines the performance of the building-integrated amorphous silicon PV system and applicability for covering residential loads. A simple model of system performance is also developed and is presented.

1. INTRODUCTION

The National Renewable Energy Laboratory conducts in situ technical evaluations of photovoltaic (PV) modules and systems at its Outdoor Test Facility in Golden, CO.

A triple-junction, amorphous silicon roofing shingle array from United Solar Systems Corp. was installed on June 30, 1998. Data acquisition started on July 1, 1998. This new system rated at 1.2 kW replaced a 1-kW dual-junction prototype roofing array that was provided by United Solar Systems Corp. The purpose of this testing is to determine the long-term performance and reliability of the roofing shingle system.

The system consists of 72 roofing shingle PV modules. The modules are made of triple-junction amorphous silicon with germanium in the bottom junction. Each PV shingle is 12.7 cm (5 in.) by 220 cm (86.67 in.) and has an aperture area of 0.28m^2. The surface of the module is textured and looks similar to the surrounding conventional shingles. The modules are nailed in place on conventional roof decking. Lead wires from the back side of each module pass through the roof deck, allowing connections to be made in the attic structure. A strip of ethylene vinyl acetate (EVA) on the back of each module, once it is warmed by the sun, holds the modules together for wind and water resistance. These modules are UL listed to UL-1703. The module electrical specifications are listed in Table 1.

Table 1. Module Electrical Specifications

	Power	Voc	Isc	Vmax	Imax
Rated at STC	17 (W)	12 (V)	2.5 (A)	8.6 (V)	2.0 (A)
Temp. Coeff (%/°C)	-0.29	-0.4	+0.1	-0.45	+0.1

Figure 1. Roofing Shingle PV System

The array is wired in 12 strings of 6 modules each to form a 48V_{dc} configuration. The array is connected to a Trace 4048PV inverter. The system is connected to the utility grid and sends all energy produced by the array to the utility. The array is fixed at a 40° tilt angle from horizontal and has a total aperture area of 20.2 m^2.

The data acquisition system is based on a Campbell Scientific 21X datalogger. Data are sampled every five seconds and stored as 15 minute averages. Data collected includes dc voltage and current, plane-of-array irradiance, ac voltage and current, ac power, back-of-module temperature, air temperature, inverter temperature, roof temperature, and attic temperature.

2. ROOFING SHINGLE SYTEM PERFORMANCE

Array Performance

The data in Figures 2 and 3 were taken when the plane-of-array irradiance was between 950-1050 W/m^2 and between the dates of July 1, 1998 and January 31, 1999. Data were removed when the inverter was not peak power tracking (see inverter performance section). Figure 2 shows the array dc power output (normalized to 1000 W/m^2), array temperature, and air temperature. This graph shows that the array power has remained stable over the time period. The data also show that the array performance is not greatly affected by temperature; even as the air temperature drops from 30°C to 10°C, the array power remains between 1000 and 1200 watts. The initial performance of this array is slightly unusual compared with other amorphous systems found in the literature [1]. Most systems experience an initial drop in array power because of Staebler-Wronski degradation. This lack of an initial performance drop may be because this system was exposed for 2-weeks prior to the start of data acquisition. The system also does not show the usual 10% seasonal fluctuation caused by thermal annealing. This will be explored further once a year of data are collected. The array normalized power during the test period was between 1184 W and 1007 W. The average array power was 1082 W at an average array temperature of 57°C and average air temperature of 23.5°C.

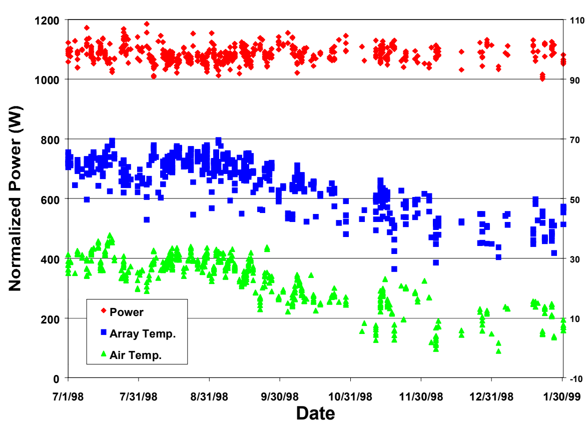

Figure 2. Array Normalized Power Output, Array Temperature, and Air Temperature vs. Time

Figure 3 shows the array power output vs. array temperature. This graph shows a weak inverse correlation between array temperature and power output.

