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### A REVIEW OF PV SYSTEM PERFORMANCE AND LIFE-CYCLE COSTS FOR THE SUNSMART SCHOOLS PROGRAM

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#### ABSTRACT

In January of 2003, the Florida Department of Environmental Protection/Florida Energy Office (DEP/FEO) allocated \$600,000 in hardware funds toward the installation of photovoltaic (PV) solar systems on Florida schools. As a result of this program, grid-connected PV systems less than six kilowatts in size were installed on 29 schools in the State of Florida. The Florida Solar Energy Center (FSEC) has monitored these systems for approximately one year of operation<sup>1</sup>. The performance of 28 of these systems was analyzed using standard performance parameters such as the performance ratio, PV array efficiency, inverter efficiency, and PV system efficiency<sup>2</sup>. In addition, a life-cycle cost analysis was conducted using new cost data values and updated market assumptions. These data will serve as a benchmark to compare against future systems with respect to performance vs. installed system cost.

#### INTRODUCTION

Performance and reliability data are key to assessing the status and needs of the technology, and feedback of this information to manufacturers, designers and integrators is critical to ensure growth and developments within industry. The objective of this research effort is to determine the current state of the industry in terms of component and system performance and cost. Using standardized metrics, these data serve as a benchmark that can be used to determine appropriate directions for research within the Solar Energy Technical Program<sup>3</sup>. By determining the performance and costs of PV systems installed today, the Department of Energy can learn where to spend its research dollars in the future.

#### PROCEDURE

Each PV system was installed with a Campbell 10X datalogger and appropriate transducers to monitor the following parameters: irradiance (LICOR), module

temperature (type T thermocouple), DC current (shunt) and voltage (voltage divider), and AC power output (watt-hour transducer). Data was collected at five-second intervals and stored as fifteen-minute averages. Data was stored in the datalogger and retrieved each day. The data was rigorously reviewed periodically for problems either with the equipment or the datalogger itself. Due to the hurricane season, several systems/dataloggers had to be repaired or reset due to damage. As a result, the data was appropriately screened so as not to include issues related to problems with the dataloggers.

Using a format utilized by IEA PVPS Task 2, Performance, Reliability, and Analysis of Photovoltaic Systems<sup>2</sup>, the raw data was converted into monthly averages and recorded as the following three variables:

- Hi: Monthly global irradiation, in array plane (kWh/m<sup>2</sup>)
- EII: Monthly DC energy input into the inverter (kWh)
- EIO: Monthly AC energy output from the inverter (kWh)

From those values, the following performance parameters were calculated:

- Performance Ratio (PR): This is a dimensionless number that is derived by dividing EIO by the product of the nominal rating of the of the PV array at standard test conditions (STC) and Hi. By multiplying PR by the STC rating of the PV array, one can calculate an equivalent AC power rating for the PV system at 1000 W/m<sup>2</sup>.
- Array Efficiency: This parameter is derived by dividing the PV array output by the product of Hi and the PV array area.
- Inverter Efficiency: This parameter is derived by dividing the inverter output (EIO) by the PV array input (EII).
- System Efficiency: This is the product of the PV array and inverter efficiencies.

# RESULTS

## IMPACTS ON PERFORMANCE

Table 1 below shows the average PR, array efficiency, inverter efficiency, system efficiency, and installed cost for these eighteen systems.

Table 1. System performance and cost averages for all systems.

Parameter	Average Result
PR	0.73
Array Efficiency	9.43%
Inverter Efficiency	90.9%
System Efficiency	8.58%
Installed Cost	\$7.97

Figures 1 through 4 show the distribution of each of the four calculated performance parameters as they vary from system to system as well as the average for all eighteen systems.

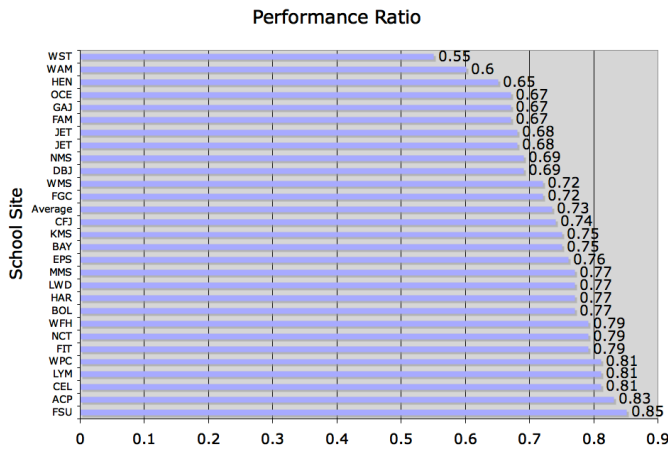


Figure 1. The calculated Performance Ratio (PR) from each of the systems as well as the overall average.

