ANALYSIS OF PV SYSTEM PERFORMANCE VERSUS MODELED EXPECTATIONS ACROSS A SET OF IDENTICAL PV SYSTEMS

Jeff Perlman
Andy McNamara
Dante Strobino
Big Apple Solar Installation Commitment (BASIC)
37 W. 28th St, 12th floor
New York, NY 10001
jperlman@brightpower.biz
am004k@mail.rochester.edu
destrobi@ncsu.edu

ABSTRACT

In this paper, we seek to compare the measured output of eight 2 kW photovoltaic (PV) systems, consisting of the same hardware installed on different locations throughout New York State, with the output predicted by models.

Our data is from the set of NYSERDA School Power… Naturally (SPN) systems. A variety of performance characteristics of these systems are logged by a Heliotronics data collection system and posted to an online database.

Our analysis shows that individual systems perform consistently, but often not as predicted, and quite different from each other. It is admittedly incomplete. However, it does begin to show the opportunity for detailed performance characterization, data verification and model development that the SPN systems present. Further, it is the authors' hope that some of their simple modeling development will be incorporated into curriculums that use the PV systems as a teaching tool in science classes.

1. INTRODUCTION

Our initial intent for this project was to create a simple, accurate model of expected PV system output given time of day, sunlight level, angle of the solar modules and latitude. While we are aware that such models exist, we were not able to find one matching our specific need: to quickly determine the peak load reduction benefit of a collection of PV systems. The peak load reduction benefit of grid-tied PV systems is potentially extremely valuable in places such as New York City, where peak demands on the electrical grid are high.

To test our model we chose the real-world data from the New York State Energy Research and Development Authority (NYSERDA) School Power… Naturally (SPN) Program. All fifty 2 kW SPN systems consist of twenty 100 Watt Astropower (now GE) Sunline photovoltaic (PV) modules, one Sunny Boy 2500 Watt inverter, and a Heliotronics Feynman data collection system. Numerous system performance measurements are collected every 15 minutes by Heliotronics hardware and posted on the internet. We would expect the different systems, if installed similarly and subjected to similar light levels, to reveal similar performance characteristics.

2. ORIGINAL MODEL

Based on the modeling work of Richard Perez, we constructed an Excel model with several system specific parameters and the following data streams:

> **T_{MOD}** – Module Temperature
> **Irr** – Irradiance or Total Power of Available Sunlight (W/m2)

This model was tested with data collected at the schools. We were able to make a respectable approximation of modeled system performance (Figs. 1 & 2) using the following formulae:

Equation 1 $T_{DEG} = (T_{NOC} - T_{MOD}) * MPTC$

Where T_{DEG} is the temperature degradation factor, T_{NOC} is the normal operating condition temperature, T_{MOD} is the temperature of the module and MPTC is the maximum power temperature coefficient.

Equation 2 $Eff_{CELL} = (1-T_{DEG})*Eff_{NOC}$

Where Eff_{CELL} is the cell efficiency at a given module temperature and Eff_{NOC} is the Efficiency at Normal Operating Temperature.

Equation 3 $P_{DC} = I_P*Eff_{CELL}*A_{Arr}*Eff_{Arr}$

Where P_{DC} is the DC Power Out, I_P is the plane of array irradiance, A_{Arr} is the area of the solar array (including mechanical structure) and Eff_{Arr} accounts for the area of the array not containing photovoltaic material and other losses in the array.

Equation 4 $P_{AC} = P_{DC}*Eff_{INV}$

Where P_{AC} is AC Power Out and Eff_{INV} is the inverter efficiency. Eff_{INV} was calculated by numerically transposing an inverter efficiency graph to the computer from a printout. Eff_{INV} is 94% at array power output above 500 Watts and values less than 94% at lower power levels, determined by curve-fit equations.

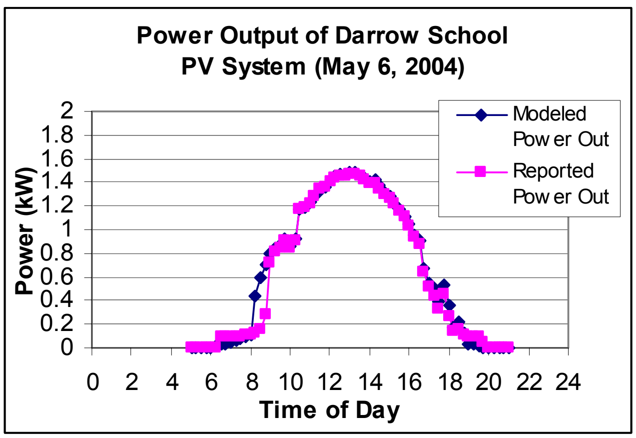

Fig. 1: Test of original model on system with low power output.

