

PHOTOVOLTAIC POWER PLANT EXPERIENCE AT TUCSON ELECTRIC POWER

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ABSTRACT

Tucson Electric Power Company (TEP) currently has nearly 5.0 MWdc of utility-scale grid-connected photovoltaic (PV) systems that have been installed in its service territory since 2000. Most of this installed PV capacity is in support of the Arizona Corporation Commission Environmental Portfolio Standard (EPS) goal that encourages TEP to generate 1.1% of its energy generation through renewable resources by 2007, with 60% of that amount from solar. The EPS program provides for multi-year, pay-as-you-go development of renewable energy, with kWhac energy production as a key program measurement. A total of 26 crystalline silicon collector systems, each rated at 135 kWdc, have been installed at the Springerville, AZ generating plant by TEP making this one of the largest PV plants in the world. These systems were installed in a standardized, cookie-cutter approach whereby each uses the same array field design, mounting hardware, electrical interconnection, and inverter unit. This approach has allowed TEP to achieve a total installed system cost of \$5.40/Wdc and a TEP-calculated leveled energy cost of \$0.10/kWhac for PV electrical generation. During this time, much has been learned regarding performance, cost, maintenance, installation and design. This paper presents an assessment of these topics and a perspective associated with this PV experience.

INTRODUCTION

The Arizona Corporation Commission Environmental Portfolio Standard (EPS) program has provided a significant stimulus for the construction and operation of renewable-resource energy generating capacity, particularly photovoltaic (PV) systems, in the state of Arizona [1]. Through EPS, nearly 10 MWdc of grid-connected PV are currently installed in Arizona, primarily by the state's two largest investor-owned utilities, Arizona Public Service (APS) and Tucson Electric Power. The EPS program provides for multi-year, pay-as-you-go development of renewable energy, with kWhac energy production as a key program measurement. The program has established a goal for Arizona's utilities that 1.1% of the energy

generation in the state, with 60% of that from solar, must be derived from renewable resources by 2007. To achieve that goal, upwards of 100 MWac of solar power systems will need to be installed in the state in addition to large quantities of non-solar renewable plants.

The vast majority of the state's installed generating capacity of utility-scale PV systems (100 kW and larger) utilizes flat-plate, crystalline-silicon collector technology. The APS experience has focused on one-axis, north-south oriented, horizontal tracking arrays [2]. The TEP systems incorporate standardized, fixed arrays. The TEP experience with these systems, including performance, cost, maintenance, installation, and design is the topic of this paper.

TUCSON ELECTRIC POWER

TEP is the second-largest investor owned utility in Arizona, providing electricity to nearly 370,000 residential, commercial and industrial customers in Tucson and surrounding areas in southeastern Arizona [3]. With about 2,000 MW of net generating capacity (primarily coal-fired), TEP supplies most of the power it distributes. The company operates nearly 15,000 miles of transmission and distribution lines throughout its service territory of 1,155 square miles. The utility is involved in a very active renewable energy program that directly supports the EPS initiative. Primarily focused on landfill gas and PV, the program also includes solar thermal electric, wind, biomass and geothermal [4].

The utility-scale PV generation effort is centered at the Springerville Generating Station Solar System in eastern Arizona. Shown in Figure 1, this facility, one of the largest PV generating plants in the world, includes 4.6 MWdc of installed



Figure 1. Springerville PV Generating Plant

PV systems. Covering 44 acres, this PV generating plant is grid-intertied with a 34.5-kV TEP transmission line. Although the Springerville plant includes other collector technologies including amorphous silicon and cadmium telluride, crystalline silicon accounts for nearly 80% of the plant’s capacity and is the focus of this paper. The field experiences with these systems provide 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

The 26 crystalline silicon systems at the Springerville plant are listed in Table 1. Each of these systems is an identical copy of a standardized array field configuration that utilizes the same hardware components, wiring topology, and structural mounting plan. The standard system configuration includes ASE Americas (now RWE Schott Solar) ASE-300-DG/50 modules and a Xantrex PV-150 inverter. The arrays are mounted at a fixed tilt of 34 degrees facing due south with 450 modules per array. Based on each system’s areal footprint of 300 feet north-south and 140 feet east-west, the system power density is 110.6 kWac per acre of ground. Each array string includes 9 modules with two strings per row. The power per string is 2.7 kW and the maximum string design voltage is 595 V at -22 degrees F. The operating voltage of each string is 380-430 volts. The Xantrex PV-150 inverter converts the variable voltage DC power to 208 volt 3 phase AC power. The inverters have a maximum rating of 157 kVA, at which point they will limit output or come off line, followed by an automatic restart. Each unit has a DC disconnect, 208 to 480 volt step-

