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PHOTOVOLTAIC LIGHTING SYSTEM PERFORMANCE

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ABSTRACT

The performance of 21 PV-powered low pressure sodium lighting systems on a multi-use pathway has been documented in this paper. Specific areas for evaluation include the vandal resistant PV modules, constant voltage and on/off PV charge controllers, flooded deep-cycle lead-antimony and valve regulated lead-acid (VRLA) gel batteries, and low pressure sodium ballasts and lights. The PV lighting system maintenance intervals and lessons learned have been documented over the past 2.5-years. The above performance data has shown that with careful hardware selection, installation, and maintenance intervals the PV lighting systems will operate reliability.

INTRODUCTION

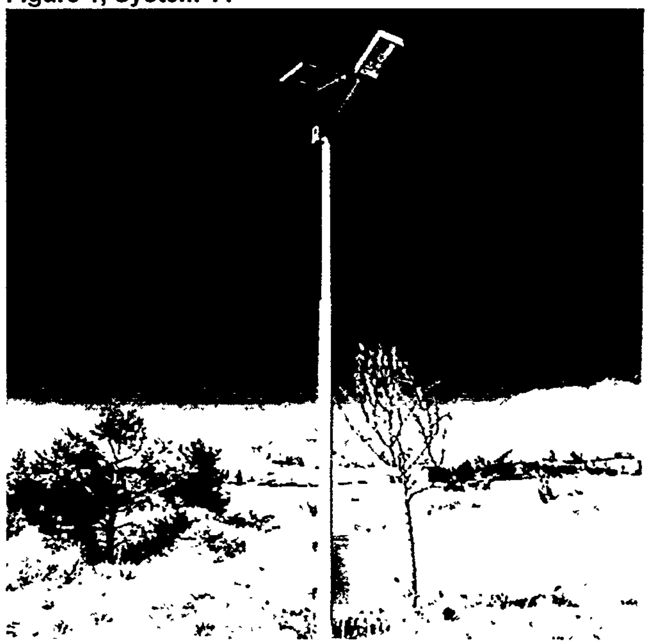
PV lighting systems for municipalities represents one of the largest cost effective markets for PV now. The installation cost of just one or two utility power poles can justify the initial cost of a PV lighting system. Many previous PV lighting systems have experienced a number of component failures including premature charge controller, battery, and ballast/luminaire failures. Vandalism is also a failure mechanism that needs to be considered when purchasing hardware. [1] This paper documents how 21 well designed PV lighting systems operated with the presently available balance of systems (BOS) hardware.

The Parks and Recreation Department of the City of Albuquerque installed 21 PV-powered area lighting systems on a multi-use pathway (Figure 1). The initial Installation of 21 lighting systems was formally completed in late August 1991. The systems experienced a number of problems shortly after installation such that only six systems were operational after 8-months. The Photovoltaic Design Assistance Center (PVDAC) at Sandia was asked by the city to assess system status and monitor implementation of system refurbishment. The systems were refurbished by the city in the fall of 1993, which resulted in functioning lights for the city and a collaborative field test site for Sandia's PVDAC and the city to evaluate BOS components.

SYSTEM DESIGN

In April 1992, systems 11 & 12 were refitted with new gel valve regulated lead-acid (VRLA) batteries (2-JCI Dynasty 6v200b). System 11 batteries were installed with a constant voltage PV charging and lighting controller (Polar Products/SLC 12-06-BTHU, Vr=14.1v)

Figure 1, System 11



and system 12 batteries were installed with an on/off PV charging and lighting controller (SunAmp PBRT 12-15A, Vr=14.2v). Systems 1-10 & 13-21 were refitted in September 1993 with new flooded deep-cycle lead-antimony batteries (2-Trojan T105 6v @ 217 AH). Systems 1-10 were installed with the same Polar Products constant voltage PV charge and lighting controllers using a regulation voltage (Vr) of 14.4 volts and systems 13-21 were installed with the same SunAmp on/off PV charge and lighting controllers using a Vr of 14.7 volts and a regulation voltage hysteresis (Vrh) of 0.8 to 1.0 volts. All Vr setpoints are referenced to 25^{o}C and all systems had a low voltage disconnect (LVD) of 11.4 volts. Both controllers are temperature compensated and have integral lighting timer functions using the PV array to sense dusk. After installation all systems were tested for proper operation.

Installation of dataloggers on selected systems was implemented to increase understanding of PV lighting system operation. Previous testing and evaluation of charge controllers and batteries at Sandia and the Florida Solar Energy Center provided insight into recommended set-points for charging flooded lead-antimony batteries.[2,3].