TABLE 1: PARAMETERS OF FIGURE 1

Array Area in m2 (A_{ARR})	19.458
NOC Temperature in deg C (T_{NOC})	45
Efficiency at T_{NOC} (Eff_{NOC})	8.9%
% eff loss per deg C (MPTC)	-0.5
Array Efficiency (Eff_{ARR})	90%

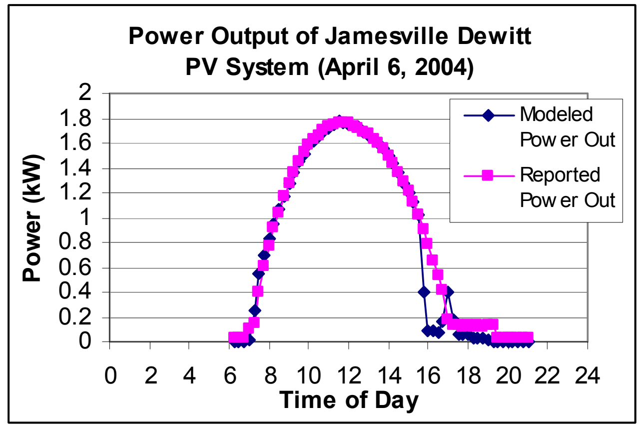

Fig. 2: Test of original model on system with high power output.

TABLE 2: PARAMETERS OF FIGURE 2

Array Area in m2 (A_{ARR})	19.458
NOC Temperature in deg C (T_{NOC})	45
Efficiency at T_{NOC} (Eff_{NOC})	10.5%
% eff loss per deg C (MPTC)	-0.5
Array Efficiency (Eff_{ARR})	98%

Both Figures 1 and 2 represent relatively good modeled curve fits. However, notice that in order to arrive at reasonable curve fits for the different schools, we needed to change the efficiencies of both the cells (Eff_{NOC}) and arrays (Eff_{ARR}). We would expect these parameters, like all the others, to be almost the same for both systems.

A desire to understand this seeming discrepancy between systems led us to the bulk of this paper.

3. DATA & METRICS

We analyzed the data from eight SPN systems – identical except in location. These are the eight systems that had at least 25 days of good data collected before November 1, 2004. We did not use data after October 31 because snowfall affects system output in unpredictable ways.

After exploring a variety of ways to analyze the data, we arrived at the following simple test: Array Efficiency vs. Module Temperature. The beauty of this metric is that it is independent of time-of-day, time-of-year and system size. It has some dependence on light level (irradiance), but mostly at lower light levels. Therefore, we limited our analysis to irradiance levels above 400 W/m2 to avoid this dependence.

Commonly used PV system design and modeling programs, such as PVSYST, calculate a predicted curve for Array Efficiency vs. Module Temperature based on the maximum power temperature coefficient (MPTC) and the standard operating temperature (SOT). For the Astropower (now GE) modules used in these systems the values of these parameters are MPTC = -0.5%/ºC and SOT = 25ºC. So, for an AP-100W module running at 10ºC above standard operating temperature, the module will have a maximum power reduction of 5W resulting in a maximum power output of 95W. If array efficiency (DC Power out)/(Irradiance x Area) is plotted versus module temperature using the above parameters, this yields a predicted equation of

$$y = -0.0512x + 11.523$$

which is graphed in Figure 3 . This is the baseline model to which we compare the actual system output data.

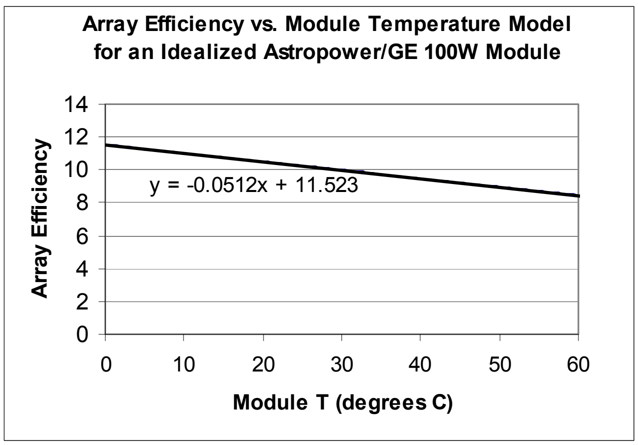

Fig. 3: Modeled Array Efficiency vs. Module Temp.

4. SYSTEM PERFORMANCE

We then graphed the data from each school in a similar fashion, and determined a linear fit. The results are in Table 3.

The variety in both slopes (from -0.0313 to -0.0618) and y-intercepts (from 9.91 to 12.26) is quite striking. Deviation from the "MODEL" line is in Table 4 below.

