

## Chapter 14

# Commissioning, Maintenance and Troubleshooting

System Commissioning • Maintenance Plans •  
Diagnostics



# Overview

- ▶ **Describing the purpose for system commissioning and the tasks and procedures involved.**
- ▶ **Identifying required maintenance for PV systems and their components, and developing a maintenance plan.**
- ▶ **Understanding the importance of system performance data in verifying expectations and in identifying problems.**
- ▶ **Understanding basic troubleshooting principles.**



# The Importance of PV System Testing and Commissioning

- ▶ Many PV systems are not satisfactorily evaluated prior to being placed into service, and few have scheduled maintenance or testing over their lifetime.
- ▶ This often leads to unsafe and underperforming systems with reduced value to their owners.
- ▶ Any electrical system can be tested to verify performance and to evaluate the condition of the wiring systems and equipment.

# Commissioning

- ▶ Commissioning PV systems verifies that the installation has been satisfactorily and safely completed according to plans.
- ▶ Key steps of a commissioning procedure include:
  - ◆ Completing final installation details
  - ◆ Completing a checkout and visual inspections for NEC compliance
  - ◆ Conducting electrical verification tests
  - ◆ Completing system documentation and labeling requirements
  - ◆ Conducting user training
  - ◆ Performing initial start-up and operations
  - ◆ Verifying expected output and performance



# IEC 62446

- ▶ **IEC 62446 defines minimum documentation, commissioning tests and inspection criteria for grid-connected PV systems.**
- ▶ **This standard is intended to verify the safe and proper operation of PV systems, and to serve as a guide for designers, installers and service personnel.**
- ▶ **Compliance with the IEC 62446 standard is required for many PV projects in Europe, and correlate directly with NEC requirements for the verification of safety for all electrical systems.**



# Final Checkout

- ▶ **A final checklist should be used to confirm that the installation is complete before beginning operations.**
  - ◆ Verifying that all components are installed in a neat and workmanlike manner, including wire management practices.
  - ◆ Verifying that all structural and electrical components are properly installed and secured.
  - ◆ Verifying disconnects are open and lockout/tagout procedures are in place.
  - ◆ Visually inspecting all components and connections and verifying terminal torque specifications.
  - ◆ Identifying and completing any unresolved items.
  - ◆ Verifying system and equipment labels, marking and placards are correct and in the proper locations.
  - ◆ Verify that any calibrations or adjustments for inverters, charge controllers or other equipment are properly set or programmed.



# PV System Testing

- ▶ ***Continuity and resistance testing*** verifies the integrity of grounding and bonding systems, conductors, connections and other terminations.
- ▶ ***Polarity testing*** verifies the correct polarity for PV dc circuits, and proper terminations for dc utilization equipment.
- ▶ ***Voltage and current testing*** verifies that PV array and system operating parameters are within specifications.
- ▶ ***Insulation resistance testing*** verifies the integrity of wiring and equipment, and used to detect degradation and faults to wiring insulation.
- ▶ ***Performance testing*** verifies the system power and energy output are consistent with expectations.

# Insulation Resistance Testing

- ▶ Insulation resistance testing verifies the integrity of wiring systems, and can be used to detect damaged wiring and ground faults in PV system circuits.
- ▶ Insulation resistance testing measures the resistance between ungrounded circuits and ground under the application of high voltage.



Fluke 1587 Insulation Tester



# Insulation Testing Procedures

- ▶ **Baseline insulation resistance testing can be compared to measurements over time to assess degradation of PV arrays or wiring.**
- ▶ **Procedures include:**
  - ◆ Circuits must be isolated from one another, and surge protection devices removed.
  - ◆ The positive and negative poles of the array are connected together, and the test voltage is applied between this circuit and ground.
  - ◆ Testing is repeated for individual array source circuits in the array and other system circuits.
- ▶ **Faulted circuits will shows a significant drop in insulation resistance.**
  - ◆ Wet insulation testing can be used to pinpoint fault locations within the array.



# Insulation Resistance Testing and Safety

- ▶ Always use insulated rubber gloves with leather protectors when conducting insulation tests.
- ▶ Never connect insulation testers to energized circuits, batteries or other energy sources.
- ▶ Isolate circuits for testing by opening disconnects, and verify that circuits are de-energized using LOTO procedures prior to connecting insulation tester.
- ▶ Grounded test lead should always be the first to make, and last to break any circuit measurement.
- ▶ Never use insulation testers in an explosive environment or around combustible materials.
- ▶ Never use insulation testers on circuits with any electronic equipment, including inverters, charge controllers, or instrumentation, or surge suppression equipment, as the application of high test voltages can damage this equipment.
- ▶ Always ensure that circuits are properly discharged before and after insulation tests, either through the test equipment or externally with a load resistor.

# Seaward Solar PV100 Installation Test Kit



<http://www.sewardsolar.com>

- ▶ Tests to IEC 62446 with a single button.
- ▶ Simple, safe, user interface.
- ▶ Rugged, robust and handheld.
- ▶ Earth continuity measurement.
- ▶ PV string open circuit voltage measurement and polarity up to 1000V DC.
- ▶ PV string short circuit current measurement up to 10A DC.
- ▶ PV array insulation test at 250/500/1000V.
- ▶ Operational AC and DC current using supplied current clamp.
- ▶ Store results for up to 9 strings and compare for variances.