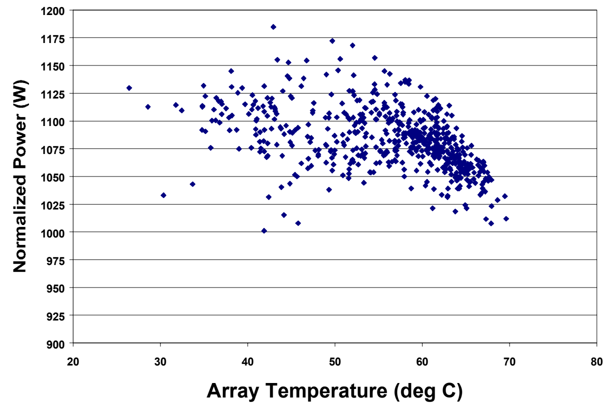

Figure 3. Array Normalized Power Output vs. Array Temperature

Inverter Performance

The Trace 4048PV inverter has continued to run during the test period with no down time. Although this is the case, the inverter has two noticeable problems that affect its performance. First, there are problems with how well the inverter tracks peak power. When in automatic peak-power tracking mode, the inverter will run the array at 35V during the parts of the day when the array voltage at peak power should be 45V. This results in approximately 130W (11%) power loss at full array power. One reason for this may be that the 4-kW inverter is running a 1-kW array. Since the array is only 1 kW, the inverter will never run above 25% of rated power. This fact also leads to the second potential problem, which is the level of current total harmonic distortion (THD). When the inverter was operating at 1 kW (25% of rated power), the current total harmonic distortion was 17%. THD measurements were made with a BMI power profiler. According to IEEE 929 [2], the inverter is required to have less than 5% current THD at full rated power for grid connection, but this type of inverter, when used with small arrays, seems to create more than 5% THD.

System Performance Summary

Overall, the system has performed quite well over the test period. The system has not experienced any down time or failures. The array appears to have stable performance. The inverter -although functioning- is oversized for the system and not performing as anticipated. When designing a PV system, it is recommended to match the size of all components.

3. RESIDENTIAL PV SYSTEM APPLICATIONS

The typical size of most residential grid-connected PV systems is 1-4 kW. Using the output of the 1-kW PV system and matching it to various residential loads, we can see how well the system would operate on a residence under different weather conditions. Figures 4-6 show the output of the PV system matched to the average residential load of Public Service Company of Colorado (PSCO) for particular days. The loads are the average residential load demand per day for PSCO's service area. Since these are average residential loads for all customers, they do not contain high short-term demand peaks that are present in most individual residences. The demand is normalized to 13 kWh per day, which is the consumption of a nominal 1200 square foot home.

Figure 4 shows the PV system output and residential load for a sunny-cool day on August 28, 1998. On this day there was lots of sun, which contributed to the high solar output of the system. The day was relatively cool for August with a maximum air temperature of 28°C. This contributed to a lower total electrical demand. During the day, the PV system produced 8 kWh compared to the load of 12.8 kWh. From 9 a.m. to 4 p.m., the PV array actually produced 3 kWh more energy than the load required. This electricity would be put back onto the utility grid in net-meter or sell-back operation.

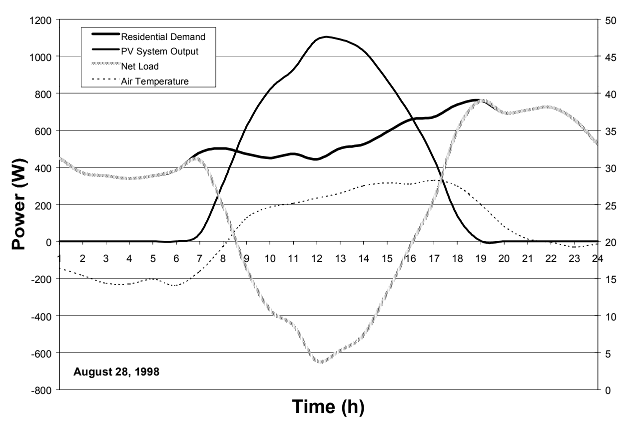

Figure 4. PV Output and Residential Load on a Sunny- Cool Day

Figure 5 shows the system performance and residential load for August 8,1998, a sunny-hot day. The air temperature during this day rose to a maximum of 34°C. This accounts for the high afternoon demand of 901 W, compared to 760 W for the sunny-cool day. The PV system performance still remains high during the day and decreases the overall demand by 7 kWh. If leveling the demand is important, some type of storage (like batteries) would be useful for storing the extra energy produced during the day and using this to cover the high, early-nighttime (5-8 p.m.) load.