up/isolation high efficiency transformer, revenue meter and AC disconnect. Groups of four units are connected in parallel to each of eleven 500 kVA 480 volt to 34,500 volt high efficiency step up transformers. Each transformer has a continuous rating of 500 kVA and can accommodate up to 650 kVA for brief intervals. The high voltage sides of the transformers are connected in parallel in a daisy chain configuration to a 34.5 kV underground distribution line which connects to the overhead 34.5 kV distribution line that feeds the well field pumps of the nearby 760 MW coal-fired Springerville Generating Station. The pumps operate continuously with an average load of about 6,000 kW.

Table 1. List of Springerville Crystalline Silicon Systems

System	Array Size (kWdc)	Install Date
SGS-135C-1	135	13-Jul-01
SGS-135C-2	135	13-Jul-01
SGS-135C-3	135	17-Aug-01
SGS-135C-4	135	2-Oct-01
SGS-135C-5	135	23-Oct-01
SGS-135C-6	135	14-Dec-01
SGS-135C-12	135	30-May-02
SGS-135C-7	135	1-Aug-02
SGS-135C-8	135	1-Aug-02
SGS-135C-9	135	1-Aug-02
SGS-135C-10	135	17-Sep-02
SGS-135C-11	135	24-Jun-02
SGS-135C-13	135	15-Jun-03
SGS-135C-14	135	15-Jul-03
SGS-135C-15	135	15-Jul-03
SGS-135C-16	135	30-Jul-03
SGS-135C-29	135	15-Oct-03
SGS-135C-30	135	30-Oct-03
SGS-135C-31	135	15-Aug-03
SGS-135C-32	135	30-Aug-03
SGS-135C-26	135	22-Jun-04
SGS-135C-27	135	22-Jun-04
SGS-135C-28	135	24-Jun-04
SGS-135C-23	135	20-Jul-04
SGS-135C-25	135	21-Jul-04
SGS-135C-24	135	23-Jul-04

The array configuration is designed to minimize the array-field balance-of-system (BOS) cost. The dual-stanchion array structural supports are fabricated steel with powder coating to minimize corrosion. The steel supports are staked to the ground to prevent wind-induced uplift and sliding. The site

preparation includes minimal surface disturbance/leveling of the natural terrain while retaining the native vegetation as much as possible to reduce surface erosion and to minimize dirt splash on the modules. Mounting of the arrays to the terrain may result in a slightly jagged array appearance along the row due to surface variations but the PV output effects are near zero. The array electrical interconnection uses 600-volt rated dc equipment and underground power distribution to minimize cost. Each system is installed exactly the same using a trained local labor pool. This standardized approach has resulted in a total system BOS cost of less than \$1.00/Wdc [5].

A Springerville system is shown in Figure 2. Note the white inverter enclosure at the back of the arrays near the center of the picture.



Figure 2. Typical 135 kWdc System

A close-up photo of the Xantrex PV-150 inverter and enclosure is shown in Figure 3.

SYSTEM PERFORMANCE

To describe the system performance of the Springerville 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 [6]. 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 [7].



Figure 3. Xantrex PV-150 System Inverter

The final 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/m² solar irradiance and 25°C cell temperature.

$$Final\ Yield = kWhac/kWdc$$

It represents the number of 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 average monthly final yield for all 26 Springerville systems over the 3 ½ year operating history is shown in Figure 4. The average annual final yield is 1673 kWhac/kWdc. The average final yield for 2004 is 1720 kWhac/kWdc.

The reference yield is the total in-plane solar insolation (kWh/m²) 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 kW/m²; therefore, the reference yield is the number of peak sun-hours.

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

The monthly reference yield for the Springerville arrays in 2004 is shown in Figure 5. The annual reference yield for 2004 is 2175 sun-hours.

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 [8].

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

The average monthly performance ratio for all the systems in 2004 is shown in Figure 6. The average annual performance ratio for all systems in 2004 is 0.79.