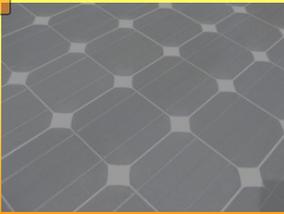
# PV System Documentation

- ▶ All PV installations should have adequate documentation providing details of the system design and all components and materials used in its construction.
- ▶ Proper system documentation helps ensure safe and reliable system operations, and is generally required for the following purposes:
  - ◆ Plan review and permitting process with local building officials
  - ◆ Interconnection approval from the local utility
  - ◆ Installation and maintenance contractors
  - ◆ Owners and caretakers



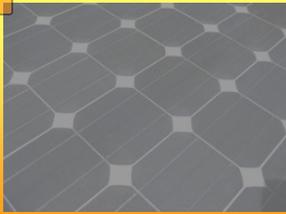
# PV System Documentation

- ▶ **A complete PV system documentation package should include the following:**
  - ◆ System DC and AC power ratings.
  - ◆ Manufacturer, model and quantity of PV modules, inverters, batteries, controllers and all other major components.
  - ◆ The names and contacts the customer/owner, system designer, installation contractor and any other responsible parties or subcontractors.
  - ◆ A site layout identifying equipment locations on buildings or relative to property lines or easements, including a shading analysis as applicable.
  - ◆ A single line diagram depicting the overall system design, including the types of modules, total number of modules, modules per string and total number of strings; the types and number of inverters; and any other major components.
  - ◆ The types, sizes and ratings for all balance-of-system components, including conductors, raceways, junction boxes, source circuit combiner boxes, disconnects, overcurrent protection devices, and grounding equipment, as applicable.



# PV System Documentation

- ◆ Specifications for PV modules, inverters and other major components, including module mounting systems.
- ◆ Operation and maintenance information including procedures for verifying proper system operation and performance.
- ◆ Operating guidelines, safety procedures and maintenance plans.
- ◆ Warranty details on major components indicating the terms and conditions.
- ◆ Copies of all commissioning test reports and verification data.
- ◆ Contracting and financial details, building permits, inspection certificates, interconnection agreements, and applications and approvals from incentive programs, such as rebates and tax forms as applicable.



# Owner/Operator Training

- ▶ **Training for system owners and operators helps ensure safe and successful system operations, and should cover the following items:**
  - ◆ A walk through of the entire installation
  - ◆ Identification of major components and their functions
  - ◆ Principles of operation and procedures
  - ◆ System design drawings and documentation
  - ◆ Location of disconnecting means
  - ◆ Safety information
  - ◆ Use of monitoring systems and expectations for energy production
  - ◆ Maintenance requirements
  - ◆ Warranties and service agreements

# Start-Up

- ▶ **The initial start up for a PV system is conducted after all inspections and checks have been completed with all outstanding items resolved.**
  
- ▶ **Start up procedures include:**
  - ◆ Installing overcurrent devices
  - ◆ Closing all DC and AC disconnects and turning on inverter
  - ◆ Verifying output



# System Functional Testing

- ▶ Verifying the proper operation of disconnecting means and component connection and disconnection sequences.
- ▶ Verify that interactive inverters and ac modules de-energize their output to utility grid upon loss of grid voltage [690.61].
- ▶ Verify that interactive inverters automatically reconnect to their output to the grid once the voltage has been restored for at least 5 minutes [690.61].
- ▶ Verify that battery-based interactive inverters disconnect ac loads from the utility source when operating in stand-alone mode [690.61].
- ▶ Verify the proper grid voltage and frequency to operate inverters, including evaluating voltage drop between the inverter ac output and point of connection to the grid.

# Performance Measurements

- ▶ Operating parameters in PV systems are measured to verify expected performance.
- ▶ Most inverters include integral monitoring and displays as standard features.
- ▶ Measurement on any energized equipment should be performed by qualified persons using appropriate test instruments and PPE.

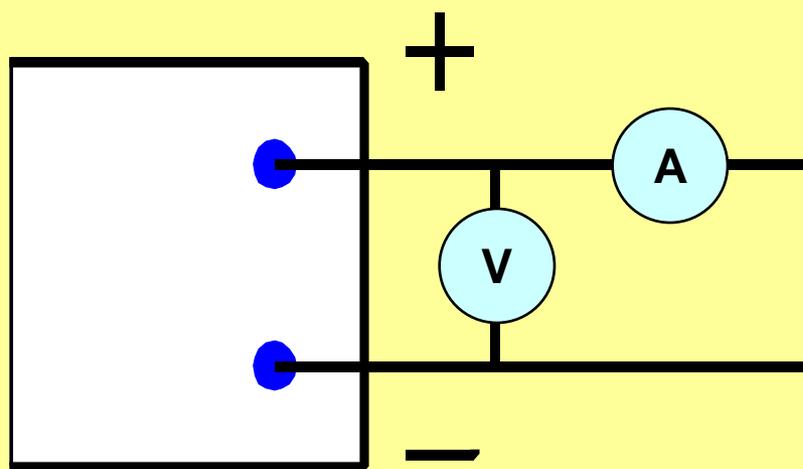




# I-V Measurements

- ▶ Determine the true array maximum power point in relation to the operating voltage for inverters, battery systems and other dc utilization equipment.
- ▶ Determine voltage and power degradation rates from baseline measurements and subsequent measurements over time.
- ▶ Determine changes in array series and shunt resistance over time.
- ▶ Identify array wiring problems or module failures.
- ▶ Analyze the effects of shading on electrical output.
- ▶ Evaluate losses due to module mismatch and array wiring methods.
- ▶ Establish module or array ratings for performance guarantees or warranty purposes.
- ▶ Locate open bypass diodes; requires I-V curve test or dc power supply that reverse biases (applies negative voltage) to the module under test.

