

# Five Years of Residential Photovoltaic System Experience at Tucson Electric Power

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## ABSTRACT

Tucson Electric Power Company (TEP) is a U.S. utility leader in the early adoption of photovoltaic power generation with over 6.0 MWdc of grid-connected photovoltaic (PV) systems installed in its service territory since 2000. A significant element of the TEP photovoltaic effort is the SunShare PV hardware buy-down program that has been offered to TEP customers since 2001. During the past five years, 282 residential-size systems totaling 655 kWdc of crystalline silicon collectors have been installed in the Tucson area through SunShare. Much has been learned regarding performance, cost, maintenance, installation, and design of these systems. This article presents an assessment of these topics and a perspective associated with a family of systems within this PV program.

## INTRODUCTION

The Arizona Corporation Commission's Environmental Portfolio Standard (EPS) program has provided a significant stimulus for the construction and operation of renewable-resource energy generating

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capacity, particularly photovoltaic (PV) systems in the state of Arizona [1]. To support EPS, TEP has installed nearly 4.6 MWdc of utility- scale (system size > 100 kWdc) PV generation at the Springerville Generating Station Solar System in eastern Arizona, making this facility one of the largest PV generating plants in the world at the time of installation. The ongoing field experience with the cost, performance, and reliability of these fixed-orientation, ground-mounted, utility-scale systems has recently been documented [2]. In addition, 426 grid-tied systems (less than 15 kWdc in size) incorporating both crystalline and amorphous silicon collectors totaling 1172 kWdc have been installed in TEP's service territory [3]. Of these 426 systems, 282 are residential-size systems (less than 5 kWdc with a single inverter) that incorporate crystalline silicon collectors and were purchased by TEP residential customers through the SunShare program. The SunShare program allows TEP customers to install PV systems and receive an upfront payback from the utility to reduce the initial system cost. This article focuses on these 282 residential SunShare PV systems. A variety of manufacturers' commercially available PV modules and inverters are included in the SunShare systems. TEP's experience with these systems—including performance, cost, maintenance, installation, and design—is the topic of this article.

## TUCSON ELECTRIC POWER/SUNSHARE

Tucson Electric Power is the second-largest investor-owned utility in Arizona, providing electricity to nearly 400,000 residential, commercial and industrial metered customers in Tucson and surrounding areas in southeastern Arizona [4]. With about 2,350 MW of net generating capacity, TEP supplies most of the power it distributes. The company operates nearly 15,000 miles (24,135 km) of transmission and distribution lines throughout its service territory of 1,155 square miles (2991 square km). The utility is involved in a very active renewable energy program. Primarily focused on landfill gas and PV, the program also includes solar thermal electric, wind, biomass, and geothermal [5].

With the approval of the Arizona Corporation Commission, TEP began offering the SunShare hardware buy-down program in 2001. The program originally offered two options for customers to receive a buy-down subsidy on the purchase of a PV system [6]. A third option was approved and offered in 2003.



**Figure 1. SunShare Residential System**

Systems for each customer option must have a nameplate rating of at least 1200 Wdc and no more than 15 kWdc. To qualify, each must also be compliant with IEEE-929 (Recommended Practice for Utility Interface of Photovoltaic Systems) and the latest version of the National Electrical Code. Additionally, the inverter must meet UL-1741 (Power Conditioning Units for use in Residential Photovoltaic Power) and the PV modules must meet UL-1703 (Standard for Flat Plate Photovoltaic Modules and Panels). The inverter and modules must be covered by a non-prorated manufacturer's warranty of at least two years and 10 years, respectively. Each system must also meet TEP and Arizona Corporation Commission interconnection requirements for self-generation equipment.

### **Option 1**

Under this option, the customer can install any qualifying PV system. TEP will pay the owner \$2000 per kWac of installed generating capacity. All unscheduled maintenance labor and an annual service inspection will be provided by TEP at no cost to the customer through the end of 2012. TEP provides maintenance labor and troubleshooting while the owner is responsible for the cost of repair materials after warranty.

This report reflects the performance of 12 crystalline silicon systems installed through this option.

### **Option 2**

Under this option, the customer could purchase a packaged kit system from TEP to include PV modules, mounting hardware, inverter, meter and meter socket, and standard interconnection design documentation for a purchase price of \$4000 per kWdc of capacity. The customer was responsible for the installation. All unscheduled maintenance labor, an annual service inspection, and any labor for repairs or upgrades would be provided by TEP at no cost to the customer through the end of 2012. The owner would be responsible for the cost of repair materials. This report documents the performance of 157 crystalline silicon systems installed through this option. Option 2 was discontinued at the end of 2006.