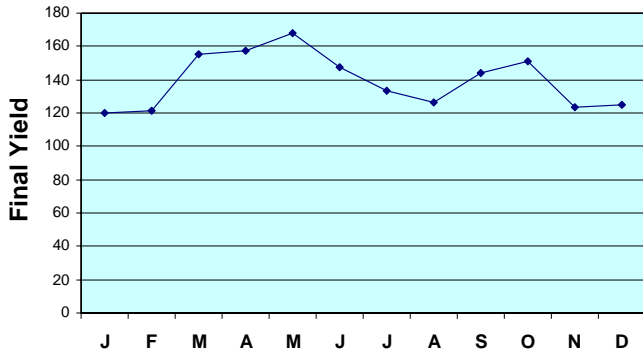


Figure 4. Average Monthly Final Yield for All Systems Over Operating History

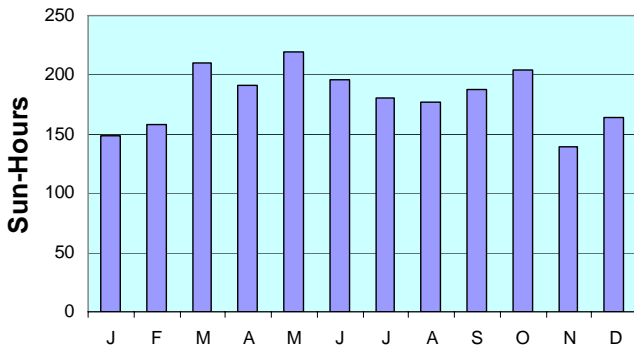


Figure 5. Monthly Reference Yield (Sun-Hours) for 2004

SYSTEM MAINTENANCE EXPERIENCE

For the past five years, Sandia has been working to develop a comprehensive database model to track the lifecycle costs of PV systems [9]. 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, allows 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

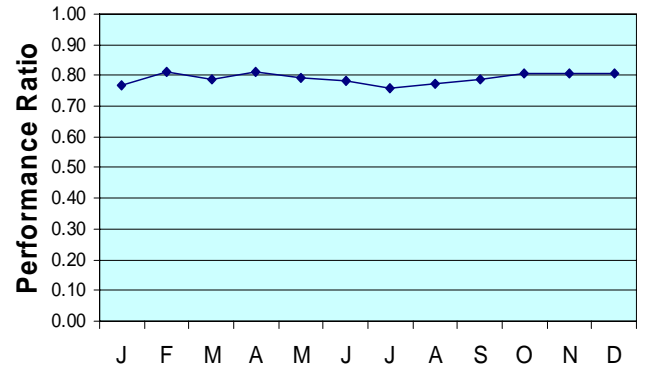


Figure 6. Average Monthly Performance Ratio for All Systems in 2004

(failure and repair), and costs (labor, parts, and travel) were captured and analyzed from system maintenance activity logs covering the period of mid-2001 through 2004. From these data, analyses of failure modes and O&M costs were made.

The Springerville systems provide a significant database for assessing the reliability and maintenance needs for a utility-scale generating plant operating in a utility environment. Altogether, a total of 11,700 identical PV modules and 26 identical inverters have been installed since mid-2001.

Over the operating history from mid-2001 through 2004, a total of 85 unscheduled maintenance events were recorded for Springerville systems. The events are grouped by categories including data acquisition systems (DAS), inverters, junction boxes, modules (PV) and systems. Figure 7 presents the breakdown of these events by component as a percentage of the total number of events.

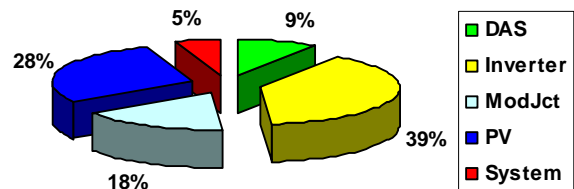


Figure 7. Unscheduled Maintenance Events by Component

The unscheduled events resulted in a loss of generating capacity that affected one or more systems 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 of damage resulting from a lighting strike (the plant experienced strikes in years 2003 and 2004). Figure 8 presents a breakdown of unscheduled events by component as a percentage of the total unscheduled repair costs. Through January 1, 2005, the 26 crystalline silicon Springerville systems had provided 582 system-months of continuous operation since installation. Over that same period, a total of 85 unscheduled maintenance events were recorded which provides a mean time between unscheduled service per system of 6.9 months of operation.

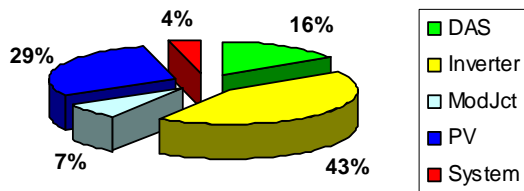


Figure 8. Unscheduled Maintenance Costs by Component

Scheduled maintenance was conducted on the plant each year. This included mowing the native vegetation as well as visual inspections of the arrays and power handling equipment. In 2004 the bolt torque settings on all current carrying connections were also checked. Table 2 lists the annual maintenance cost, both scheduled and unscheduled, as a percentage of the cumulative capital investment by year. The average annual maintenance costs since the initial Springerville installations are 0.16%.