# I-V Measurement Methods

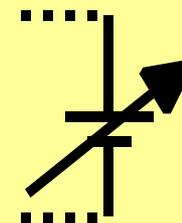


PV Device



Variable resistor

Electrolytic capacitor



Variable battery

# Solmetric PVA-600 PV Analyzer



# Monitoring

- ▶ **Performance data can be used to verify output expectations and identify problems that require service or maintenance.**
  
- ▶ **For simple interactive PV systems without energy storage, the key indicators for system performance are:**
  - ◆ AC power output (kW)
  - ◆ AC energy production (kWh)
  
- ▶ **Performance verification for stand-alone systems with battery storage is more complex, and involves measurements of:**
  - ◆ Battery voltage, amp-hours and state-of-charge
  - ◆ PV array, battery and load currents
  - ◆ Load availability and other factors

# Inverter Monitoring

- ▶ Most faults and performance issues with PV systems are identified by inverter monitoring systems.



# Measuring Power

- ▶ A standard watt-hour meter can be used to measure average power over brief intervals.
- ▶ The watt-hour constant ( $K_h$ ) indicates the watt-hours accumulated per revolution of the meter disk.
- ▶ Multiply  $K_h$  by the disk revolution rate to calculate average power through the meter.



$$P_{avg} = K_h \times N_{rev} \times 3600$$

where

$P_{avg}$  = average power (W)

$K_h$  = meter constant ( $\frac{\text{Wh}}{\text{rev}}$ )

$N_{rev}$  = disk revolution rate ( $\frac{\text{rev}}{\text{sec}}$ )

# AC Power Output

- ▶ The AC power output of an interactive PV system at any moment can be compared with expectations using basic translations for solar irradiance and temperature.

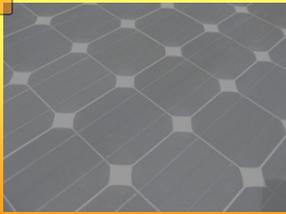


# Verifying AC Power Output

## INTERACTIVE PV SYSTEM PERFORMANCE WORKSHEET

### Estimating and Verifying System AC Power Output

<b>PV Array DC Power Rating at STC - 1000 W/m<sup>2</sup>, 25 °C (kW)</b>	<b>10</b>
<b>Derating Factors</b>	
Nameplate Ratings	0.95
Inverter and Transformer	0.95
Module Mismatch	0.98
DC Wiring	0.98
AC Wiring	0.99
Soiling	1.00
Age	1.00
<i>Combined Derating Factors</i>	0.86
<b>Estimated System AC Power Output at STC - 1000 W/m<sup>2</sup>, 25 °C (kW)</b>	<b>8.6</b>
<b>Temperature Adjustments</b>	
Array Power-Temperature Coefficient (%/°C)	-0.5
Measured Array Operating Temperature (°C)	60
<b>Estimated System AC Power Output at 1000 W/m<sup>2</sup> and Operating Temperature (kW)</b>	<b>7.1</b>
<b>Solar Radiation Adjustments</b>	
Measured Solar Irradiance in Plane of Array (W/m <sup>2</sup> )	850
<b>Estimated System AC Power Output at Operating Temperature and Solar Irradiance (kW)</b>	<b>6.0</b>