### **Option 3**

This option is a direct hardware buy-down program whereby the customer may purchase an installed qualifying system on the open market and receive a rebate per rated kWdc (standard test conditions) of the system. The rebate is \$3000 per kWdc. The customer is responsible for all maintenance and repairs. TEP provides an annual inspection visit at no cost to the customer. This report documents the performance of 113 crystalline silicon systems installed through this option.

The field experiences with these 282 systems provides a treasure of information that not only establishes a baseline for today's state-of-the-art system capabilities, but also can help guide the development of PV system technology for the future. These are the reasons that TEP and Sandia National Laboratories entered into a collaborative effort to track, analyze and document the cost and field performance as well as operations and maintenance (O&M) experience associated with these systems.

## **DESIGN AND INSTALLATION EXPERIENCE**

These 282 systems include crystalline silicon PV modules of various sizes (typically rated at between 100 and 200 Wdc per module). Most of these modules were manufactured by BP Solar, but modules

from Kyocera, Sharp, Photowatt, Shell Solarworld, SunPower, and Schott are also represented. Likewise, while most of the inverters were Xantrex models, inverters from ASE America, Sharp, SunPower, SMA, and Fronius are also represented. The system designs and packages for options 1 and 3 represent the state-of-the-art capability for the US PV industry. The system design for option 2 is based on a standard packaged configuration developed through extensive testing conducted by TEP. All the systems are roof mounted on either flat or pitched roofs and in fixed south-facing configurations at or near latitude tilt of 32 degrees.

## SYSTEM PERFORMANCE

To describe the performance of these systems, the authors have chosen to utilize PV energy parameters that have been established by the International Energy Agency (IEA) Photovoltaic Power Systems Program as described in the IEC standard 61724 [7]. Three of the IEC standard 61724 system performance parameters—final yield, reference yield, and performance ratio—define the system field performance in terms of energy production, solar resource, and system losses. These provide an easily understood method to not only compare system performance with other system options but also to permit system owners/customers to determine if system performance is meeting expectations. This process has been proposed for wide-spread adoption here in the U.S. and the authors certainly support this effort [8].

### **Final Annual Yield (FAY)**

The final annual yield is the net ac energy output of the system divided by the aggregate nameplate power of the installed PV array at standard test conditions (STC) of 1000 W/m<sup>2</sup> solar irradiance and 25°C cell temperature.

$$\text{Final Annual Yield} = \text{kWhac/kWdc}$$

It represents the number of annual hours that the PV array would need to operate at its rated power to provide the same energy. All UL-listed modules require a nameplate on the back of the module that identifies the STC rated dc power. The aggregate array power can

easily be determined by summing the nameplate power ratings for the array.

The energy outputs of the SunShare systems were recorded on separate revenue grade utility meters for the PV generation. These kilowatt-hour meters have a tested accuracy of  $\pm 0.25$  percent. The PV meters are read and recorded every 6 months by TEP personnel. The homeowners are encouraged to also read the PV generation meter more frequently to help identify any problems with the systems that might require a TEP maintenance visit.

### **Reference Yield (RY)**

The reference yield is the total in-plane solar insolation ( $\text{kWh}/\text{m}^2$ ) divided by the array reference irradiance. It represents an equivalent number of hours at the reference irradiance. The reference irradiance is typically equal to  $1 \text{ kW}/\text{m}^2$ ; therefore, the reference yield is the number of peak sun-hours.

$$\text{Reference Yield} = \text{Total plane of array insolation}/1 \text{ kW}/\text{m}^2$$

The plane of array insolation for the SunShare systems was determined from total horizontal radiation measurements for Tucson from the Arizona Meteorological Network (AZMET) operated by the University of Arizona [9]. These data are recorded by a LiCor LI200 hourly each day. The instrument is calibrated annually against an Eppley Precision Spectral Pyranometer (PSP) radiometer for quality control. The total horizontal data are converted to plane of array insolation for a latitude tilt of 32 degrees.

### **Performance Ratio (PR)**

The performance ratio is the final yield divided by the reference yield and is dimensionless. It represents the total losses in the system when converting from nameplate dc rating to ac output. Typical system losses include dc wiring, module mismatch, bypass diodes, module temperature effects, inverter conversion efficiency, as well as others [10].

$$\text{Performance Ratio} = \text{Final Yield}/\text{Reference Yield}$$

These three performance metrics for the SunShare systems by year are shown in Table 1.