The system with the lowest output, WST, had problems with one of its two inverters. When the output of inverter reached close to 100% of its capacity, it would shut down. This problem is being investigated further. This issue affects the results found in both the PV array efficiency calculation (Figure 2) and the system efficiency calculation (Figure 4). Two other systems, WAM and HEN, both have battery systems with no maximum power point tracking. As a result, their performance ratio is lower as well.

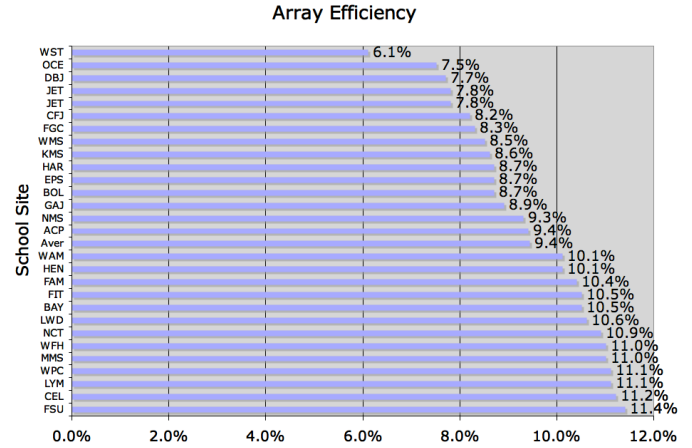


Figure 2. The calculated PV array efficiency from each of the systems as well as the overall average.

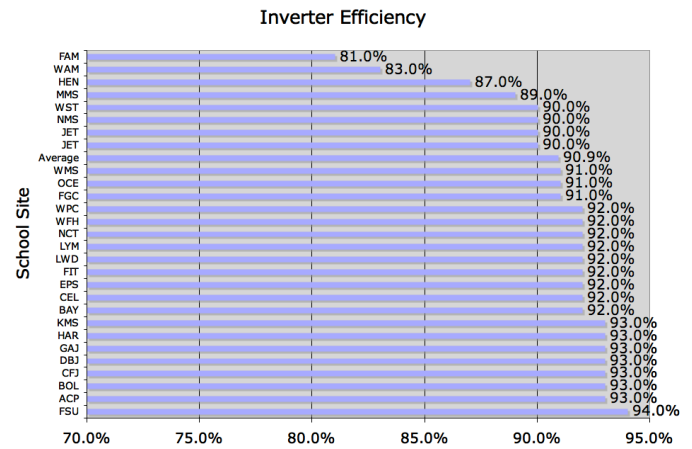


Figure 3. The calculated inverter efficiency from each of the systems as well as the overall average.

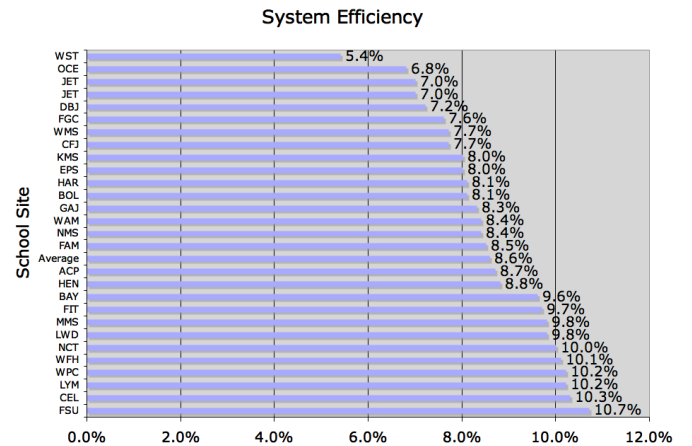


Figure 4. The calculated overall system efficiency from each of the systems as well as the overall average.

## IMPACT ON INSTALLED COSTS

In order to qualify for the subsidy program, contractors had to agree to itemize the price of the system paid by the customer. In Table 2 below<sup>4</sup>, the costs for all 29 systems are averaged and normalized in terms of dollars per watt.

Table 2. Average Cost Data for SunSmart Schools Program

Average Program Value	Value (\$/Watt)
Module Cost	4.31
Inverter Cost	1.00
BOS Cost	0.61
Installation Cost	1.73
Design Cost	0.50
Permit Cost	0.01
Warranty Cost	0.23
Total Average System Cost	7.97

The total average system cost for these systems includes all hardware costs as well as the cost of labor to install and design the system, permits and service warranty. Total hardware costs include module costs, inverter costs and Balance of System (BOS) costs. Each component value is averaged separately since a few installers sold packaged systems that didn't break down the hardware costs. This results in a total average value of greater than \$7.97 in the value column of Table 2 even though this is the calculated average system cost value.

It is relevant to note that the warranty cost is a pre-paid expense for a five-year period. Warrantees were required by the installer or vendor to participate in the program. Design costs were varied considerably from project to project depending on the level of standardization used. Sites using packaged designs may have required only minimal design work, thus skewing the average cost of design labor downward for the program. Permitting costs were generally insignificant for most sites.