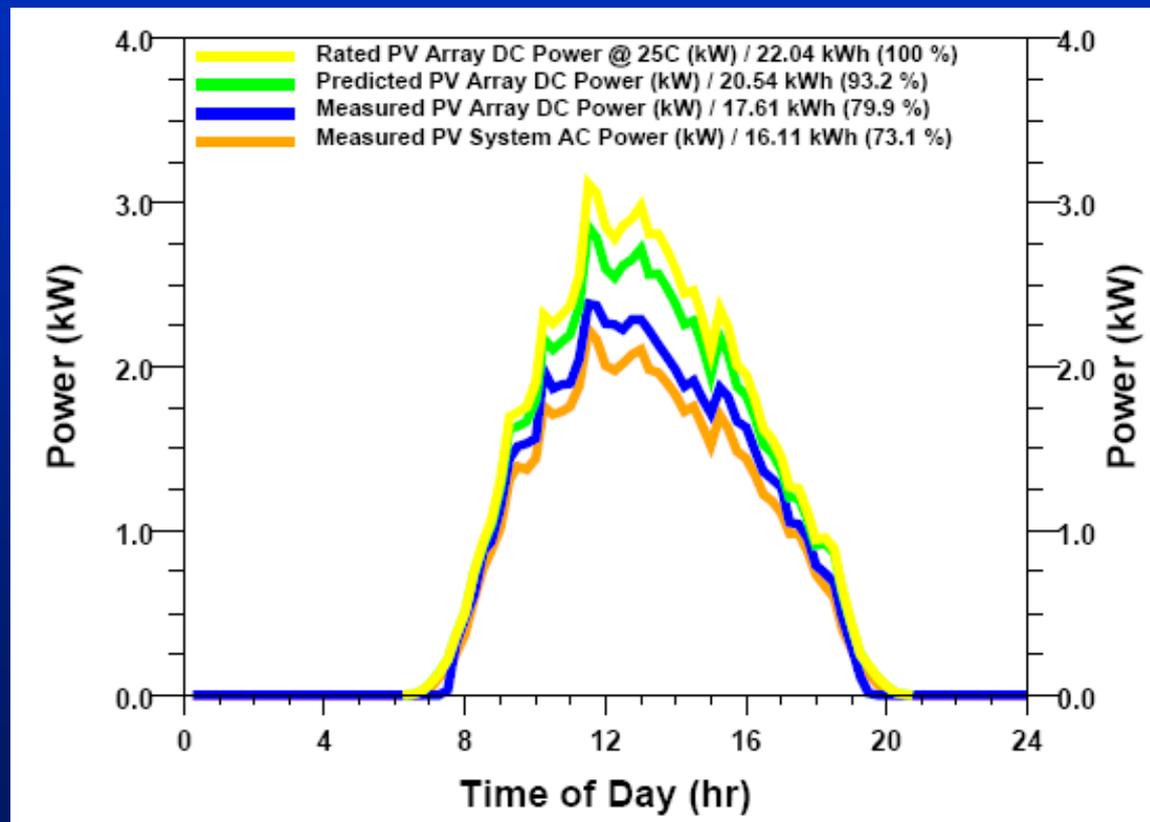


# AC Energy Production

- ▶ The AC energy production (kWh) for grid-connected PV systems is measured over periods of months and years to compare with sizing and long-term performance expectations.
- ▶ Online software tools such as PVWATTS are used to estimate AC energy production based on historical solar radiation and temperature data.
  - ◆ Actual solar irradiation (insolation) and array temperatures can be used to more precisely compare with the AC energy produced.
- ▶ The average daily AC energy production divided by the product of the PV array DC peak power rating at STC and peak sun hours is a key indicator of system performance:
  - ◆  $AC \text{ kWh} / (DC \text{ kW} \times PSH) = 0.7 \text{ to } 0.85$

# Verifying Performance

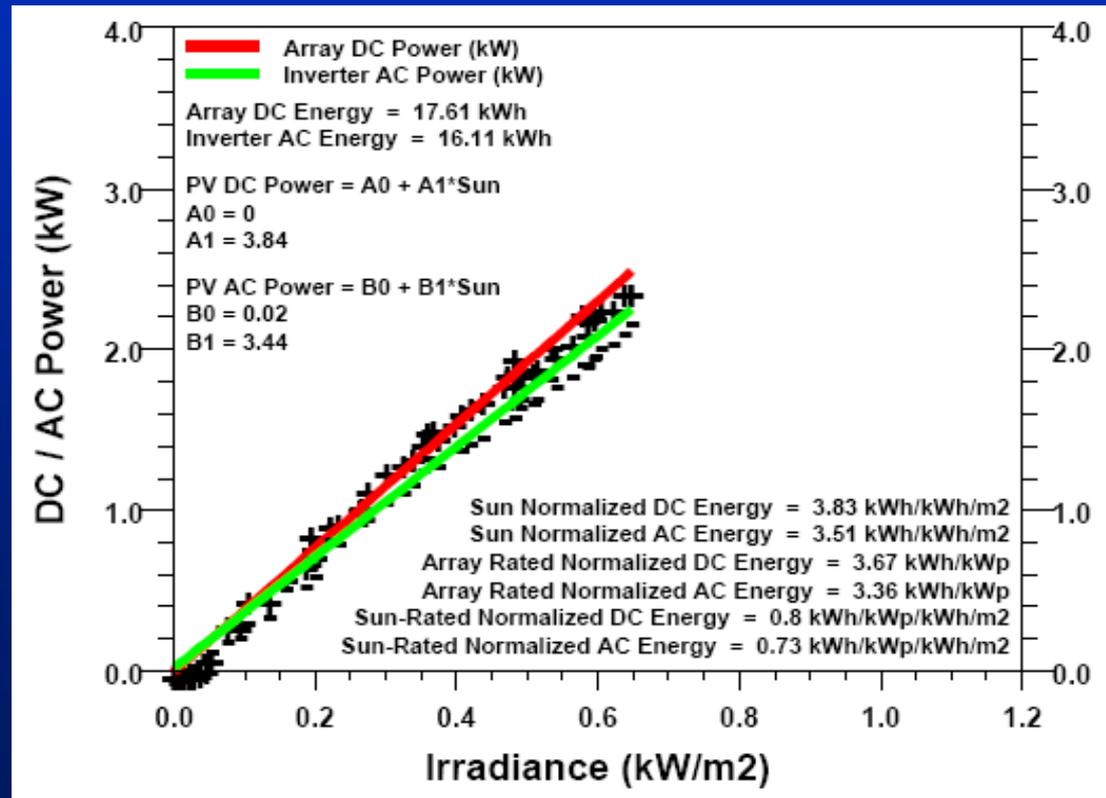
- ▶ AC output will be less, but should follow the expected array DC output for interactive PV systems.



Note: Green and yellow lines are based on measured irradiance.