**Table 1. SunShare System Performance by Year**

YEAR	RY	FAY	PR
2003	2274	1444	0.64
2004	2332	1426	0.61
2005	2285	1440	0.63
2006	2330	1468	0.63
2007	2367	1557	0.66
5 YR AVG	2321	1467	0.63

## SYSTEM MAINTENANCE EXPERIENCE

For the past five years, Sandia has been working to develop a comprehensive database to track the lifecycle costs of PV systems [11]. This database, which continues to undergo improvements, was utilized to capture, document, and track scheduled and unscheduled maintenance service, repairs, replacements, and labor and travel costs associated with maintenance activities for these systems. Based on Microsoft Access, the database architecture is modular to support future additions. It supports associations at the component level, allows multiple components to be tracked with a system, and provides for multiple failures to be documented as a result of a maintenance visit. Failure modes (what and why), activity dates (failure and repair), and costs (labor, parts, and travel) were captured and analyzed from TEP system maintenance activity logs for the 169 option 1 and 2 systems covering the 5-year period of July, 2002, to October, 2007. From these data, analyses of failure modes and O&M costs were made.

Over the operating history from 2002 through 2007, a total of 330 maintenance events were recorded for the option 1 and 2 SunShare systems. The events included 30 unscheduled visits and 300 scheduled visits. The unscheduled events resulted in a loss of generating capacity and required human intervention to restore the system(s) to full operational capacity. These events could be as simple as a manual restart of a tripped inverter or considerably more complex such as the repair/replacement of a failed inverter. The 30 unscheduled events included three visits associated with the array and 27 visits for inverter problems. The 300 scheduled events included 134 general maintenance/inspection

visits, and 166 pre-acceptance visits required for systems to be accepted into the SunShare program. In many cases, these acceptance inspections identified installation as well as hardware problems and in large part are responsible for minimizing the unscheduled maintenance problems.

Through October 2007, the SunShare option 1 and 2 systems had provided 3337 system-months of continuous operation since installation. Over that same period, the total of 330 maintenance events provides a mean time between services per system of 10.1 months of operation. The maintenance cost per system-year of operation is \$226.

Table 2 lists the total annual maintenance cost by component and by year for the SunShare option 1 and 2 systems.

**Table 2. Total Maintenance Cost by Components**

<i>Year</i>	<i>Parts (\$)</i>	<i>Labor (\$)</i>	<i>Travel (\$)</i>	<i>Total (\$)</i>
2002	225	400	300	925
2003	3,000	950	650	4,600
2004	1,260	2,125	1,550	4,935
2005	0	2,600	2,500	5,100
2006	650	13,300	13,200	27,150
2007	1,475	9,300	9,300	20,075
Total	6,610	28,675	27,500	62,785

As noted in Table 2, the costs for labor and travel associated primarily with annually scheduled maintenance and system acceptance visits by TEP personnel account for nearly all the total maintenance costs for the systems. These annual maintenance visits are felt to be directly responsible for the very low number of unscheduled maintenance events experienced by the SunShare systems. A large number of the unscheduled visits were related to the replacement of 31 failed inverters from a major supplier in the January through October 2007 time period. These inverters were initially installed in 2007 systems, but a printed circuit board (PCB) problem led to early failures. They were replaced under warranty by the manufacturer after a determination that replacing the complete inverter was more cost efficient than just replacing the PCB. Labor and travel costs were incurred by TEP for these unscheduled events, and the supplier reimbursed TEP for these expenses.



The annual cost of maintenance as a percentage of the cumulative cost of systems installed for years 2002 through 2007 is presented in Table 3.

**Table 3. Annual Maintenance Cost as a Percentage of Total Installed System Cost**

<i>Year</i>	<i>Maintenance Cost (%)</i>
2002	1.43
2003	3.81
2004	1.23
2005	0.61
2006	1.12
2007	0.63

The average annual maintenance cost over the 5-year period is 1.47 percent of the initial installed capital cost of the system.

## SYSTEM COST EXPERIENCE

The 113 Option 3 SunShare systems installed from November 2002 through October 2007 and tracked in this report provide an industry market price for installed residential systems. The average price per year in 2007 dollars for these systems is shown in Figure 2.

