Evaluation of Grid-Connected Photovoltaic Systems at The Nature Conservancy – Disney Wilderness Preserve

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The Nature Conservancy – Disney Wilderness Preserve

Prepared by
Florida Solar Energy Center
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Executive Summary

This report presents the results of an evaluation of two grid-connected photovoltaic (PV) systems installed at the Disney Wilderness Preserve, in Kissimmee, FL. Conducted by the Florida Solar Energy Center (FSEC), this evaluation consisted of visual inspection of the equipment and installation, as well as electrical performance measurements on the PV array and operating system. Following lists the key results from this evaluation.

- The two grid-connected PV systems at this site were functioning properly and their operational performance is within expectations. The photovoltaic array installation is generally pleasing and complete, and uses listed equipment (PV panels, inverter and combiner box).

- With a few exceptions the system installations meet National Electrical Code requirements such as wire sizing, overcurrent protection, disconnect requirements and grounding. The exceptions include labeling and identification requirements for PV system equipment, source circuits and back-feed breakers at the service panels. The open junction box for the System #2 inverter AC output circuit wiring should be covered.

- Readily accessible on-site documentation is needed for these systems, including the inverter user manual, drawings, and operation and maintenance procedures. Some of the information in this report may also be appropriate for on-site documentation.

- Two types of shading concerns exist for the array installations – shading from the ridge cap at the top and shading from the standing seams between the roofing panels. Simulated shading tests were conducted on a sample panel to quantify the effects of this shading on array and system performance.

- It is suggested that minimal AC output monitoring (watt-hour meters) be installed on these systems, and readings and other observations be recorded at least once per week by on-site caretakers to help document the long-term performance of these systems. This is particularly important for System #2, where the difficult attic access to the inverter and combiner box make it likely that any system problems will go undetected. These meters could be part of an informative and interactive public display, allowing interested parties to readily evaluate daily and seasonal energy production, as well as the power output as a function of time of day and as clouds pass by.

1. Introduction

Owned and managed by The Nature Conservancy, the Disney Wilderness Preserve is an 11,500-acre nature preserve at the headwaters of the Florida Everglades system. To promote renewable energy technologies, two building-integrated grid-connected photovoltaic (PV, solar electric) systems were installed on the conservation and learning center, which opened to the public in October 1999 (Figure 1).

Figure 1. BIPV Systems at The Nature Conservancy - Disney Wilderness Preserve.

On 3 November 1999, technical staff from the Florida Solar Energy Center conducted an initial evaluation of these two grid-connected PV systems. This evaluation is part of an overall effort by the U.S. Department of Energy, Florida Energy Office and Sandia National Laboratories to gain performance and reliability information associated with the design, equipment, installation, operation and maintenance of these systems. This report provides an overview of the installations, summarizes the results of the evaluation and provides follow-up recommendations where applicable. This information may be applicable to the equipment manufacturers in product development efforts, to system designers in configuring these products, to installers in terms of electrical and building integration and to the operation and maintenance practices of the system user/operator.

2. System Information and Configurations

Two individual grid-connected PV systems are installed on two separate buildings at this site, each consisting of an array of PV modules/panels, source circuit wiring and combiner boxes, and an inverter/power-conditioning unit. During the day, the PV array produces DC power in proportion to the sunlight intensity. The inverter converts this DC power to AC power and back feeds the electric utility service to the facilities, helping to offset the on-site loads or sending excess power onto the electric utility distribution network. There is no on-site energy storage operating with this system.

The two systems are similar in that they both employ triple-junction amorphous silicon PV modules laminated to architectural standing-seam metal roofing panels. This building-integrated PV (BIPV) product is manufactured by United Solar Systems Corp., Troy, MI. Each system also utilizes the same 5.5 kVA utility-tie inverter manufactured by Trace Engineering, Arlington, WA. Specification sheets for the PV modules and inverter are contained at the end of this report.