The results can be grouped into 4 categories:

A. Better than Predicted (Sites 16 and 23)
B. Close to Predicted (Sites 50 and 29)
C. Worse than Predicted in Colder Temperatures (Sites 39 and 24)
D. Worse than Predicted Always (Sites 18 and 48)

TABLE 4: % DEVIATION OF LINEAR FITS

Site ID	slope	% dev.	y-int.	% dev.
MODEL	*-0.0512*	--	*11.523*	--
16	-0.0362	29.3%	12.092	4.9%
18	-0.0326	36.3%	10.329	-10.4%
23	-0.0618	-20.7%	12.256	6.4%
24	-0.0313	38.9%	10.504	-8.8%
29	-0.0490	4.3%	11.441	-0.7%
39	-0.0322	37.1%	10.649	-7.6%
48	-0.0307	40.0%	9.9073	-14.0%
50	-0.0516	-0.8%	11.708	1.6%

TABLE 3: THE EIGHT SCHOOLS USED IN THE ANALYSIS

Site ID	School	Date Operational	Analyzed Dates	Array Eff. vs. Module Temp. Equation
MODEL	*IDEALIZED MODULE (GEPV100)*			*y = -0.0512x + 11.523*
16	Jamesville Dewitt MS	1/5/2004	9/4/04 – 10/31/04	y = -0.0362x + 12.092
18	Beaver River	4/2/2004	5/1/04 – 10/31/04	y = -0.0326x + 10.329
23	Canton Central School	9/23/2004	10/5/04 – 10/31/04	y = -0.0618x + 12.256
24	Carthage Central HS	8/12/2004	9/1/04 – 10/31/04	y = -0.0313x + 10.504
29	Dryden Junior Senior HS	6/9/2004	7/1/04 – 10/31/04	y = -0.0490x + 11.441
39	McGraw ES	8/11/2004	9/1/04 – 10/31/04	y = -0.0322x + 10.649
48	AA Kingston MS	7/23/2004	8/1/04 – 10/31/04	y = -0.0307x + 9.9073
50	Colonie Central HS	9/7/2004	9/7/04 – 10/18/04	y = -0.0516x + 11.708

In the following figures we show an example from each category.

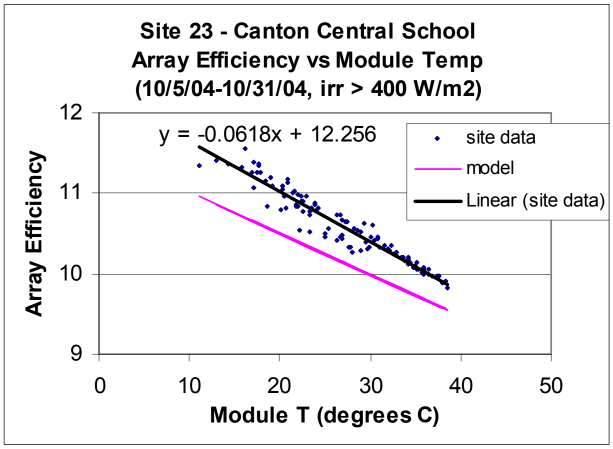

Fig. 4: Example of a Category A system.

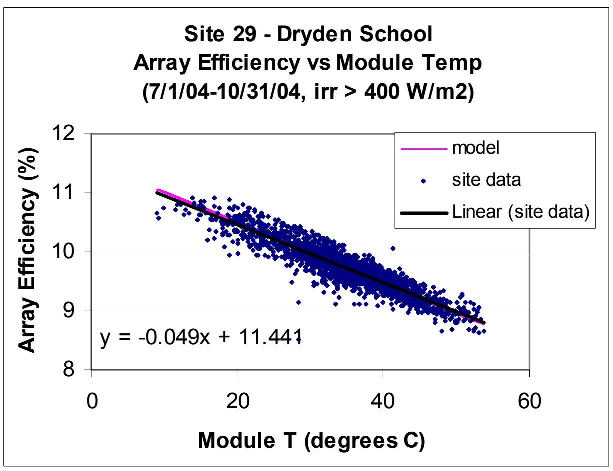

Fig. 5: Example of a Category B system.

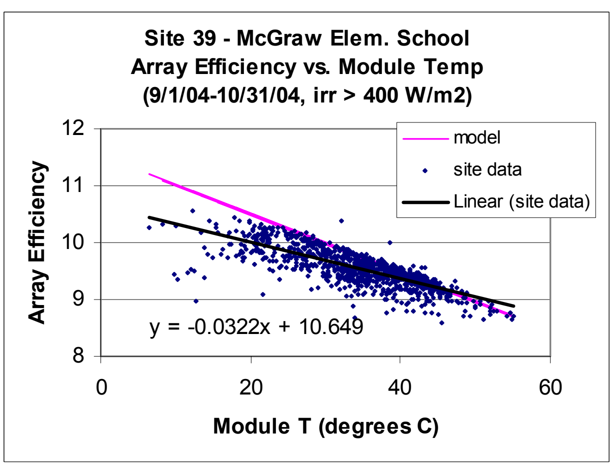

Fig. 6: Example of a Category C system.