Table 2. Maintenance Cost as a Percentage of Capital Investment

Year	Scheduled %	Unscheduled %	Total %
2002	0.08	0.01	0.09
2003	0.07	0.22	0.29
2004	0.06	0.05	0.11

While the above maintenance costs include unscheduled repair/service on the inverters, costs of inverter rebuild (anticipated every 10 years) are not included. Including this expense on an amortized basis is estimated to increase the annual maintenance cost by an additional 0.1 percentage point. Prior to 2004, software revisions were made allowing for remote resolution of most fault conditions, resulting in fewer unscheduled site visits in 2004. Daily performance analysis

tools pinpoint underperforming units allowing for timely resolution of problems with minimal lost energy production. Consequently, overall system effective availability was 99.78% in 2003 and 99.72% in 2004.

SYSTEM COST EXPERIENCE

Tucson Electric Power is realizing significant cost benefits by incorporating standardized products, volume purchasing and efficient array field design and installation. The Springerville experience has documented some of the lowest installed system costs ever reported thereby establishing a benchmark for state-of-the-art utility-scale systems. A cost breakdown for systems installed in 2004 is presented in Table 3.

Table 3. Cost Breakdown for Springerville Systems

System Component	\$/Wdc	\$/Wac
Modules	3.33	4.22
Array Field BOS	0.56	0.71
- Site Prep (\$0.10/Wdc)		
- Structure (\$0.15/Wdc)		
- Electrical (\$0.30/Wdc)		
- AC Intertie \$0.01/Wdc)		
Inverter/Transformers	0.40	0.51
Indirect/Overhead/Profit	1.11	1.40
Total	5.40	6.84

Modules

The module price reflects a bulk purchase from the module manufacturer.

Array Field Balance-of-System

The site preparation cost includes ground leveling, fencing and underground wiring. Structure cost includes mechanical mounting of the modules, support structure hardware and foundation staking. The electrical work includes module interconnect wiring, conduit, junction boxes for both the string and row buses, disconnect switches, system protection and wiring on the ac side of the inverter to the 480-V transformer and the DAS. The ac intertie cost includes the wiring and installation labor from the 480-V transformer to the 34.5-kV transformer.

Inverter/Transformers

This cost includes the purchase price of the Xantrex PV-150 inverter, the 208/480-V transformer for each system, and ¼ of the 480/34.5-kV transformer cost (each 34.5 transformer gathers 4 of the systems). Installation labor for these components is included.

Indirect/Overhead/Profit

Indirect costs include system design, procurement, construction management and project engineering. The overall project management for the Springerville installations is provided via contract by Tucson-based Global Solar Energy.

Energy Cost Figure-of-Merit

The true measure for comparing different PV system options is the cost of delivered kWhac energy. To put the Springerville 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 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 (note that levelized energy cost for TEP is addressed in the next section). For 2004, this energy cost figure-of-merit is \$0.10/kWhac for the Springerville systems. Interestingly, the Springerville energy cost figure-of-merit for fixed flat-plate systems is nearly identical to the energy cost figure-of-merit reported for one-axis, tracking horizontal flat-plate systems installed at Prescott, AZ [2].

ECONOMIC PERSPECTIVE

The experience at Springerville provides a valuable utility perspective on the future use and needs of PV technology. These include actual utility based energy generating costs, capacity factors and emission benefits associated with solar electric generation.

Energy Cost

The Solar Energy Industries Association (SEIA) recently announced a roadmap with established goals for expanding the use of solar power generating capacity here in the U.S. [10]. The roadmap goal over the next decade for PV systems is a selling price of \$3.68/Wac in 2015 and a cumulative installed U.S. capacity of 9.6 GW. Coupling the TEP cost experience at Springerville with this SEIA cost goal provides an interesting perspective for the future of PV. Table 4 presents a comparison of today’s benchmark system costs for Springerville and a proposed breakdown of a 2015 utility-scale PV system meeting the roadmap goal in today’s dollars.