Solar Design Associates of Harvard, MA designed the PV systems, including the electrical configuration and architectural integration. These drawings are included at the end of this report for reference. Sustainable Energy Systems of Sarasota, FL bonded the PV laminates supplied by USSC to the metal roofing panels at their facility in Florida. The roofing contractor installed the PV panels along with the conventional roofing panels during construction in July 1999. Sustainable Energy Systems and their electrical subcontractors completed installation of PV equipment and wiring, and commissioned the system in September 1999.

2.1 System #1 Overview

System #1 is the larger of the two systems and is located on the northernmost building at the site. This system consists of two models of the standing-seam PV roofing panels from United Solar, models ASR-60 and ASR-120. Both panels are UL listed for rooftop applications. The ASR-120 panels are twice the length, and have twice the voltage output as the ASR-60 panels, and both have the same current output. The array is facing due south and is tilted 34 degrees from horizontal (8/12 pitch). The array surface area is 79.5 m^2 (855 ft^2). Figure 2 shows the array layout on the rooftop for System #1, with the ASR-120 panels to the left, and the ASR-60 panels to the right.

Figure 2. System #1 photovoltaic array.

The PV array for System #1 consists of twenty-three (23) total source circuits, each having the same current-voltage characteristic. Three (3) of these source circuits have three (3) ASR60 panels connected electrically in series, and twenty (20) of the source circuits have one (1) ASR60 panel and one (1) ASR120 panel connected in series. There are twenty-nine (29) ASR60 panels and twenty (20) ASR120 panels in the array, a total of forty-nine (49) individual panels. Table 1 gives the STC-rated IV parameters for the panels, source circuits and the entire System #1 array.

Table 1 - IV Parameters for System #1

IV Parameters at STC (1 kW/m^2, 25 ^{o}C)	ASR60 Panel	ASR120 Panel	Source Circuit	Array
Open-Circuit Voltage (V)	23.8	47.6	71.4	71.4
Short-Circuit Current (A)	4.5	4.5	4.5	103.5
Maximum Power Voltage (V)	16.5	33	49.5	49.5
Maximum Power Current (A)	3.6	3.6	3.6	82.8
Maximum Power (W)	60	120	180	4140

The inter-module and source circuit wiring terminations for the PV array are made above (at the top) of each 16-inch wide panel and underneath the ridge caps. The connections are made using crimped "butt" splices, and all source circuit wiring is #12 AWG THWN, except for factory installed wiring on the PV panels, which is #16 AWG. A wire duct installed beneath the ridge cap routes the source circuit wiring to two separate combiner boxes, also located in the attic.

The combiner boxes are manufactured by Pulse Energy Systems, Nevada City, CA and are UL listed. In the combiner boxes, the positive leg of each source circuit passes through an 8-amp series fuse, and is combined electrically in parallel with the other source circuits at a terminal block. The combiner boxes also include silicon oxide varistors (SOVs) connected between the positive and negative legs of the array source circuits to ground. Figure 3 shows the combiner boxes for Systems #1. The combiner box on the left combines eleven (11) of the array source circuits, and the box on the right combines twelve 12 of the source circuits. The wiring from the two terminal blocks in the combiner boxes is connected in parallel, and a single pair of #2/0 AWG THW conductors makes the approximate ten (10) meter (~30 feet) run to the inverter.

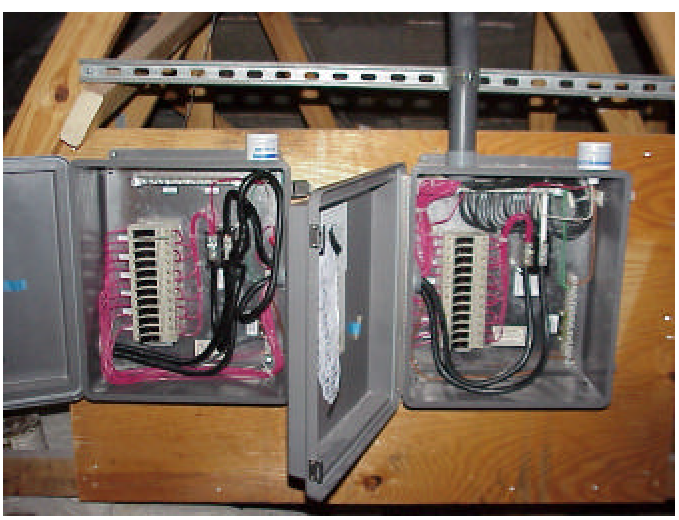

Figure 3. Source circuit combiner boxes for System #1.