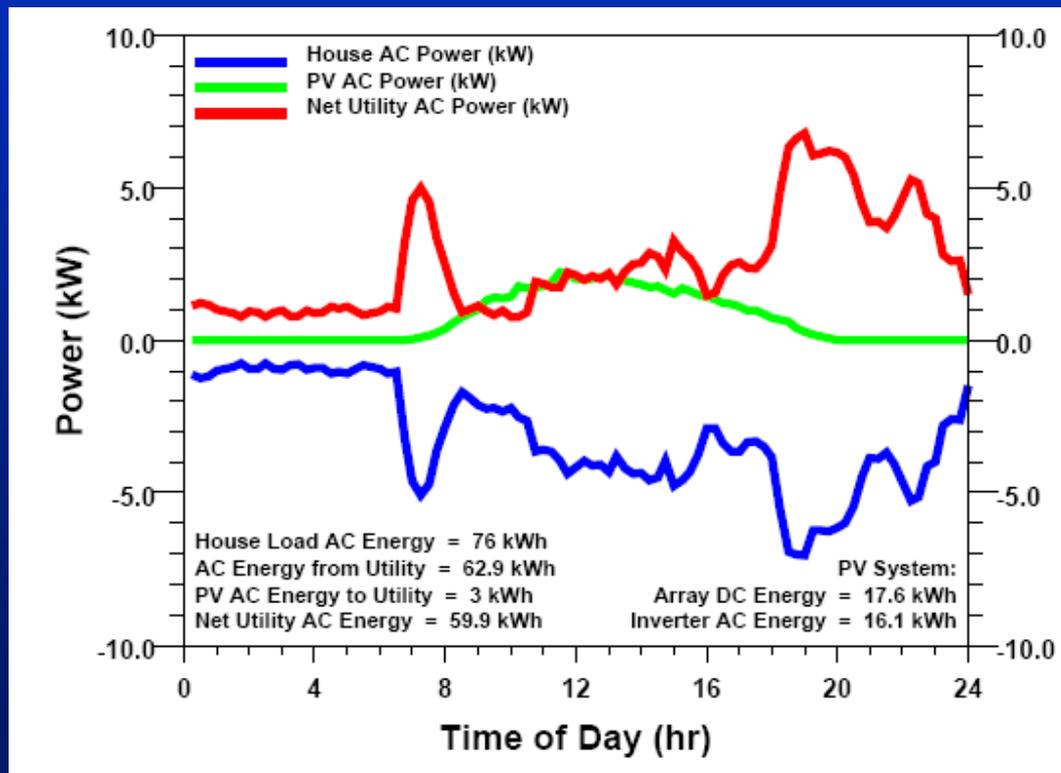
# Verifying Performance

- ▶ The DC and AC power output for interactive PV systems is a direct function of solar irradiance.



# Load Power and Energy

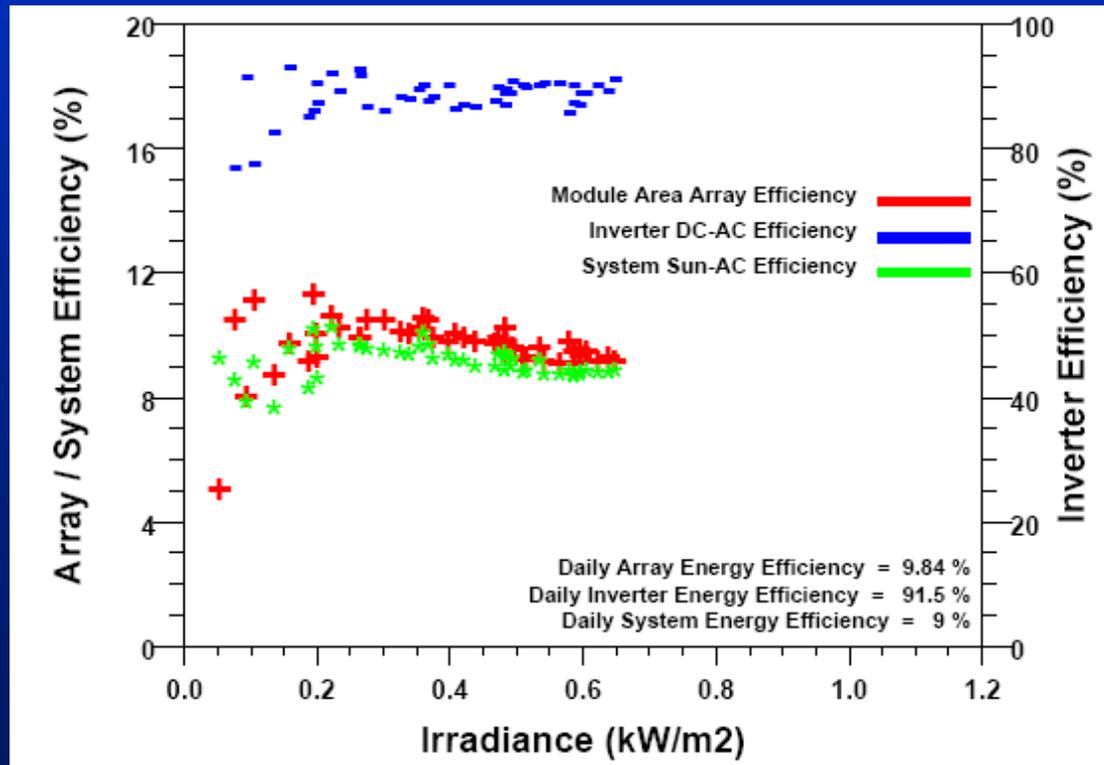
- ▶ Separate watt-hour meters may be used to measure PV system AC output, net utility power, building loads or branch circuits.