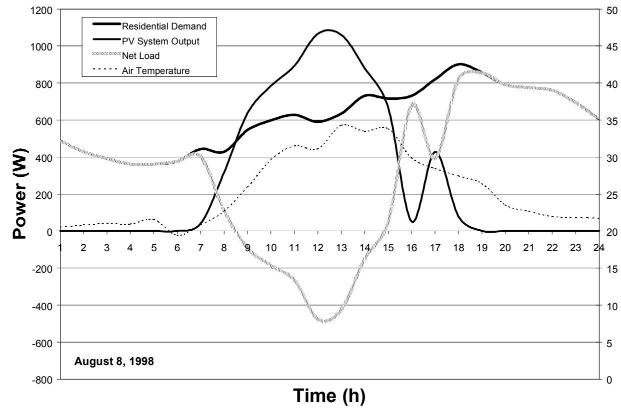

Figure 5. PV Output and Residential Load on a Hot summer day

Figure 6 shows the output of the PV system and residential load on a cloudy day. On this day, even though the PV array produced only 3.4 kWh, that was enough to send some electricity back to the utility.

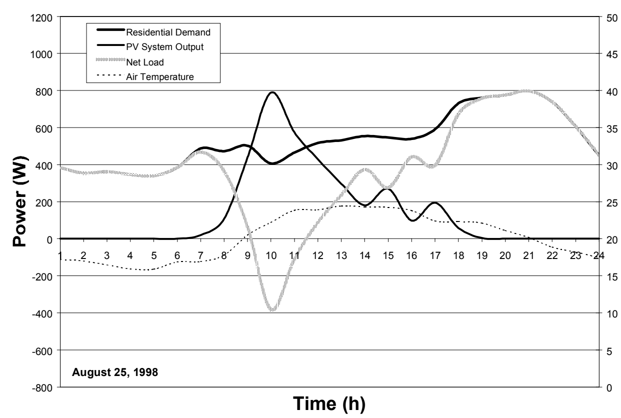

Figure 6. PV Output and Residential Load on a Cloudy Day

4. SYSTEM MODELING

To determine system performance under all meteorological conditions, a model of the system performance must be used.

A simple model was developed that takes the basic parameters of a PV system and the meteorological conditions and predicts the AC power output. This model is intended for use with grid-connected PV systems that use inverters with good peak power tracking abilities. This model does not have any corrections for unusually low irradiance response, high incident angles, or spectral responses of the PV modules. The ac part of this model develops an inverter curve based on the manufacturer's basic inverter specifications. This allows for flexibility with different inverters. This model also disregards the inverter idle loss at night.

The simple PV model uses the following variables:

N = total number of modules
P = module power at STC in watts (1000 W/m^2, 25°C)
TC = module temperature coefficient for power (%/°C)
SL = module soiling loss in % (default value = 3%)
ML = module mismatch loss in % (default value = 3%)
POA = Plane-of-array irradiance (W/m^2)
MT = module temperature (°C)
DC = Total DC power from system in watts
INVeff = Inverter Efficiency (%)
TL = turn on power in watts (typically 1-5% of rated power)
PEL = inverter efficiency at maximum power in percent (default = .90)
MAX = maximum rated power of inverter
AC = Total AC power from system in watts

The simple model uses the following three equations to determine the AC power output of the PV system:

DC = (N)(P)(POA/1000)(1+(MT-25)*TC)(1-(SL+ML)) (1)

INVeff = 1.0 – (TL/DC) - (1.0-PEL)*(DC/MAX) (2)

AC = DC*INVeff (3)

Array Modeling

The array model adjusts the module's power at standard test conditions (STC) for actual irradiance and operating temperature. Two additional terms are added for soiling losses and module mismatch. The soiling loss will vary throughout the year, but studies have shown this number to be approximately 3% for modules on at least a 40° tilt. [3] The mismatch parameter is approximated by using 3%.