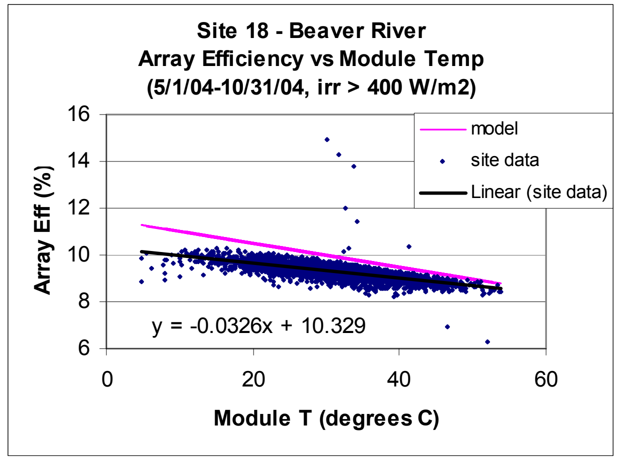

Fig. 7: Example of a Category D system.

All eight plots are graphed in Figure 8.

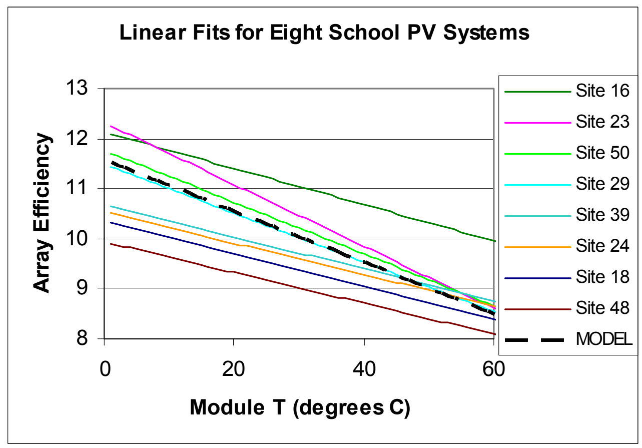

Fig. 8: A comparison of the performance of different 2kW PV systems with identical components.

5. POSSIBLE EXPLANATIONS FOR VARIATION BETWEEN SYSTEMS

We made the assumption that the irradiance measurement devices (pyranometers) are measuring plane-of-array irradiance, and furthermore, that no parts of the arrays are shaded when the pyranometers are not shaded. We also assumed proper calibrations of all equipment.

Therefore sources of variation include:

- if the pyranometers are measuring global irradiance, we need correction factors for angle and orientation of the modules
- shading (particularly on parts of array but not on pyranometer)
- measurement device calibration
- variations between modules, wiring and other system components

For example, a flat array installation might be expected to have the characteristics of Category C systems – lower output when the modules are cooler (i.e. in the morning and evening, when the sunlight is less strong coming from lower in the sky).

However, we also know, from communication with the systems installer, that Site 50 (Colonie) has a morning shading issue. This site nonetheless performed very close to the model. Additionally, Site 18 (Beaver River) actually has a 1.9 kW system instead of a 2.0 kW system – but this would only explain the system's reduced performance, as shown in Figure 7, if the array efficiency measurement were not calibrated to reflect the smaller system size.

6. CONCLUSIONS

The School Power… Naturally (SPN) data set provides a golden opportunity to study real world PV performance in great detail. Performance of the systems analyzed in this project varies widely. The metric of array efficiency vs. module temperature is a simple and effective way to measure system performance independent of most other factors. The wide range in performance is surprising. We hypothesize that is due largely to a combination of site-specific factors and data acquisition system calibration.

The addition of array orientation into the model would allow for better control of site specific factors that may be causing the wide range in performance. This would then reveal more accurately the variance due to equipment variation, system configuration and calibration. To do a more detailed analysis of all 50 SPN systems – using this and other metrics – would provide an invaluable resource for PV system modelers everywhere.

Furthermore, the test of PV system performance used in this paper is fairly simple and can be used on a small amount of output data. We propose that this may be a valuable addition to the SPN educational suite to teach students about scientific modeling and predicted versus actual performance of real world systems.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

(1) All school performance data used in this report is available at: http://www.sunviewer.net/portals/NYSERDA_SPN/

(2) Perez, R. et al., Experimental Evaluation of a Photovoltaic Simulation Program, Solar Energy, Vol. 52, No. 4, pp. 359-365, 1994 http://oink.asrc.cestm.albany.edu/~jim/perez/scannedPDFpapers/paper5.pdf