Note: House AC power demand is shown as a negative value; net utility power is shown as positive.

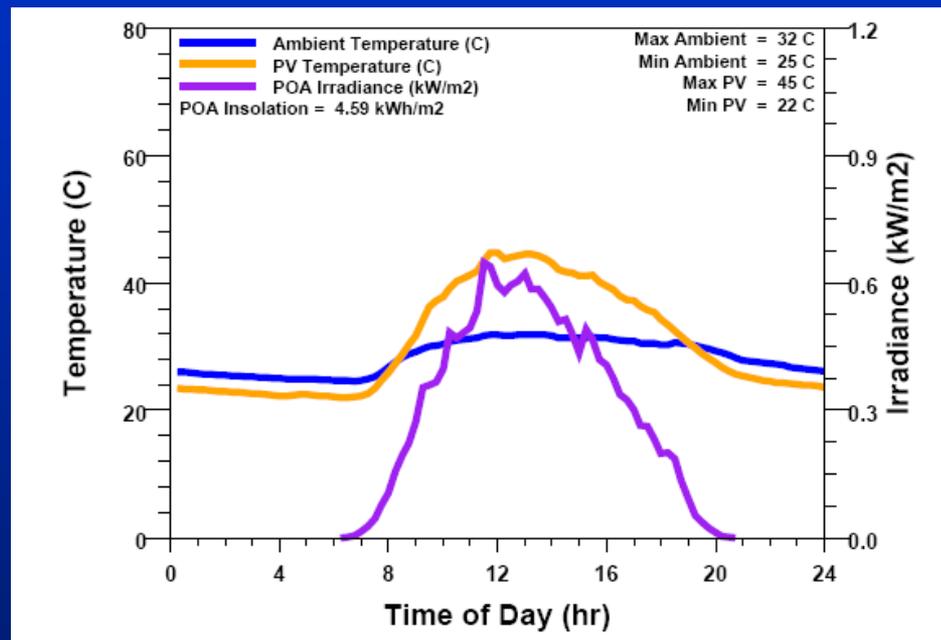
# Efficiency Measurements

- ▶ Array, inverter and system efficiencies can be calculated from measurements of DC power, AC power and solar irradiance.



# Temperature Measurements

- ▶ Array and ambient temperature measurements are used to characterize the thermal performance of PV arrays, and used to translate measured output to a reference condition.





# Maintenance Plan

- ▶ **A maintenance plan includes a list and schedule for all required system maintenance and service.**
  - ◆ Inspections of components and wiring systems
  - ◆ Evaluation of structural attachments and weathersealing
  - ◆ Cleaning and removing debris around arrays
  - ◆ Performing battery maintenance
  - ◆ Conducting electrical tests and verifying performance

# Physical Damage

- ▶ Inspect PV arrays for any signs of physical damage, such as impacts or fractures.



**Obvious impact damage**



**Less obvious fractured glass**

# PV Module Degradation

**Burned Busbars**

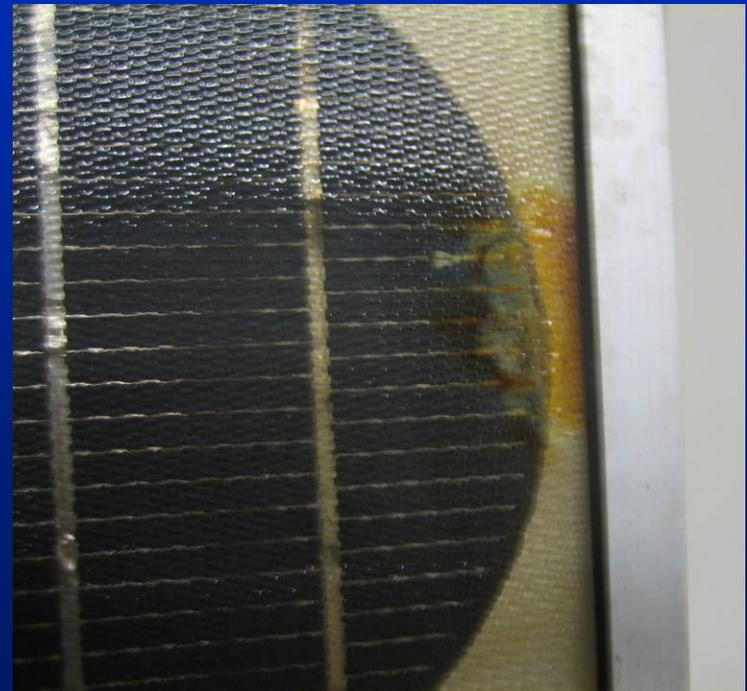


**Front Surface**



**Back Surface**

**Delamination and Corrosion**



# Shading Control

- ▶ Trees and vegetation present ongoing shading concerns, and may require trimming during maintenance to prevent excessive array shading.



# Array Soiling

- ▶ Cleaning soiled PV arrays is a common maintenance need.