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The above systems provided a sample size with statistical significance to verify the conclusions of those previous tests.

BOS COMPONENTS

During the fall 1993 refurbishment, all the lamps were changed out and the old ones were saved as spares by the city. Lamp ballasts were not changed due to the expense and the long lead time encountered for orders. The original components are listed below. A single crew from the City Parks & Rec. Dept. changed out all the components and became well versed in DC wiring and photovoltaic lighting systems.

Original components used by all systems include:

- 2-Photocomm DV-50 PV modules - (vandal resistant with aluminum back substrate and Tefzel® top film, rated by Photocomm @ 50 watt ea.)
- 1-Zomeworks FRPT02/DV array mount
- Western Lighting Lumistar 35-watt LPS Lamp
- Bodine 12LPS35E ballast, 3.2A @ 12vdc with output at 360ma @ 19 kHz, 80v operating voltage
- Junction box, NEMA 3R
- 6 Hydrocaps®/system
- 1-Zomeworks Cool Cell™
- Zomeworks 2 piece pole (pole and lamp arm) 20 feet tall

SYSTEM ENERGY MANAGEMENT

The above PV lighting systems are designed to operate for 6-hrs per night providing power for a total load of about 19.2 amp-hours (Ah). Using $PVCAD_{tm}$[4] to establish available array Ah at 45° tilt, the minimum calculated array to load ratio for the above systems in Albuquerque is 1.27 in December. The array to load ratio is an important parameter in PV system design because it indicates how quickly the system is capable of recovering from a deficit charge period (previous night's discharge with below normal recharge). Array to load ratio also determines how much charge current will be available to compensate for battery and charge controller inefficiencies

SYSTEM EVALUATION

Batteries And Charge Controllers

After receiving the batteries from the local supplier, a boost charge before installation per the manufacturer's recommendations was conducted (14.4 volts for 10 hrs, JCI gel VRLA - and 15.3 volts for 3 hours, Trojan T-105 flooded). A 38% increase in capacity was observed after the boost charge procedure on flooded batteries. After the boost charge, capacity was between 180 and 220 Ah for the flooded batteries. It is unlikely the batteries would have reached that capacity if installed without the boost charge. Considering the low currents and voltages involved in PV lighting systems, the batteries may have never recovered the capacity lost from self-discharge that normally occurs during shipping and storage.

After 18-months, there was one battery failure on system 10 due to unknown causes. It was replaced with new T-105's. The specific gravity of batteries charged using constant voltage charging averaged 1.261 and ranged from 1.240 to 1.279. The specific gravity of batteries charged using on/off charging averaged 1.254 and ranged from 1.230 to 1.285. Manufacturers specifications for specific gravity at a full state of charge is 1.277. Battery state-of-charge based on specific gravity appears to be slightly higher using the constant voltage charge controller setting.

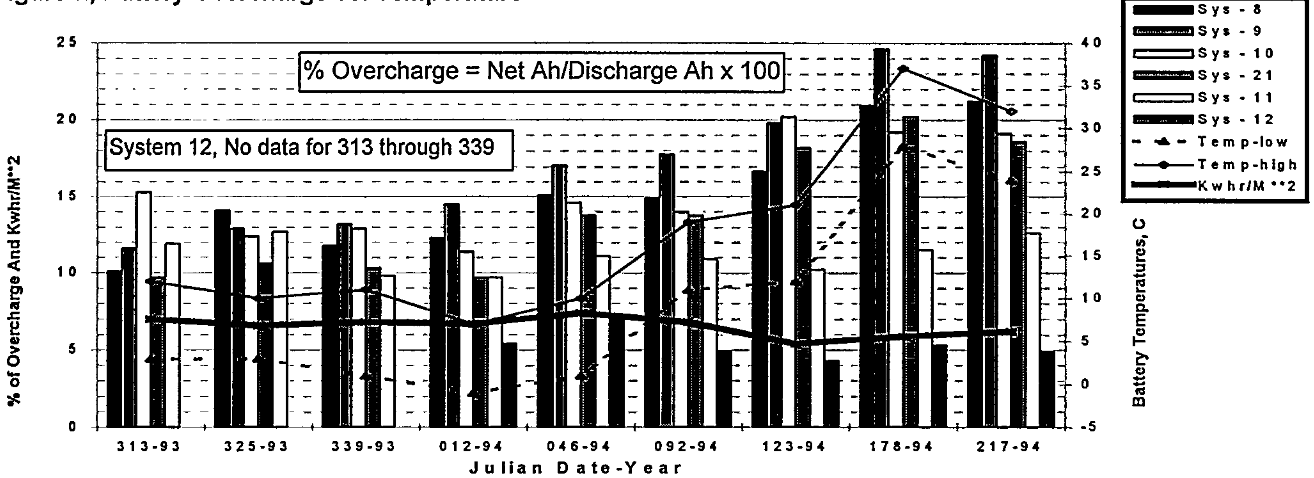
After 2.5-years of operation, battery capacity tests were conducted on fully operational systems and on failing systems with reduced PV output. The fully operational systems included batteries from systems 16 and 18 charged with on/off charge controllers. Their individual 6 volt capacities ranged from 130 to 181 Ah. The 6 volt battery capacities in system 8 (fully operational), charged with a constant voltage charge controller, were 184 and 186 Ah. The batteries in three systems that were failing because of the loss of one PV module all had capacities of about 50 Ah. These failing systems (number 4, 5, and 21) were reaching LVD every night and had batteries that were sulfated due to long periods at the low state of charge. Battery capacity was recovered using the manufacturers recommended charging procedure, which was to charge at a 20-amp rate until battery temperature reached 45°C and/or specific gravity reached 1.270. This resulted in over 500 Ah of charging into the flooded battery and full recovery of capacity.