The inverter for System #1 is model SW5548 UPV manufactured by Trace Engineering and is designed for utility-interconnection. The inverter is enclosed in an outdoor cabinet and mounted under the eave on the north wall of the building, and adjacent to the main disconnect panel for the facility (Figure 4). The inverter cabinet includes external AC and DC circuit breakers, and a ground fault protection circuit. The sine wave inverter is nominally rated at 5.5 kVA, 240-volts single-phase output. The PV array DC input range is 34-75 volts for operation, and 44-66 volts for peak power tracking. There are no user adjustable settings, only a few monitoring functions are available from the front panel display. The AC output from the inverter is connected to a double-pole 40-amp circuit breaker in the adjacent main disconnect panel for the facility, using #8 AWG THWN conductors.

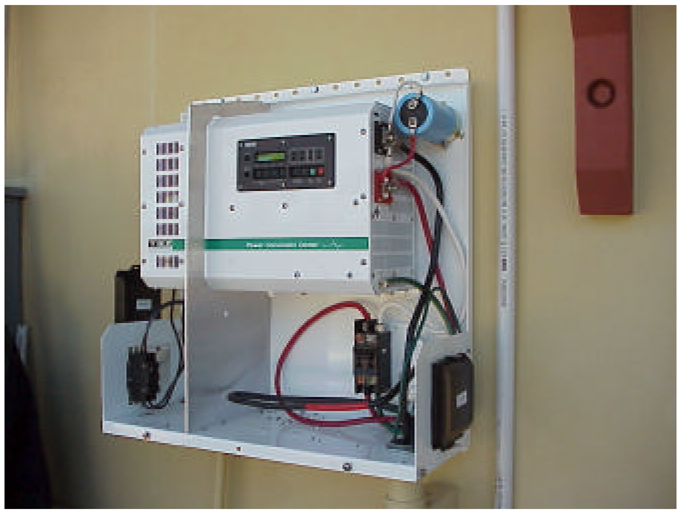

Figure 4. System #1 inverter.

2.2 System #2 Overview

Slightly larger than one-half the size (surface area) as the array for System #1, System #2 uses only the model ASR60 PV roofing panel and is located on the southernmost building at the site. There are 39 total ASR60 panels in the array, consisting of 13 source circuits with three (3) ASR60 modules connected electrically in series. This array is facing 20 degrees west of due south and is tilted 34 degrees from horizontal (8/12 pitch). The array surface area is 45.9 m^2 (494 ft^2). Table 2 gives the STC-rated IV parameters for the panels, source circuits and the entire System #2 array. Figure 5 shows the array layout on the building rooftop for System #2.

Table 2 - IV Parameters for System #2

IV Parameters at STC (1 kW/m^2, 25 °C)	ASR60 Panel	Source Circuit	Array
Open-Circuit Voltage (V)	23.8	71.4	71.4
Short-Circuit Current (A)	4.5	4.5	58.5
Maximum Power Voltage (V)	16.5	49.5	49.5
Maximum Power Current (A)	3.6	3.6	46.8
Maximum Power (W)	60	180	2340

Figure 5. System #2 photovoltaic array.