*Jim Tetra*



*Sharp Solar*

# Degraded Weathersealing





# Battery Maintenance

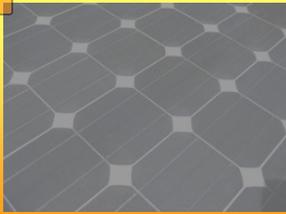
- ▶ **Battery maintenance involves various tasks depending on the type of battery and manufacturer requirements, including:**
  - ◆ Inspecting and cleaning battery racks, cases trays and terminations
  - ◆ Inspecting battery disconnects, overcurrent devices and wiring systems
  - ◆ Checking termination torques
  - ◆ Measuring voltage and specific gravity
  - ◆ Adding water
  - ◆ Inspecting auxiliary systems
  - ◆ Load and capacity testing
  
- ▶ **Observe all safety precautions and wear appropriate PPE when conducting any battery maintenance.**

# Battery Maintenance Safety

## ▶ Personal safety precautions for battery maintenance include:

- ◆ Face shields, aprons and rubber gloves
- ◆ Eye wash facilities, water and baking soda for flushing and neutralizing spilled electrolyte.
- ◆ Disconnecting means to isolate battery system
- ◆ Fire protection equipment



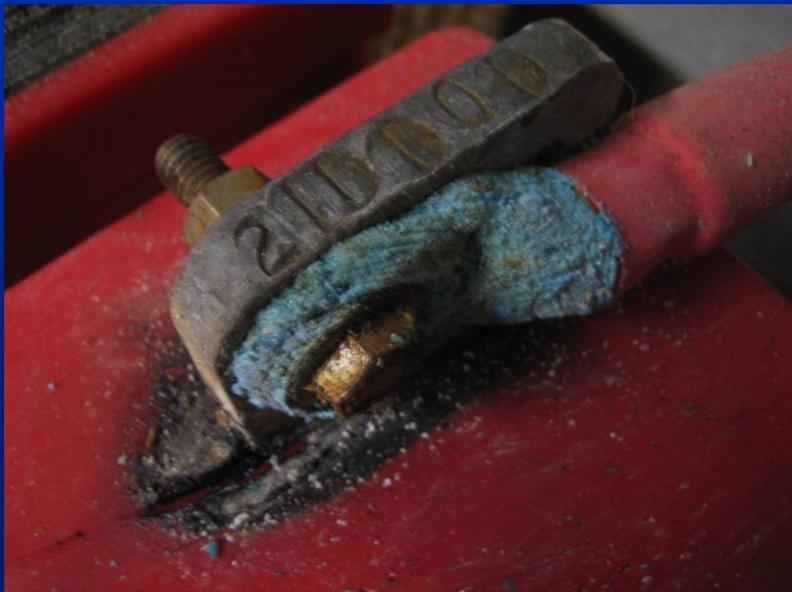


# Battery Test Equipment

- ▶ DC voltmeters are used to measure battery and cell voltages.
- ▶ DC ammeters (clamp-on type) are used to measure battery currents.
- ▶ Hydrometers are used to measure electrolyte specific gravity.
- ▶ Load testers discharge the battery at high rates for short periods while the voltage drop is recorded.
- ▶ Impedance and conductance testers may be used on some VRLA batteries.

# Battery Terminations

- ▶ Periodic battery maintenance should include checks of all terminals for corrosion and proper torque.



# Battery State-of-Charge

- ▶ Battery specific gravity and open-circuit voltage are measured during maintenance to evaluate battery health and estimate state-of-charge.

For typical lead-acid battery at 25°C

State-of-Charge	Specific Gravity	Open-Circuit Voltage (V)
100%	1.265	12.6
75%	1.225	12.4
50%	1.190	12.2
25%	1.155	12.0
0	1.120	11.8

# Hydrometers

- ▶ Hydrometers measure electrolyte specific gravity (SG).
- ▶ Archimedes hydrometers use a float and buoyancy principles to measure SG.
- ▶ Refractive index hydrometers use a prism and optics to measure SG by the angle that light refracts through a droplet of electrolyte.



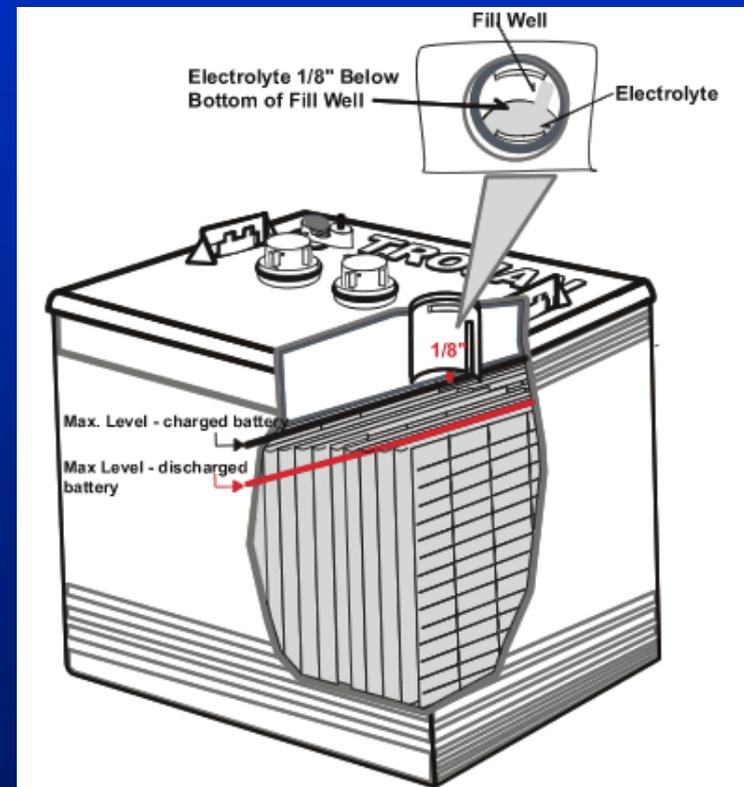
Archimedes Hydrometer



Refractive Index Hydrometer

# Water Additions

- ▶ Open-vent flooded batteries lose water due to electrolysis and gassing during charging.
- ▶ Water loss increases with temperature, charge rates and age of battery.
- ▶ Use distilled water to prevent from poisoning battery and do not overfill.