After 3.5-years, the JCI Dynasty VRLA gel batteries in systems 11 and 12 are still functioning well as verified by data logging.

Figure 2 shows the percentage of overcharge and the effect temperature has on it from Nov. 9, 1993 (313) through Aug. 5, 1994 (217). The PV array is tilted at 45° to optimize for winter operation which results in a fairly even distribution of solar energy on the array throughout the year. The days picked are clear days of full sun. The batteries are still affected by temperature changes from the seasons even though the charge controllers have temperature compensation. All of the systems use a Zomeworks $Coolcell_{tm}$ which reduces the battery temperature swings. Outside ambient temperatures are not available. As seen in Figure 2, the batteries in systems 8, 9, 10, and 21 are all flooded deep-cycle lead-antimony batteries and received 10 to 25% overcharge; they require about 15-25% overcharge. The constant voltage systems 8 and 9 appear to deliver slightly more overcharge than the on/off controllers in system 10 and 21. The batteries with more overcharge should have a higher specific gravity, higher water consumption, and higher available capacity.

Systems 11 & 12 use VRLA batteries and require less overcharge (≈ 5-10%). Overcharge for the VRLA batteries appears to be less affected by the increase in temperature when compared to flooded batteries and more affected by

Figure 2, Battery Overcharge vs. Temperature



the type of charge control. The two charging strategies show significant differences (50%) in the overcharge delivered to the VRLA batteries. These systems will be monitored until end of life to determine the effect of the variations in measured overcharge.

Illumination Measurements

Basic measurements of the luminaire output were taken on all the lights on September 21, 1994 (no moon at time of measurements). Measurements were taken with a Tektronics J17 Luminance meter with a J1811 head. The measurement head was held directly underneath the luminaire, level with the base of the pole. The outputs varied significantly between 0.9 and 2.0 foot-candles and do not seem to correlate with any other system function examined in this evaluation. One lamp, system 21, was noticeably (visually & measured) brighter than the others and there is no explanation for this. Likewise the other lamps with lower outputs do not seem to have any system problems or blackening of the electrodes. Experience with another low pressure sodium ballast has shown that the ballast can play a major roll in the illumination level and that these lamps are capable of a significantly higher illumination level. There are now only two known LPS, DC-ballast suppliers in the U.S. LPS lamp reliability improvement will require a more stable ballast.

PV Modules

After 18-months a number of systems had developed poor fill factors and reduced power output. These systems include 14, 16, 17, 18, 19, and 20. After 2.5-years, one module from system 4, 5, and 21 has failed completely resulting in only half of the required power output. The cause of the module power loss and failure is not known, but it may be related to a manufacturing flaw associated with the vandal resistant design. The manufacturer states the problems have been resolved, and the new modules should work as specified. The module manufacturer has agreed to replace any defective modules at no cost even though the warranty period has expired.

Water Replacement

Water replacement in systems with Hydrocaps® on flooded batteries was initially at 18-months. After the 18-month watering, systems 1, 2, 3, 6, 15, and 18 had a few cells that began to consume water at twice the previous rate. This increased water consumption was due to a "wetted" catalyst in the Hydrocaps®. At the recommendation of the manufacturer a total of 22 Hydrocaps® were baked out at 101°C for 6-hr, after which they were all tested and proven to be fully functional again.

LPS Bulbs And Ballasts

One failed bulb was discovered after the 18-month inspection (system 15) and another failed bulb was discovered after the 30-month inspection (system 7). At the 18-month inspection one ballast was found to have failed on system 16, a new brand of ballast was used as a replacement.