A cost breakdown for the average of the 22 SunShare option 3 systems installed January through October 2007 is presented in Table 4. This breakdown was developed by the authors based on program documentation and private discussions with the system owners and system suppliers. The cost of the inverter is normalized by the size of the array and not by the inverter rated capacity.

### Energy Cost Figure-of-merit

The true measure for comparing different PV system options is the cost of delivered kWhac energy. To put the SunShare cost experience in perspective, the authors have utilized an energy cost figure-of-merit, defined as the average installed system cost (\$/kWdc) divided by the

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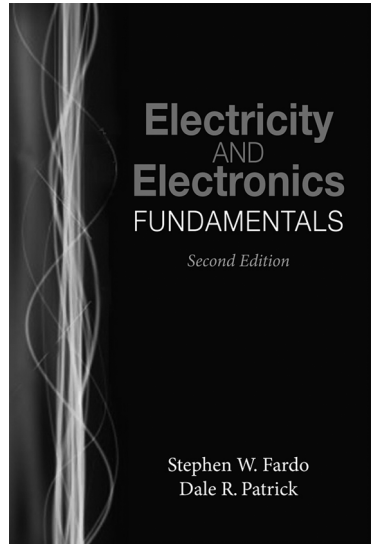
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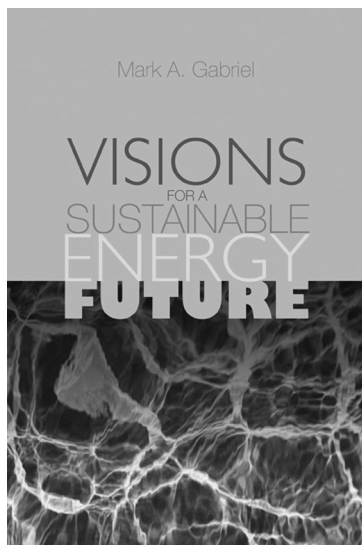
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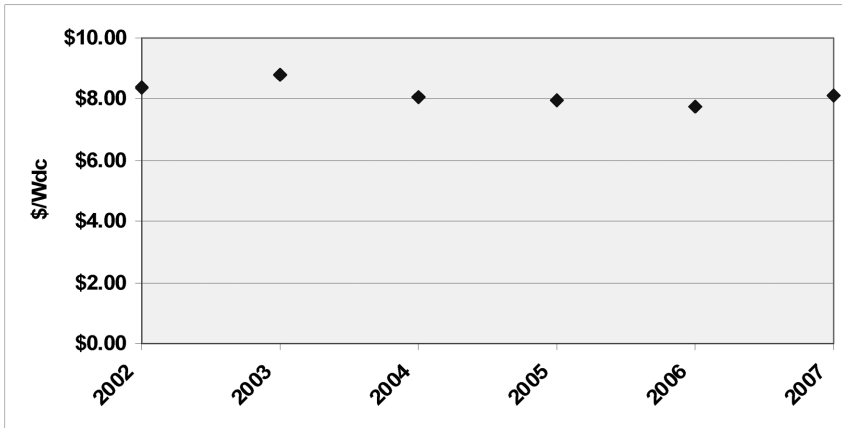


Figure 2. Installed System Cost by Year of Installation

Table 4. Cost Breakdown for 2007 SunShare Systems

<i>System Component</i>	<i>\$/Wdc</i>	<i>\$/Wac</i>
Modules	4.15	6.48
Inverter	1.01	1.58
Installation	2.96	4.63
Total	8.12	12.69

energy output (kWhac/kWdc) expected over a 30-year period. Although the resulting cost figure represents \$/kWhac, this figure does not include financing costs, the cost of capital, O&M costs, or any tax considerations and, thus, is not a levelized energy cost and is not portrayed as such. For 2007, this energy cost figure-of-merit is \$0.186/kWhac for the SunShare systems. It is interesting to note that the SunShare residential-size system energy cost figure-of-merit is \$0.086/kWhac higher than the comparable figures-of-merit of \$0.10/kWhac for large (>100 kW) fixed flat-plate systems installed by TEP at Springerville, AZ, and large one-axis tracking horizontal flat-plate systems installed by Arizona Public Service at Prescott, AZ. (2,12).

The energy cost of system O&M can also be described by a figure-of-merit defined as the annual cost of O&M divided by the annual energy output. As noted above, this is not a levelized energy cost.