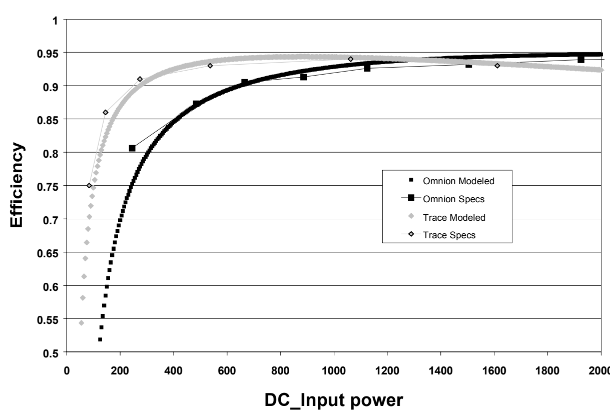

Figure 7. Modeled vs. manufacturers specifications for two grid-tied inverters

Inverter modeling

The inverter model we developed was based on a minimum amount of information given by the inverter manufacturers. This included the inverter turn-on power, the maximum rated power output of the inverter, and the inverter efficiency at maximum power. Figure 7 shows the modeled inverter efficiency vs. the manufacturer's specifications for two popular grid-tied inverters: Omnion 2400 and Trace 4048PV.

5. MODELING ACTUAL SYSTEM PERFORMANCE

For modeling the output of the 1-kW amorphous silicon roofing array, we used the following input parameters based on the manufacturer's specifications:

Module Characteristics:
N = 72 modules
P = 17 watts
TC = -0.29%/°C = (-0.0029)
SL = 3% = (0.03)
ML = 3% = (0.03)

Inverter Characteristics:
TL = 40 watts
PEL = .9
MAX = 4000 watts

The inverter efficiency was modeled using the inverter characteristics listed above. Figure 8 shows the measured efficiency vs. the modeled efficiency for this system.

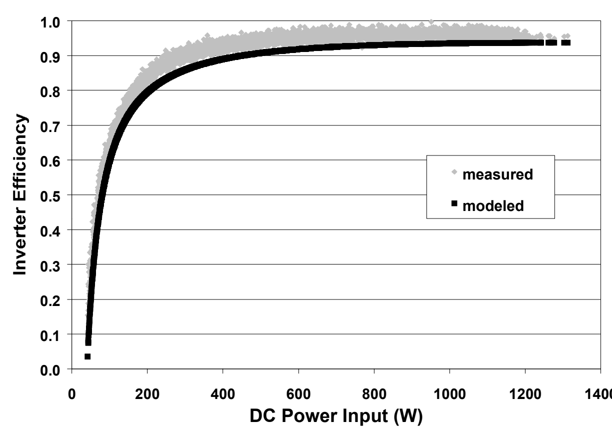

Figure 8. Modeled Inverter Efficiency

The system AC output was modeled using the measured POA irradiance and array temperature. Figure 9 shows the measured and modeled data for a sunny day, while figure 10 shows the results for a cloudy day. From these graphs, we can see that the model performs fairly well over various conditions and can be used for determining a system's energy production on any type of day.

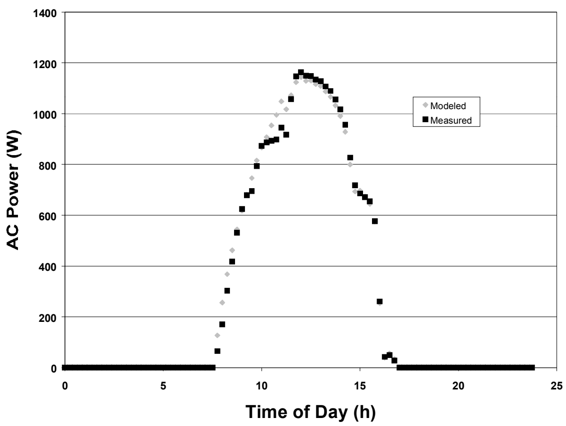

Figure 9. Measured and Modeled AC Power Output on a sunny day

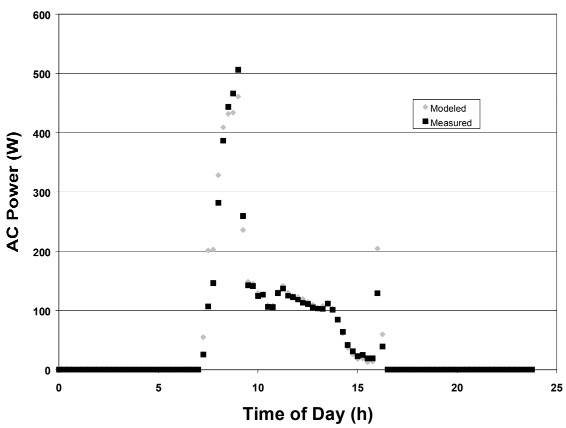

Figure 10. Measured and Modeled AC Power Output on a cloudy day

Figure 11 shows the percent of error in the modeled AC power over the 7-month period. This data is filtered for bad peak-power tracking data and snow conditions. The figure shows the error is less than 20% for most conditions.