Miscellaneous

At the 18-month inspection array connections required repair on systems 4 and 15, a luminaire arm had a sheared top bolt at pole connection, and a light pole was wobbly because base bolts needed to be tightened on system 14 (3/4 turn).

CURRENT STATUS

At present, two PV lighting systems are not functioning because of burned out LPS bulbs (system 15 and 7) and three systems are operating for only 3-hrs per night because each has a failed PV module (system 4, 5, and 21). Sixteen other PV LPS lighting systems have been operating normally for 6-hrs per night for the last 3.5 to 2.5-years.

LESSONS LEARNED

1. **Procurement:** Purchase complete, pre-packaged hardware if you do not have prior experience with PV.

2. Make sure your supplier has experience with this exact type of application. Ask for references.
3. **Specifying The System:** Detail your illumination requirements, site location, climate conditions, maintenance capabilities, and expectations when specifying your system or project.
4. **PV Modules:** Modules that meet industry qualification standards should be specified ("JPL Block V" or "IEEE 1262 Recommended Practice For Qualification of Photovoltaic Modules").
5. **Installation:** 1) Timely delivery and installation of the components is critical to alleviate problems with incomplete assembly or activation of the systems. 2) Installation crews should be knowledgeable and experienced in handling low voltage DC systems. 3) Someone in the organization needs to take ownership of the systems. 4) Acceptance testing is a must to assure proper initial operation.
6. **Operation & Maintenance:** While PV systems may be low maintenance, they are not maintenance free. Maintenance requirements will vary depending on the hardware chosen and ambient operating conditions. A maintenance contract with an experienced PV systems house can provide regular dependable maintenance.
7. **Hardware Considerations:** Keep the hardware simple, the fewer parts, the better. Purchase components with integrated functions so they will work well together. This also minimizes the number of spare parts required. Establish sources for acquiring replacement parts before they are needed.

MAINTENANCE REQUIREMENTS AND COSTS

Regular Performance Checks: It is important to conduct regular system performance checks at least every 6-months to ensure that all components are working. If failure of an LPS light, ballast, battery, Hydrocap®, charge controller, or PV module is encountered, then proper actions can be taken. In many cases further damage to the system can be prevented. Each system would require about ½-hour for inspection.

Batteries: Both flooded and VRLA batteries using constant voltage and on/off charge methods appear to maintain the batteries at an acceptable state-of-charge based on data logging, capacity measurements, and specific gravities. The cost tradeoffs between flooded and VRLA batteries require balancing the initial lower cost of flooded batteries (½ to 1/3 the cost) with their higher maintenance costs (watering every year), and longer cycle-life (about 2X over VRLA). Batteries must be chosen based on individual system priorities. Maintenance costs will be significantly reduced if the battery is easily accessible. It is also important to include the inspection and maintenance of the Hydrocaps® in the required maintenance schedule. Each system would require about ½-hour for watering.

LPS Lights: In the past 2.5-years since refurbishment, five ballasts and two lamps out of 21 LPS systems have failed. Conventional utility powered lighting bulbs and ballasts are expected to last 10,000-hours. This would mean that the above LPS bulbs and ballasts should not need replacement until they are over 4-years old. The cost of individual ballasts and bulbs is relatively low, but the cost of their replacement can exceed $500 per day for a Bucket Truck. A Bucket Truck is required to reach the 20-feet high light fixture. Each system will probably require about 2 to 3-hours for bulb and/or ballast replacement.

PV Modules: Ten of 44 modules need to be replaced by the manufacturer because of blistering at the top surface and three of these modules have stopped producing power. Even though the manufacturer has promised to replace the modules free of charge, installation costs will exceed $500 per day. Each system will probably require about 2 to 3-hours for module replacement.

CONCLUSION

The case study in this report demonstrates that stand-alone PV lighting systems can provide reliable lighting in remote locations if quality hardware is used, system installation is conducted correctly, and proper periodic maintenance is performed. Throughout this study, the evaluation has identified problems with several of the system components. Several of these components were redesigned or fixed by the manufacturer as a result of this effort and are working reliably now. Some other PV system components have not yet reached the reliability level expected by the general consumer, but progress is being made. These PV lighting systems have demonstrated that in over 2.5-years of operation, only limited repairs were required. The insight gained from this case study should provide a guide for the future application of reliable stand-alone PV systems.

ABOUT THE AUTHORS

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[4] PVCAD Is a photovoltaic system design program developed by Photovoltaic Resources International, Tempe, AZ.

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