The inter-module and source circuit wiring terminations are the same as for System #1, except for the thirteen (13) source circuits are combined in a single combiner box, located in the attic (Figure 6). The length of wiring from the terminal block in the combiner box to the inverter is approximately 1 m (~3 ft) - as the inverter is also located in the attic for System #2 - and uses #4 AWG THW conductors. System #2 uses the same Trace Engineering model SW5548 line-tie inverter as System #1, however this unit is only operated at a lower power level (Figure 7). The AC output from the inverter is connected to a double-pole 30-amp branch circuit breaker in the distribution panel for the southernmost building using #10 AWG THWN conductors in ½-inch EMT.

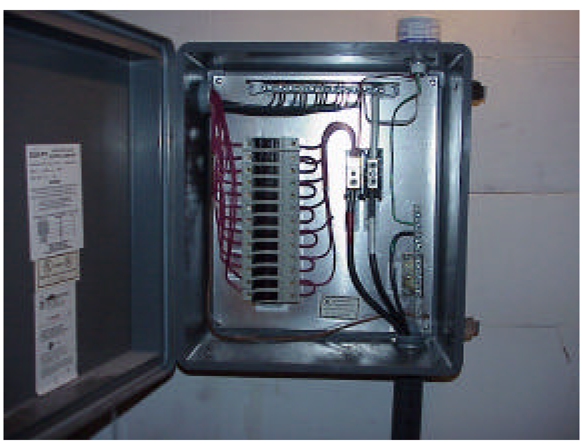

Figure 6. System #2 source circuit combiner box.

Figure 7. System #2 inverter.

3. Evaluation Results

The principal objectives of the evaluation were to obtain performance and reliability information associated with the design, equipment, installation, operation and maintenance of these systems. The BIPV products used in these systems represent emerging technologies, and relatively few of these installations exist to date. Since this evaluation was conducted soon after installation – it provides essential baseline information for comparison with future evaluations and long-term performance.

The evaluation consisted of visual inspections of the equipment and installation, and electrical performance measurements on the photovoltaic array and inverter. The weather conditions were ideal for the electrical tests – perfectly clear skies and an ambient temperature of about 18^o C (64^o F). All tests were conducted within 2-½ hours of solar noon, and the plane of array (POA) solar irradiance was generally greater than 1 kW/m^2 and very stable during the electrical measurements.

Detailed results of the electrical performance measurements, analysis and observations are provided in the two spreadsheets in the Appendix for Systems #1 and #2, respectively. A summary of current-voltage (IV) measurements for both arrays is also contained in the Appendix.

3.1 Results from System #1 Evaluation

- Upon arrival at the site, this system was on-line and producing over 3 kW AC output.
- With the inverter switched off-line and the source circuit fuses removed, open-circuit voltages (Voc) and short-circuit currents (Isc) were measured and recorded for each of the twenty-three (23) array source circuits.
- Array temperature and solar irradiance were measured simultaneously with electrical data for translation to Standard Test Conditions (STC, 1 kW/m^2 irradiance and PV temperature of 25^o C). The array temperature rise coefficient was determined to be approximately 30 ^{o}C/kW/m^2 above ambient.
- The open-circuit voltages for the 23 source circuits were very consistent, averaging 59.6 volts with a standard deviation of 0.3 volts. Using a conservative voltage-temperature correction coefficient of –0.4%/^{o}C, the translated average was approximately 7 percent below the manufacturer's STC rating.
- The irradiance-normalized short-circuit currents were also very consistent, averaging 4.44 amps with a standard deviation of 0.01 amp. The translated current measurements were approximately 4 percent below manufacturer's STC rating.
- With the inverter off-line, current-voltage characteristics (IV curves) for each source circuit, as well as for each half of the array were measured. The translated peak power output for the entire System #1 array was 3.83 kW, or about 7.4 percent below the manufacturer's STC rating.
- With the inverter on-line and operating under steady conditions, the operating voltages and currents for each array source circuit were measured and recorded. The irradiance-normalized operating currents averaged 3.3 amps, approximately 11 percent below the manufacturer's rated maximum power current of 3.6 amps and consistent with the maximum power current from the IV curves. The operating voltage was the same for all parallel source circuits at 42.8 volts, which is the approximate average of the maximum power voltages from the source circuit IV curves. The average normalized operating power at 1 kW/m^2 was 145 watts, which was consistent with the normalized peak power from the source circuit IV curves.

- Inverter efficiency measurements were performed with the system on-line and operating under steady conditions. The inverter DC to AC power conversion efficiency was approximately 85 percent operating at a power factor above 0.97 and at a power level of approximately 60 percent of the 5.5-kVA rating. Based on the overall panel dimensions (including seams and spacing, provided by manufacturer), the PV array and overall system sunlight to AC electrical energy efficiencies were approximately 4.2 and 3.6 percent, respectively. The irradiance-normalized AC output averaged 69 percent of the manufacturer's STC-rated array output. Table 3 gives the results of these measurements.

Table 3 – System #1 Inverter and System Operating Parameters

Parameter **Test Number:**	**1**	**2**
DC Operating Voltage (V)	43.4	42.3
DC Operating Current (A)	88.30	83.80
DC Power (kW)	3.83	3.54
Inverter AC Output (kW)	3.20	3.04
Inverter AC Output (kVA)	3.31	3.05
Power Factor	0.97	1.00
Reference Cell / Pyranometer (mA/mV)	11.25	10.62
Irradiance (kW/m^2)	1.125	1.062
Array Sunlight - DC Power Efficiency, panel area (%)	4.28	4.20
Inverter DC-AC Power Conversion Efficiency (%)	83.5	85.8
System Sunlight-AC Power Efficiency, panel area (%)	3.58	3.60

3.2 Results from System #2 Evaluation

- When first inspected, this system was on-line and producing 1.75 kW AC output.

- The open-circuit voltages for were very consistent, averaging 59.6 volts with a standard deviation of 0.6 volts. Using a conservative voltage-temperature correction coefficient of –0.4%/^{o}C, the measured average was approximately 8 percent below the manufacturer's rating.

- The irradiance-normalized short-circuit currents were also very consistent, averaging 4.25 amps with a standard deviation of 0.01 amp. The translated current measurements were approximately 8 percent below manufacturer's rated value of 4.5 amps.

- With the inverter off-line, current-voltage characteristics (IV curves) for each source circuit as well as the entire array were measured. The translated peak power output for the entire System #2 array was 2.12 kW, or about 9.2 percent below the manufacturer's STC rating.

- With the inverter on-line and operating under steady conditions, the operating voltages and currents for each array source circuit were measured and recorded. The irradiance-normalized operating currents averaged 3.3 amps, approximately 11 percent below the manufacturer's rated maximum power current of 3.6 amps and consistent with the maximum power current from the IV curves. The operating voltage was the same for all parallel source circuits at 43.3 volts, which is the approximate average of the maximum power voltages from the source circuit IV curves. The average normalized operating power at 1 kW/m^2 was 145 watts, which was consistent with the normalized peak power from the source circuit IV curves.

- Inverter power quality and efficiency measurements were performed with the system on-line and operating under steady conditions. The inverter DC to AC power conversion efficiency was approximately 87 percent operating at a power factor above 0.98 and at a power level of approximately 30 percent of the 5.5-kVA rating. Based on the overall panel dimensions (including seams and spacing, provided by manufacturer), the PV array and overall system sunlight to AC electrical energy efficiencies were approximately 4.2 and 3.6 percent, respectively. The irradiance-normalized AC output averaged 71 percent of the manufacturer's STC-rated array output. Table 4 gives the results of these measurements.

Table 4 - System #2 Inverter and System Operating Parameters

Parameter Test Number:	**1**	**2**
DC Operating Voltage (V)	43.7	43.8
DC Operating Current (A)	46.0	43.2
DC Power (kW)	2.01	1.89
Inverter AC Output (kW)	1.75	1.65
Inverter AC Output (kVA)	1.78	1.69
Power Factor	0.98	0.98
Reference Cell / Pyranometer (mA/mV)	10.55	9.76
Irradiance (kW/m^2)	1.055	0.976
Array Sunlight - DC Power Efficiency, panel area (%)	4.15	4.22
Inverter DC-AC Power Conversion Efficiency (%)	87.1	87.2
System Sunlight-AC Power Efficiency, panel area (%)	3.61	3.68

3.3 General Evaluation Results

This section includes observations and test data that are generally applicable to both systems. Included are issues concerning the system design, equipment and installation, operational performance and maintenance.