But it does provide a perspective on the cost impact of maintenance experience with the SunShare systems. Using the average annual maintenance cost of 1.32 percent of installed system cost, the annual O&M energy cost is \$0.070/kWhac. This compares with an annual O&M energy cost of \$0.007/kWhac for the large Springerville systems, an order of magnitude lower.

### **SunShare Cost Perspective with Other State Programs**

To put the SunShare cost experience in perspective, residential system costs from two other large state-sponsored rebate programs were examined for comparison. The California Energy Commission (CEC) database represents a total of 2560 residential systems that were approved and installed in California during 2007 [13]. This database was modified to look only at those companies that installed more than one system per week, selected by the authors as indicative of a major system supplier. Nine industry members met this criterion, installing 1236 systems or 48 percent of the total. Furthermore, the CEC database was also modified to convert PTC ac watts to STC dc watts by normalizing with a conversion factor of 0.818 provided by CEC, allowing direct comparisons for installed costs in \$/Wdc. The nine companies had an average installed system cost of \$7.71/Wdc, ranging from a low of \$5.71/Wdc to a high of \$8.80/Wdc. The nine-company average cost compares very closely with the average installed system cost of \$7.90/Wdc for all 2560 systems.

Additionally, a residential system database for the state of New Jersey was also examined [14]. During the period from January through July of 2007, 68 systems with sizes less than 5 kW were installed by 29 companies. Five companies installed 30 of the systems or 44 percent of the total. The average installed system cost for these 30 systems is \$8.37/Wdc, ranging from a low of \$7.06/Wdc to a high of \$9.06/Wdc. The average installed cost for all 68 of the New Jersey systems is \$8.77/Wdc.

Comparing the SunShare system costs with that of both California and New Jersey shows somewhat similar installed costs for all three databases. While the SunShare average cost of \$8.12/Wdc for all systems installed in 2007 is slightly higher than that of \$7.90/Wdc for California, the New Jersey systems were the most expensive at \$8.77/Wdc.

## CONCLUSIONS

The energy data, system cost, and maintenance experience with the SunShare crystalline silicon systems provide a treasury of information that establishes a benchmark for current utility-intertied, residential-size PV systems. This article has identified a number of findings, including:

- Average annual ac system energy output over the 5 year period is 1467 kWhac per kWdc of array.
- Average annual ac system power over the 5 year period is 0.63 of the array dc nameplate rating.
- Average annual O&M cost is 1.47 percent of initial system installed cost.
- The mean time between maintenance services per system is 10.1 months of operation and the average maintenance cost per system-year of operation is \$226.
- A typical SunShare system installed in 2007 cost \$8.12/Wdc.
- A comparison with 2007 system costs in other state programs shows the SunShare costs for installed systems (\$8.12/Wdc) are higher than California (\$7.90/Wdc) but lower than New Jersey (\$8.77/Wdc).
- TEP's experience with PV generation demonstrates that the utility scale systems at Springerville, AZ, have substantially lower costs for installed system capacity and maintenance than the residential SunShare systems.

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## ABOUT THE AUTHOR

**Larry Moore** retired from Sandia National Laboratories in April 2008. Prior to that, he was program manager at Sandia National Laboratories for the rural utility photovoltaics program. He holds an undergraduate degree in mathematics and a graduate degree in physics from North Texas State University. Early in his career, Larry attended Texas A&M University for one year, studying meteorology as part of his military service. Following this time at Texas A&M, he worked as a weather forecaster for the Air Force at Patrick AFB and he also worked at Cape Canaveral Air Force Station in analytical chemistry,

conducting fuel and oxidizer analyses. Following his military service, he worked as an agricultural meteorologist for the National Weather Service. For the past 25 years, he specialized in critical infrastructure issues associated with weapons, weapon systems, explosives testing, and energy supply. His last 9 years have been spent in photovoltaic systems. His work in developing a reliability database for installed systems has been unique within the DOE program to establish lifecycle costs for viable applications. He has provided numerous workshops and presentations on photovoltaics to the rural electric community, published papers in *Progress in Photovoltaics* as well as *ASME* and *ASES* and was actively engaged in partnerships with several coops. While at Sandia, he headed the DOE/RUS interagency agreement to expand the use of renewable energy systems to the nation's rural communities. An important part of his work has been to review the Rural Business Service solar proposals since the inception of Farm Bill 2002. His outside interests include having an advanced class radio amateur license and working part-time for the New Mexico State Forest Service in the area of wildland firefighting.