IMPACT ON LIFE-CYCLE COSTS

A life cycle cost analysis, also sometimes referred to as a levelized energy cost analysis, was run using recent performance data from currently available systems. This technique used to conduct the LCC analysis was developed by Chris Larsen and the Florida Solar Energy Center and involves the use of Monte Carlo Technique to generate a range of values from a given mean value<sup>5</sup>. This technique assumes that each range is normally distributed and selects values within a certain number of standard deviations of the mean as specified by the analyst to generate the required data needed to complete a full life-cycle cost analysis. This allows the analyst to fill in data gaps for parameters that lack large quantities of data, but are essential to the LCC calculation.

When these values were compared with cost data acquired from systems installed prior to 2003, the overall average LCC value improved from 30.4 cents/kWh to 21.7 cents/kWh. (Larsen, Szaro, Wilson, 2003).

This reduction in average LCC was achieved primarily through changes in the competitive environment and improved equipment performance. The first major LCC savings occurred through a reduction in installed costs. Initial capital costs were reduced from an average installed cost of \$9.73 per nameplate Watt to \$7.97 per watt. This was due to slightly lower equipment costs, reduced labor hours for system installations and an increase in the number of available installers.

Table 3. Levelized Energy Cost Analysis

	Mean Total per kW	Mean Total per kWh	Stand Dev
System Life	24.4 years		5.4 yrs
Total kWh	30,535.66		6,386
Installed cost	\$8,077.95	\$0.28	\$0.095
Reliability/Maintenance costs	\$929.90	\$0.03	\$0.018
Maintenance contract	-	-	
Insurance	\$365.89	\$0.01	
Decommissioning	\$75.85	\$0.00	
Permitting	\$50.00	\$0.00	
<b>TOTAL Costs</b>	<b>\$9,499.59</b>	<b>\$0.33</b>	
Electric savings	(\$3,271.67)	(\$0.11)	\$0.003
Salvage	(\$45.53)	(0.00)	
<b>TOTAL Savings</b>	<b>(\$3,317.20)</b>	<b>(\$0.11)</b>	
<b>LCC</b>	<b>\$6,104.91</b>	<b>\$0.217</b>	<b>\$0.092</b>

The initial LCC study also assumed a dual metering compensation of \$.022 per kWh. Based on actual metering scenarios, this assumption appears to be inaccurate for the majority of sites. Net metering policies seemed more common with the majority of sites and the avoided cost of fuel had increased to \$.04 per kWh. Recent increases in electric rates contributed even more to the value of the system. The current average electric rate in Florida has recently increased by 20% to \$.12 per kWh up from a previous rate of \$.10 per kWh. Therefore, the rate of electricity price escalation was also increased based on new evidence that indicates a greater likelihood of higher energy prices in the near term. Additionally, the discount rate was decreased from 8% to 6% due to changes in world financial markets and U.S. inflation rates.

Finally, higher overall system efficiency and more reliable inverters generated more electricity, thus improving the overall average LCC. Performance data collected from this new set of PV systems showed an average system efficiency of 73% up from 70%. New cost data also revealed a drop in

the average inverter cost of \$.05. The mean time before failure (MTBF) for inverters being monitored through this program increased significantly over previous inverter models being used in system installations, thus greatly reduced O&M expenses and labor for these sites. FSEC design review activities also allowed for the detection of potential system deficiencies, leading to more streamlined and efficient mechanical and electrical designs.

FSEC expects to see further gains in the areas of installed costs, and improved system performance in future versions of this program.

## CONCLUSIONS

It is difficult to compare these performance and cost numbers to older systems. Systems installed in Florida in the late 1990's were fraught with problems, mainly with the inverter. Because of this, it was difficult to compile a complete year's worth of data comparable to the data collected on these eighteen systems. However, an average PR of 0.73 in a hot and humid climate is a good start. Setting a medium-term target for a PR of 0.80 would be a worthy goal for future systems. Florida has set aside additional subsidy funds this coming year for PV systems for schools. This will result in the collection of data from 25 more sites. It will be interesting to compare the results of those systems with the data collected here.

Progress has clearly been made in improving the LCC for PV systems installed in Florida since 1999, when this data collection effort first began. Installed costs have decreased by over 18% during this time period and average estimated LCC has been reduced by nearly 29%. Much of the additional reduction in LCC has been due to changing market conditions,

but technical improvements in PV component reliability has also contributed to achieving this cost savings. Issues that require further attention include better populating the FSEC database with additional installed cost data, and improving access to long-term operation and maintenance data. More sample points will limit the variability of the data, thus reducing spread and allowing the researchers to tighten current distribution curves for constructing the LCC analysis.

## ACKNOWLEDGMENTS

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- <sup>4</sup> K. Lynn, J. Szaro, "Identifying Key Issues in Implementing a Quality Solar For Schools Program," Proceedings of Solar 2004, A Solar Harvest: Growing Opportunities, American Solar Energy Society, Portland, OR, July 11-14, 2004.
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