3.3.1 Issues Concerning System Design and Installation

- The system installations are generally pleasing and well done.

- According to Peter Baldi of Sustainable Energy Systems, the installation required an approximate two man-week effort, not including the lamination of the PV material to the metal roofing panels, or the installation of the metal roof. The installer's had no prior experience with PV systems.

- Four (4) design drawings - including two architectural diagrams and two electrical schematics - were available from Solar Design Associates. No other documentation was readily accessible on-site or otherwise available.

- With a few exceptions the system installations meet National Electrical Code requirements such as wire sizing, overcurrent protection, disconnect requirements and grounding. The exceptions include labeling and identification requirements for PV system equipment, source circuits and back-feed breakers at the service panels. The open junction box for the System #2 inverter AC output circuit wiring should also be covered.

- A seaming problem exists between the PV and conventional metal roofing on the System #2 array. Attempts to seal the roofing at this point with caulking appear to have failed and the PV-integrated roof panels were bowed up slightly (Figure 8). Depending on the amount of overlap at the seams, this could potentially lead to a weather-sealing problem during wind-blown rain from the south.

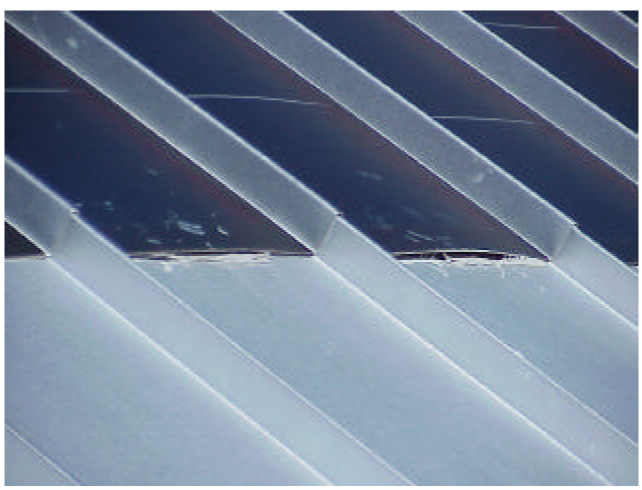

Figure 8. Seam between PV and conventional metal roofing.

- Due to the installation of the ridge caps overhanging the top part of the standing-seam metal roofing panels, up to a 2-inch shading band was observed along the tops of the PV arrays (Figure 9). This situation will be at it's worst around the summer solstice, when the sun is higher in the sky and to the north of the array. In addition, due to the projection of the standing seams above the PV material, shading occurs along the edge of the PV material whenever the sun position more than 40 or so degrees off from normal to the panel seam.

Figure 9. Shading bands along the top and sides of PV roofing panel.

3.3.2 Issues Concerning System Operation and Maintenance

- Both systems were found to be operating properly and performing within expectations

- Based the measured operating voltages and the maximum power voltages from the IV curve measurements, the inverter appeared to be doing a good job at peak power tracking the array under the test conditions, despite the operating voltage being below the inverter manufacturer's specified peak power tracking window (44-64 VDC).

- The panel source circuit wiring is generally inaccessible for routine inspection, both from on the rooftop as well as in the attic. The wire duct is located beneath the ridge cap, which is riveted to the seams in the metal roofing. This wiring is also inaccessible in the attic as the underside of the ridge is completely covered with cellulose insulation (not ventilated).

- Array source circuits are not labeled in the combiner boxes, making identification of specific source circuits on the rooftop difficult. Shading panels in the array concurrent with source circuit electrical measurement would be required to identify a panel's location in the array.