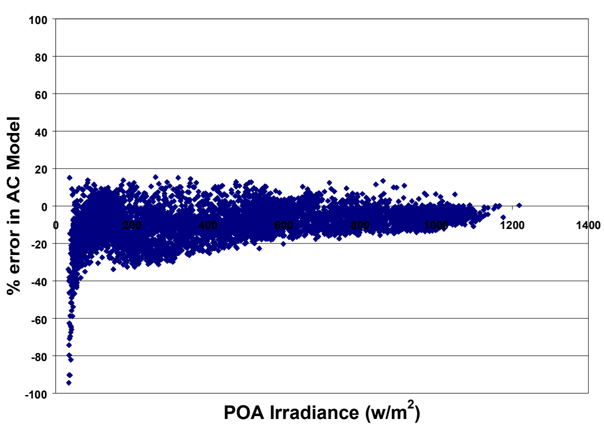

Figure 11. Percent error in modeled AC power

6. CONCLUSIONS

The 1-kW amorphous silicon PV roofing system has performed as expected, except for some minor inverter issues. The array appears to have stable performance. The inverter, although functioning, is oversized for the system.

The performance of the system showed that amorphous silicon works very well in building-integrated applications such as residences. The performance data showed that the system is not greatly affected by temperature. This means the amorphous silicon system's performance will not be greatly affected if it is integrated into a building in a way which makes the modules operate at a high temperature.

Modeling the system performance with the simple model presented gave fairly good results. More improvements could have been made by using more detailed models that incorporate angle-of-incidence and air mass corrections [4]. But these would have increased the model complexity while only reducing the overall error by less than 5%.

A model for determining inverter efficiency was also developed and shown to produce good results vs. the specifications. This model allows for a simple way to translate from dc array output to ac system output.

7. ACKNOWLEDGEMENTS

The author would like to thank Craig Williamson of Public Service Company of Colorado for providing the residential load profiles. This work is supported by the U.S.DOE under contract number DE-AC36-98-GO10337.

8. REFERENCES

[1] Kroposki, B. and R. Hansen, "Technical Evaluation of Four Amorphous Silicon Systems at NREL," 26th IEEE PVSC, 1997, pp.1357-1360.

[2] IEEE 929 "IEEE Recommended Practice for Utility Interface of Photovoltaic Systems".

[3] Hammond, R. et al, "Effects of Soiling on PV module and Radiometer Performance," 26th IEEE PVSC, pp1121-1124.

[4] King, D.L. "Photovoltaic Module and Array Performance Characterization Methods for All System Operating Conditions," NREL/SNL PV Program Review, AIP Conf. Proceedings 394, 1996, pp.347-368.

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE June 1999	3. REPORT TYPE AND DATES COVERED Conference Paper

4. TITLE AND SUBTITLE Performance and Modeling of Amorphous Silicon Photovoltaics for Building-Integrated Applications	5. FUNDING NUMBERS C: TA: PV907301
6. AUTHOR(S) B. Kroposki and R. Hansen	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393	10. SPONSORING/MONITORING AGENCY REPORT NUMBER CP-520-25851
11. SUPPLEMENTARY NOTES	
12a. DISTRIBUTION/AVAILABILITY STATEMENT National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161	12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Amorphous silicon photovoltaic (PV) modules offer several advantages for building-integrated applications. The material can be deposited on glass or flexible substrates, which allows for products like roofing shingles and integrated PV/building glass. The material also has a uniform surface, which is ideal for many architectural applications. Amorphous silicon modules perform well in warm weather and have a small temperature coefficient for power. Depending on the building load, this may be beneficial when compared to crystalline systems. At the National Renewable Energy Laboratory, we are monitoring the performance of a triple-junction a-Si system. The system consists of 72 roofing shingles mounted directly to simulated roofing structures. This paper examines the performance of the building-integrated amorphous silicon PV system and applicability for covering residential loads. A simple model of system performance is also developed and is presented.

14. SUBJECT TERMS photovoltaics ; amorphous silicon modules ; building-integrated applications ; system performance ; modeling ; roofing shingles	15. NUMBER OF PAGES 7
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL