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Applications

Five Years of Operating Experience at a Large, Utility-scale Photovoltaic Generating Plant[Z]

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Tucson Electric Power Company (TEP), headquartered in Tucson, AZ, currently has nearly 5 0 MWdc of utility-scale grid-connected photovoltaic (PV) systems installed in its service territory. These systems have been installed through a multiyear, pay-as-you-go development of renewable energy, with kWhac energy production as a key program measurement. This PV capacity includes a total of 26 crystalline silicon collector systems, each rated at 135 kWdc for a total of 3 51 MWdc, that have been installed at the Springerville, AZ generating plant by TEP making this one of the largest PV plants in the world. This facility started operations in 2001 and recently passed the 5-year milestone of continuous operations. 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 levelized energy cost of $0 062/kWhac for PV electrical generation. This paper presents an assessment of operating experience including performance, costs, maintenance, and plant operation over this 5-year period making this one of the most detailed and complete databases of utility-scale PV systems available to the US DOE Program. Published in 2007 by John Wiley & Sons, Ltd.

KEY WORDS: large grid-connected PV systems; utility PV; field performance; cost; operation and maintenance; crystalline silicon

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INTRODUCTION

Over 12 MWdc of grid-connected photovoltaic (PV) systems are currently installed in Arizona, primarily by the state's two largest investor-owned utilities, Arizona Public Service (APS) and Tucson Electric Power Company (TEP). 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.[1] The TEP systems incorporate standardized, fixed arrays.[2] The 5 years of TEP operating experience with these systems, including performance, cost, maintenance, installation, and design is the topic of this paper.

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TEP

TEP is the second-largest investor-owned utility in Arizona, providing electricity to 392 000 residential, commercial, and industrial customers in Tucson and surrounding areas in southeastern Arizona.[3] With about 2350 MW of net generating capacity (primarily coal-fired), 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 1155 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.[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 PV systems. Covering 44 acres (17 8 hectares), this PV generating plant is grid-intertied with a 34 5-kV TEP distribution 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 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.

Figure 1. Springerville PV generating plant

DESIGN AND INSTALLATION EXPERIENCE

The 26 crystalline silicon systems at the Springerville plant are listed in Table I. 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.

Standard system configuration

The standard system configuration includes ASE Americas (now Schott Solar) ASE-300-DG/50 modules and a Xantrex PV150 inverter. The arrays are mounted at a fixed latitude tilt of 34° facing due south with 450 modules *per* array. Based on each system's areal footprint of 300 feet (91 m) north–south and 140 feet (43 m) east–west, the system power density is 110 6 kWac *per* acre (273 3 kWac *per* hectare) of ground, which allows for generous access space for construction and maintenance activities. Each array string includes nine 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°F

Table I. 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-13n-24	135	23-Jul-04

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(30°C). The operating voltage of each string is 380–430 V. The Xantrex PV150 inverter converts the variable voltage dc power to 208 V three-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. The maximum inverter rating was selected by TEP to accept increased output due to cloud edge enhancement and cold temperatures. These enhancements have at times exceeded 160 kW. In addition, the higher rating allows for normal operation to be in the optimum area of the efficiency curve and allows the inverters to run cooler extending lifetime. Each unit has a dc disconnect, 150 kVA 208–480 V step-up/isolation high efficiency transformer, revenue meter, and ac disconnect. Groups of four units are connected in parallel to each of 11 500 kVA 480–34 500 V 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 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 1160 MW coal-fired Springerville Generating Station. The pumps operate continuously with an average total load of about 9000 kW.

Instrumentation/testing

The Springerville PV generating plant is a normally unmanned site that is continuously monitored remotely via an internet-based communications channel. Most operational functions such as inverter reconfiguration, fault resets, IV curve tracing, diagnostic testing, and performance analyses can be performed from the remote monitor site via the internet communications channel. Fifty points of information are taken from each of the 26 inverters and the revenue meters on 10 s scan cycles and averaged for both 10 s and 1 min archiving. Performance information is developed from the raw data for daily review and archived in spreadsheet format by a control operator. Near real-time performance is available on the internet.[5] Alarm criteria have been developed for all operational parameters and these alarms are logged and maintenance personnel are notified in case of operation of any array or inverter that is out of specifications. Spare parts are available on site and local-based service personnel are dispatched to the site to perform repairs in response to alarms. Both test equipment and trained personnel are used to diagnose and repair problems in the system in addition to continued support from the inverter and module vendors. Test equipment consists of mostly traditional utility items. For these systems, a clamp on ammeter for dc and ac with a maximum range of 0–40 Amp and a separate clamp on ammeter for dc and ac with a range of 0–1000 Amp are used. At least one, preferably two, voltmeters with a dc and ac range to 1000 V and an integral ohmmeter is essential. An optical temperature sensor, frequency counter, and a dual trace oscilloscope with a range to 100 kHz are needed. Harmonic meter measurements and a three-phase power factor meter are helpful as well. Specifications for the inverters included þ/ 1% measurements of ac and dc current and voltage, ac frequency, and IGBT temperature as well as calculated values for ac and dc power. The PV150 can acquire all ac, dc, temperature, state of operation, and power parameters at a maximum rate of one sample set *per* second. The first six inverters were installed and data taken to confirm the þ/ 1% measurement accuracy. During the first year, these inverters were routinely checked for performance against calibrated test equipment. After the one-year period, the PV150 power production data are validated using the revenue grade utility meter on the output of the 480 V transformer. These kilowatt-hour meters have a tested accuracy of þ/ 0 25%.

For each of the identical 26 individual systems, there are 50 strings of nine modules for a system standard test conditions (STC) rated array nameplate power of 135 kWdc. Each string represents 2% of the rated individual system power. Individual string power degradation can be identified when a single module fails (*i.e.*, no current in the string) or the module voltage falls to 90% or less of a good module value (*i.e.*, low voltage cannot provide more than 50% expected current). A reduction in total array power output of 1% as compared to the output expected given solar insolation, temperature, wind speed, and wind direction can be accurately identified through the continuous performance evaluation monitors implemented in the software used for system supervision. Air temperature, wind speed, wind direction, and plane-of-array solar insolation measurements are monitored and recorded on 10 s intervals from three locations within the plant footprint. The three temperature sensors are all NRG, model 110 s with Radiation Shield with þ/ 0 6°F (þ/ 0 33°C) accuracy. Wind speed is measured at the three locations with an NRG Model #40 Anemometer with þ/ 0 2 mph (þ/ 0 32 kph) accuracy and wind direction is measured at the three locations by NRG Model #200p units, with an accuracy of þ/ 1%. There are three plane-of-array solar radiation sensors used so that cross-comparison is possible. These instruments are MSX-01 reference cells each using a single square polycrystalline cell with a 1 ohm resistor in parallel with the cell output, resulting in a solar insolation measurement that exhibits very little temperature sensitivity.

Balance-of-system (BOS)

The array configuration is designed to minimize the array-field 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 during rainstorms. Mounting of the arrays to the terrain may result in a slightly jagged array appearance along the row due to surface variations but the adverse PV output effects are near zero. The array electrical interconnection uses 600 V rated dc equipment and underground ac 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.[6] The energy payback time for the Springerville BOS has been documented at 0 21 years, a significant improvement over previous central plant designs.[7]

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.

A close-up photo of the Xantrex PV150 inverter and enclosure is shown in Figure 3.

Figure 2. Typical 135 kWdc system

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.[8] 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.[9] Since all 26 Springerville systems were totally operational beginning in 2004, average performance results are presented based on data from 2004 to 2006. In addition, specific annual results are noted for each of these 3 years as well.

Final yield

The final yield is the net ac energy output of the system divided by the aggregate nameplate power of the

Figure 3. Xantrex PV150 system inverter

installed PV array at an STC of $1000\,W/m^2$ solar irradiance and 25°C cell temperature.

Final yield ¼ 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 past 3 years is shown in Figure 4. The average annual final yield is 1707 kWhac/kWdc. The average final yields for the last 3 years, 2004, 2005, and 2006 are 1720, 1669, and 1731 kWhac/kWdc, respectively.

Reference yield

The reference yield is the total in-plane solar insolation (kWh/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 $1\,kW/m^2$; therefore, the reference yield is the number of peak sun-hours.

Reference yield

¼ Total plane of array insolation/$1\,kW/m^2$

The average monthly reference yield for the Springerville arrays over the last 3 years is shown in Figure 5. The average annual reference yield over this operating period is 2138 sun-hours. The annual reference yields for the last three years, 2004, 2005, and 2006 are 2175, 2054, and 2185 sun-hours, respectively.

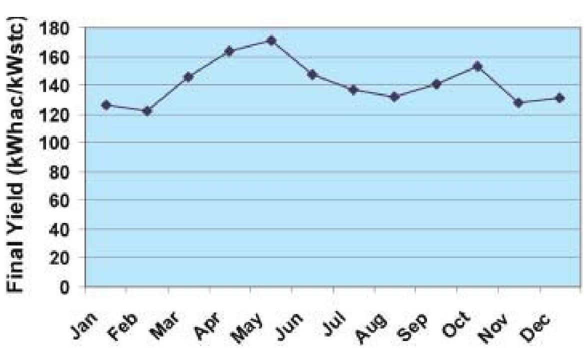

Figure 4. Average monthly final yield (kWhac/kWdc) for all systems

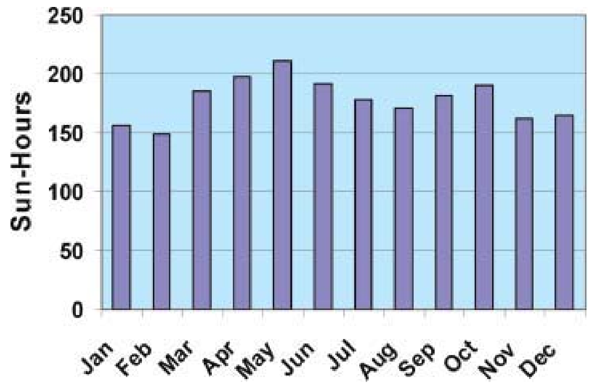

Figure 5. Average monthly reference yield (sun-hours)

Performance ratio

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]

Performance ratio ¼ Final yield/Reference yield

The average monthly performance ratio for all the systems is shown in Figure 6. The average annual performance ratio for all systems over this operating period is 0 79. The average annual performance ratios for all systems during the last 3 years, 2004, 2005, and 2006 are 0 78, 0 81, and 0 79, respectively.

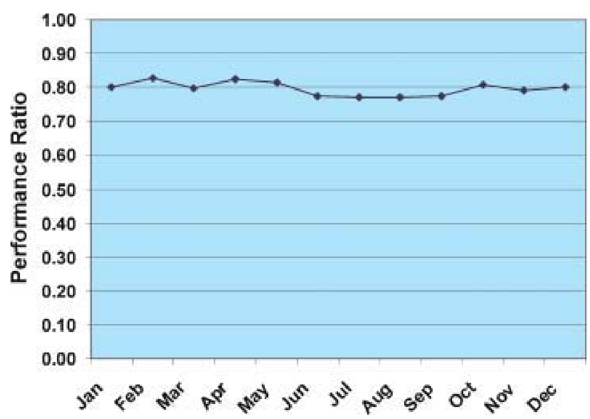

Figure 6. Average monthly performance ratio for all systems

SYSTEM MAINTENANCE EXPERIENCE

For the past several years, Sandia has been working to develop a comprehensive database model 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, 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 (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 2006. 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 2006, a total of 156 unscheduled maintenance events were recorded for the Springerville systems. The events are grouped by categories including data acquisition systems (DASs), inverters, junction boxes, arrays (PV), systems, and ac disconnects. Figure 7 presents the breakdown of these events by component as a percentage of the total number of events.

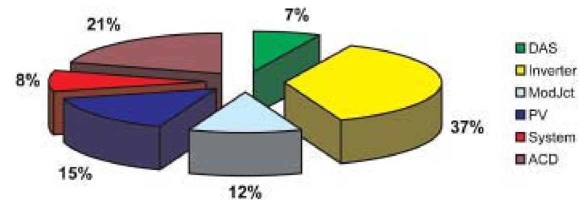

Figure 7. Unscheduled maintenance events by component

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 lightning strike (the plant experienced strikes in years 2003–2005). An examination of maintenance events by category provides some insight into just how exemplary the maintenance experience at Springerville has been. Over half of the 32 ac disconnect events were associated with high contact resistance in the 480 V outdoor rated fused disconnects. During 2006, the contacts for all Siemens brand 480 V disconnects were changed and the factory installed contact grease removed. The high-resistance problem appears to be due to dirt accumulation in the grease after 5 years of operation. Ten of the 11 failures associated with the DAS were all due to a severe 100 year lightning storm at the site in July 2003. That same storm caused 14 of the 58 problems with the inverters, 12 of which required replacing the PCU card. And, that same storm also accounted for eight of the 13 system events that involved replacing damaged utility meters. Many of the other inverter events were associated with manually resetting trips, a problem since avoided in 2004 when auto reset capabilities were added to the inverters. As for junction boxes, 11 of the 18 events were associated with replacing failed blocking diodes. Eleven of the 24 PV array events were associated with damage from another lightning storm in July 2004. In general, the reliability of the systems has been excellent and reliability of the primary PV components, modules and inverters, has been impressive.

Figure 8 presents a breakdown of unscheduled events by component as a percentage of the total unscheduled repair costs. As noted, the majority of the repair costs are associated with the inverters. A more detailed examination of the unscheduled inverter events provides a real-world perspective of the maintenance expectations in a utility environment. A breakdown of inverter events by repair category is presented in Figure 9.

The categories refer to the inverter operation. Controller includes those functions and circuit components necessary to control the power conversion

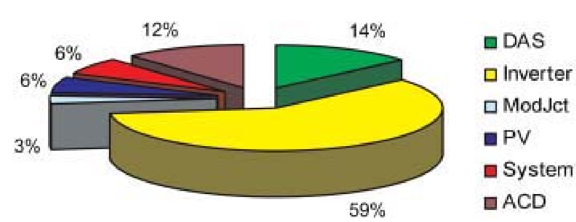

Figure 8. Unscheduled maintenance costs by category

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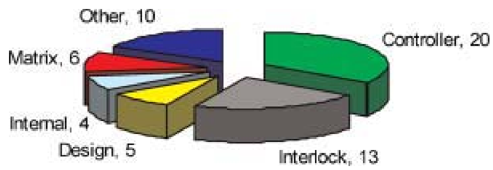

Figure 9. Inverter repairs by events and category

and protective devices. Interlock refers to the dc disconnect and door interlock alarm circuitry. Design includes cabinet weather protection. Internal refers to fault conditions within the inverter not otherwise identified. Matrix is the power electronic inverter bridge and associated switching transistors, capacitor bank, heat sink, and cooling fans. Other captures those events such as wiring and contactor problems, inoperative switches, and unknown events that signal a fault condition. As noted earlier, 12 of the 20 controller events involved the replacement of PCU cards and the addition of enhanced lightning protection due to the July 2003 lightning strike. This enhanced protection involved the addition of lightning arrestors and associated surge-resistant components in many areas of the data collection system and on the 480 voltmeter of every inverter. The other eight events primarily involved PCU card replacements due to failures and/or intermittent problems. The interlock events were all associated with dc disconnect faults ranging from connector problems and nesting rodents to unknown causes. The five design events included faults due to one roasted spider, one roasted rodent, two cases of rain, and one case of blowing snow ingress into the cabinet. Improved gasket placement has solved those problems. In each case, the internal events involved an inoperative inverter with no obvious problem that responded to a restart. The six matrix events involved two cases of matrix failure and replacement, two cases of temperature sensor failure and replacement, one case of fan assembly and motor failure and replacement, and one unknown cause of high temperature alarm on the heat sink. The 10 other events involved loose connections, replacement of switches, a failed front panel, wiring problems, and unknown causes. Although not trouble free, the 26 inverters have provided an enviable maintenance record especially in the context of other documented inverter field performance problems.[12–14]

Through 1 January 2007, the 26 crystalline silicon Springerville systems had provided 1206 system-months of continuous operation since installation. Over that same period, a total of 156 unscheduled maintenance events were recorded which provides a mean time between unscheduled services *per* system of 7 7 months of operation.

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. Table II 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 12% of initial capital cost. 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. Daily performance analysis tools pinpoint underperforming units thus allowing for timely resolution of problems with minimal lost energy production. Consequently, overall system effective availability for years 2002, 2003, 2004, 2005, and 2006 is 99 43, 99 78, 99 72, 99 81, and 99 75%, respectively, quite high for any generating technology. (Lightning created problems in 2003 were not included as performance reductions. They were in 2004 and 2005.)

SYSTEM COST EXPERIENCE

TEP 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 (the last year for system installations at Springerville) is presented in Table III.

Table II. 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 04	0 10
2005	0 06	0 01	0 07
2006	0 04	0 03	0 07

Table III. Cost breakdown for Springerville systems

System component	$/Wdc	$/Wac
Modules	3 33	4 22
Array field BOS	0 56	0 71
Site preparation ($0 10/Wdc)		
Structure ($0 15/Wdc)		
Electrical ($0 30/Wdc)		
ac Intertie $0 01/Wdc)		
Inverter/transformers	0 40	0 51
Indirect/overhead	1 11	1 40
Total	5 40	6 84

Modules

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

Array field BOS

The site preparation cost includes ground leveling, fencing, and underground wiring. Structure cost includes mechanical mounting of the modules, support structure hardware, and 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 to the 34 5-kV transformer.

Inverter/transformers

This cost includes the purchase price of the Xantrex PV150 inverter, the 150 kVA 208/480-V transformer for each system, and one-fourth of the 480/34 5 kV transformer cost (each 34 5 kV transformer gathers four of the systems). Installation labor for these components is included.

Indirect/overhead

Indirect costs include system design, procurement, construction management, and project engineering. The overall project management for the Springerville installations was 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 (LEC) and is not portrayed as such (note that LEC for TEP is addressed in the next section). Using 2004 system costs, 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] It is also interesting to note the significant energy cost figure-of-merit difference between the utility-scale Springerville systems and residential systems. A total of 82 SunShare residential systems have been installed in the TEP service territory during the past few years and are being tracked by TEP and Sandia for performance, cost, and maintenance experience.[15] These residential-size systems range from 1 2 to 5 9 kWdc. Using the average installed cost for these systems in 2004 of $7 32/Wdc and an average annual final yield of 1398 kWhac/kWdc provides an energy cost of $0 175/kWhac for the residential systems, significantly higher than the utility scale option.

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 LEC but it does provide a perspective on the cost impact of maintenance experience with the Springerville systems. Using the average annual maintenance cost of 0 12% of installed capital cost, the annual O&M energy cost is $0 004/kWhac. Including the expected inverter rebuild costs increases the annual O&M energy cost to $0 007/kWhac. Considering the SunShare residential systems noted above and using the average annual maintenance cost of 1 7% of installed system cost provides a comparative annual O&M energy cost of $0 089/kWhac, an order of magnitude higher than the utility-scale systems.

ECONOMIC PERSPECTIVE

The experience at Springerville provides a valuable utility perspective on the future use and needs of PV

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technology. These include actual utility-based energy generating costs, capacity factors, and operational aspects associated with solar electric generation.