Table 4. System Costs for the Future

System Component	Springerville System \$/Wdc	2015 System \$/Wdc
Modules	3.33	1.78
Array Field	0.56	0.58
Inverter	0.40	0.25
Fixed	1.11	0.30
Total	5.40	2.91

Using the Springerville performance ratio of 0.79, the \$3.68/Wac future system cost corresponds to an equivalent cost of \$2.91/Wdc. The 2015 system cost components follow a proposed breakdown developed elsewhere for a crystalline silicon system [8]. The 2015 module cost is based on a manufacturing cost analysis for a crystalline silicon production plant of 25 MW/year developed by Spire Corporation [11]. The proposed module cost is also consistent with crystalline silicon manufacturing cost projections developed through the US DOE Photovoltaic Manufacturing Technology (PVMaT) program [12]. While module costs and fixed costs require substantial cost reductions to achieve the 2015 goal, this comparison validates the creative system BOS approach developed by TEP at Springerville by already achieving the array field BOS target projected for the next decade. As annual PV installation quantities increase in future years it is expected that the fixed costs will be diluted over larger amounts of installed capacity and will be reduced on a \$ per Wdc basis.

The industry roadmap goal for 2015 is a levelized energy cost (LEC) of \$0.057/kWhac of PV generation. This compares to the TEP-calculated LEC in 2004 (pay-as-you-go, no financing costs) of \$0.096/kWhac for the Springerville PV generation [4]. The TEP calculation, which includes both federal income tax credits and state property tax reductions for solar, already meets the roadmap baseline 2015 LEC of \$0.115/kWhac.

Capacity Factor

The average monthly capacity factor for the Springerville systems over their operating history is presented in Figure 9. As presented here, the capacity factor is defined as the ratio of net electrical generation for the time considered to the energy that could have been generated if the system were generating at continuous full power during the same period.

$$Annual\ Capacity\ Factor = AnnualFinalYield/8760$$

The average annual capacity factor for all systems in 2004 was 19.2%.

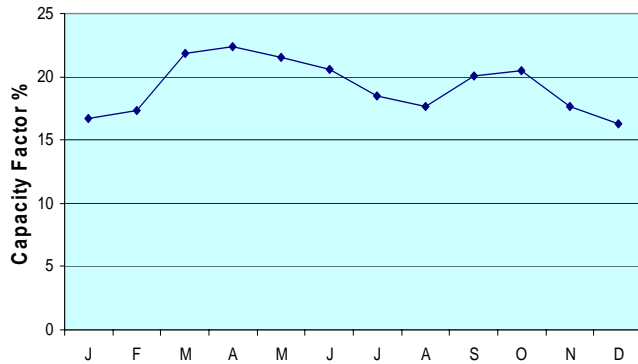


Figure 9. Average Monthly Capacity Factor for Springerville Systems

Energy Payback and Emission Reduction

A question often asked of PV generating plants is how long does it take to payback the energy required and emissions generated from fossil fuels to manufacture the PV system components. A study conducted by the Solar Hydrogen Education Project for the Springerville generating plant provides an insight into energy payback times as well emission mitigation associated with utility-scale PV systems [13]. The study found that the total energy embodied in the life cycle of the Springerville PV plant is 12,352 kWhac per kWdc of installed PV. The modules account for 88% of this embodied energy and the BOS accounts for the remaining 12%. The energy payback time for the Springerville systems is 2.8 years. The mitigation of greenhouse gases (GHG) through PV generation was also examined. The GHG - carbon dioxide, nitrous oxide and methane – are defined in terms of CO₂ equivalent emissions. The electricity produced by the Springerville plant over its 30-year life reduces GHG emissions by 36.5 tons of CO₂ equivalent emissions per kWdc of installed PV. This is a 91% reduction in GHG emissions compared to the electricity produced by a typical U.S. fossil-fueled power plant.

CONCLUSIONS

The Environmental Portfolio Standard program has proven to be a significant stimulus to increasing the installed capacity of PV systems in Arizona. The funds provided through the program have allowed TEP to install nearly 5 MW of PV systems since 2000, while the kWhac criterion has focused TEP's efforts on innovative, low-cost PV energy generation. The energy data, system cost, and maintenance experience with the Springerville crystalline silicon systems provide a treasury of information that establishes a benchmark for current utility-scale fixed flat-plate PV systems. This paper has identified a number of findings, including:

- Average annual ac system energy output in 2004 is 1720 kWhac per kWdc of array.
- Average annual ac system power in 2004 is 0.79 of the array dc nameplate rating.
- Innovative approaches including standardized array designs, low-cost array field BOS, and bulk hardware purchases have resulted in an installed system cost of \$5.40/Wdc.
- Average annual O&M cost is 0.16% of initial system installed capital cost, not including rebuild/replacement cost of the inverter.
- The mean time between unscheduled maintenance service per system is 6.9 months of operation.
- The average annual capacity factor for all systems in 2004 was 19.2%.
- The LEC cost calculated by TEP (no financing costs) is \$0.096/kWhac which meets the 2015 SEIA baseline goal for PV generation.

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