- When the case was first removed on the System #1 inverter, burn marks were noticed on the cabinet beneath and to the side of the 35-amp main AC circuit breaker (Figure 10). This was reported to have been a lightning event that occurred before the system was operational, however no obvious damage to the breaker or the inverter were found, and the system was functioning normally. Special attention should be paid to this device for heating or other problems that might occur.

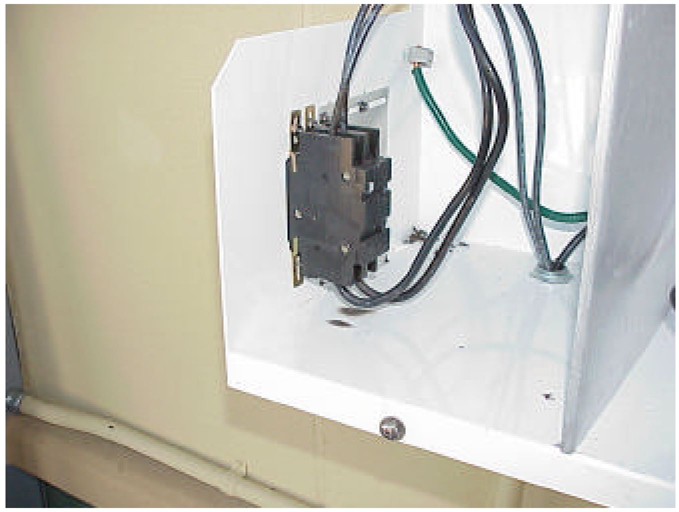

Figure 10. Burn marks below AC breaker on System #1 inverter.

- The inverter and combiner box for System #2 are located in the attic of the southernmost building, and are extremely difficult to access through a small opening at the top of a packed closet. This is not a desirable situation, and any problems with this system would go undetected. Furthermore, a hazardous condition exists where the conduit leading from the inverter to the building distribution panel runs along side condensate pipes for the air-conditioning units, and has an uncovered junction box immediately above the distribution panel (Figure 11).

Figure 11. Wiring from inverter to distribution panel, System #2.

- No metering or other means to monitor and record the PV system operational performance was present. This would be particularly desirable for Systems #2, for which the inverter is generally inaccessible and faults or nuisance trips of breakers or source circuit fuses would go undetected.

4. Conclusions

- The two grid-connected PV systems at this site were functioning properly and their operational performance is within expectations. The photovoltaic array installation is generally pleasing and complete, and uses listed equipment (PV panels, inverter and combiner box).

- With a few exceptions the system installations meet National Electrical Code requirements such as wire sizing, overcurrent protection, disconnect requirements and grounding. The exceptions include labeling and identification requirements for PV system equipment, source circuits and back-feed breakers at the service panels. The open junction box for the System #2 inverter AC output circuit wiring should be covered.

- Better on-site, readily accessible documentation is needed for these systems, including the inverter user manual, operation and maintenance procedures, and this report (including drawings, equipment specification sheets and other information in the Appendix).

- Two types of shading concerns exist for the array installations – shading from the ridge cap at the top and shading from the standing seams between the roofing panels. Results of special tests to assess the effects of shading on panel performance are included in an addendum in the Apendix.

- It is suggested that minimal AC output monitoring (watt-hour meters) be installed on these systems, and readings and other observations be recorded at least once per week by on-site caretakers to help document the long-term performance of these systems. This is particularly important for System #2, where the difficult attic access to the inverter and combiner box make it likely that any system problems will go undetected. These meters could be part of an informative and interactive public display, allowing interested parties to readily evaluate daily and seasonal energy production, as well as the power output as a function of time of day and as clouds pass by.

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5. Appendix

- System #1 Evaluation Record
- System #2 Evaluation Record
- PV Array IV Curve Summary
- Shading Tests on USSC Module
- PV Module Specification Sheets from United Solar
- Inverter Specification Sheets from Trace Engineering
- System Architectural and Design Drawings from Solar Design Associates

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