Trojan Battery Co.

# Battery Load Testing

- ▶ **Battery load testing applies very high discharge rates for a few seconds, while measuring the decrease in battery voltage.**
  - ◆ Weak or failed cells are indicated by significantly greater voltage drop.
- ▶ **Battery capacity testing involves discharging the battery at nominal discharge rates to a prescribed depth-of-discharge.**
  - ◆ Evaluates available energy storage capacity for the system.



**Battery Load Tester**

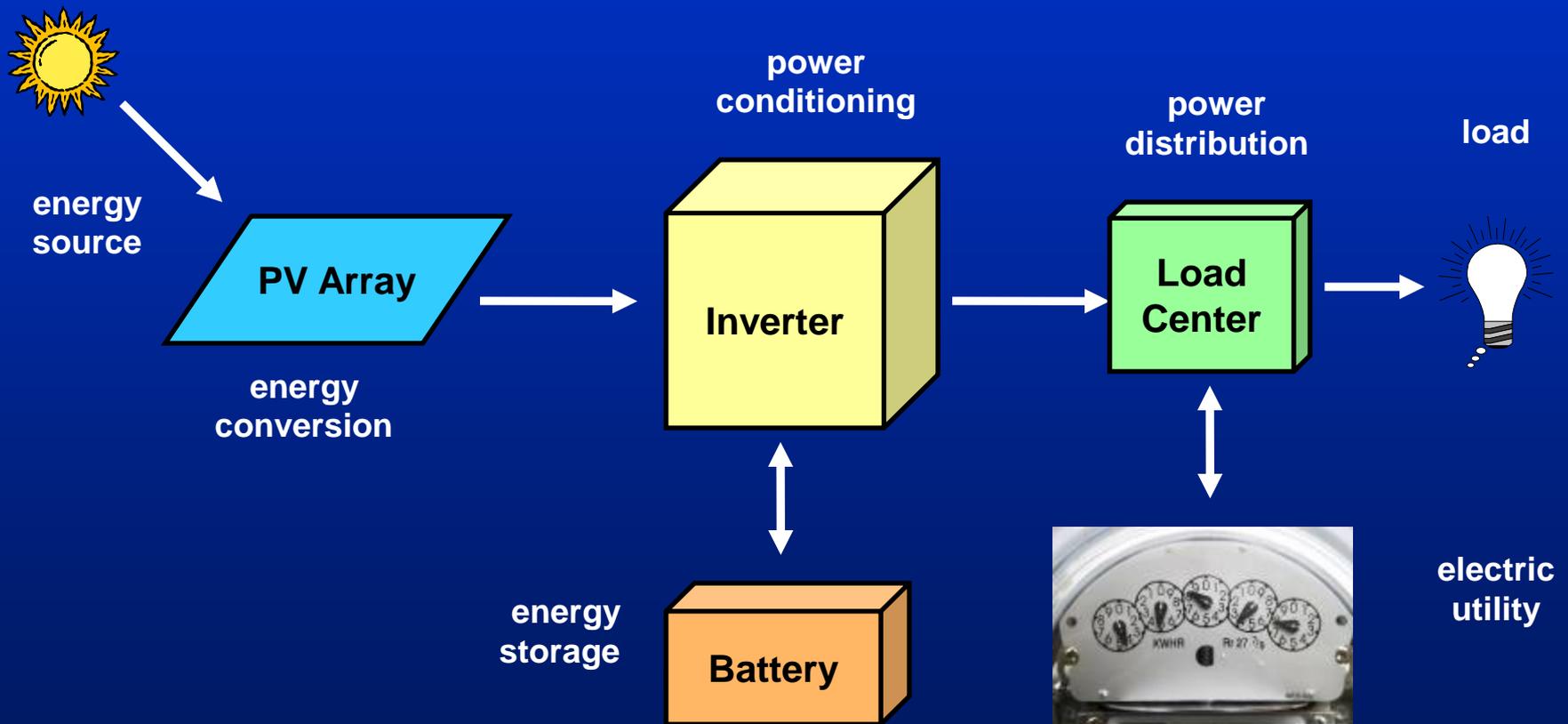
# Troubleshooting

► Troubleshooting progresses from the system, subsystem to component levels, and involves:

- ◆ Recognizing a problem
- ◆ Observing the symptoms
- ◆ Diagnosing the cause
- ◆ Taking corrective actions



# Troubleshooting Subsystems





# Summary

- ▶ **Commissioning PV systems involves the final steps, inspections and verifications prior to operating the system.**
- ▶ **A maintenance plan ensure required service is performed on a regular schedule.**
- ▶ **Troubleshooting PV systems involves observations, diagnosis and taking corrective actions.**

# Questions and Discussion