Energy cost

The Solar Energy Industries Association (SEIA) has provided a roadmap with established goals for expanding the use of solar power generating capacity here in the U.S.[16] It is of interest to note that a photo of the Springerville systems is featured in this roadmap document. 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 IV 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. 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.[10] 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.[17] The proposed module cost is also consistent with crystalline silicon manufacturing cost projections developed through the US DOE Photovoltaic Manufacturing Technology (PVMaT) program.[18] 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.

Table IV. 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

The industry roadmap goal for 2015 is a LEC of $0 057/kWhac of PV generation. This compares to the TEP-calculated LEC in 2006 (pay-as-you-go, no financing costs) of $0 062/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. It is important to note again that the TEP strategic plan to incorporate solar generation in its service territory is focused on pay-as-you-go funding to avoid the high costs of financing. The attractive TEP-calculated LEC for this facility is a direct result of this approach.

Capacity factor

The average monthly capacity factor for the Springerville systems over their operating history is presented in Figure 10. 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 ¼ Annual final yield/8760

The average annual capacity factor for all systems over the 5-year operating period was 19 5%.

Operational aspects – Capacity credit

An issue of concern with the Springerville systems as well as other utility-scale PV systems is capacity value. Cloud passages over the 44 acre (17 8 hectares) site have been observed by TEP to result in uncontrolled oscillations in the boiler-turbine controls at the nearby Springerville coal fired plant when that unit is being used for regulation in Automatic Generation Control (AGC) mode. These instabilities require a switch to

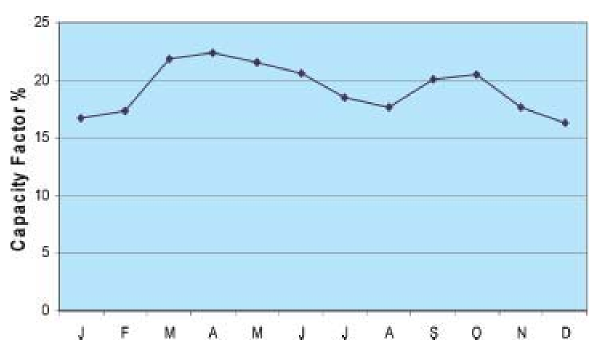

Figure 10. Average monthly capacity factor for Springerville systems

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manual mode and dispatch control to regulate with a different, less responsive and less-efficient unit elsewhere on the system in AGC. To put this in perspective, the two 400 MW coal-fired plants located nearby are electrically connected in the 345 kV switchyard to the 4 6 MW PV plant. When in AGC, the controls are set to respond to changing power output levels to keep the balance between generation and load to within 0 5 MW. With cloud passages, the changes in output of the solar units are so rapid – ramps of up to 1 36 MW in 10 s – which the controls of the coal units cannot follow accurately. Then 10 s later the solar output will change direction and the coal unit controls try to adjust to that new change. After a short time the coal plant controls are in a mode of uncontrolled oscillations and must be put into manual mode.

These instabilities in the control system associated with solar generation can lead to low capacity credit, an unfriendly situation for utilities and the use of PV. TEP and the DOE Program are looking at intelligent inverters/energy storage as a means to smooth out these generation intermittencies to improve capacity credit although this work is in its early stages.

CONCLUSIONS

The energy data, maintenance experience, and costs with the Springerville crystalline silicon systems provide a treasury of information that establishes a benchmark for current utility-scale fixed flat-plate PV systems technology. This operating assessment has identified a number of findings, including:

Average annual ac system energy output is 1707 kWhac *per* kWdc of array.

Average annual ac system power is 0 79 of the array dc nameplate rating.

Average annual O&M cost is 0 12% of initial system installed capital cost, not including rebuild/replacement cost of the inverter.

The mean time between unscheduled maintenance services *per* system is 7 7 months of operation.

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.

The average annual capacity factor for all systems was 19 5%.

The LEC cost calculated by TEP (no financing costs) is $0 062/kWhac which meets the 2015 SEIA baseline goal for PV generation.

Control instabilities associated with cloud passage over the PV plant require further efforts including possibly smart inverters and/or storage to smooth these generation transients and improve capacity credit for PV generation.

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