Operation and Maintenance Methods in Solar Power Plants

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Abstract As in any power plant, a solar power plant in operation requires maintenance. Also, as the solar power plant becomes older, operation and maintenance (O&M) becomes more and more important for improving or keeping the performance of the plant. Another aspect to be taken into account is that usually the solar power plants are in remote locations with unreliable communication infrastructure [1]. Most of the remote monitoring systems need an Internet connection, and in the absence of a reliable connection, there could be problems of lack of data logging for long periods of time [6]. This makes it very difficult to diagnose and rectify problems in a timely manner. System O&M is a broad area and is the continuing focus of several industry/government/national laboratory working groups. These groups will better define the issues and develop consensus O&M approaches over the next few years. This chapter reviews the main principles of solar generation from a perspective of O&M of these plants.

1 Introduction

The principle of solar power plants is extremely simple. They consist of a field of solar photovoltaic modules connected them in series or in parallel and connected to one or more inverters. Energy is directly transformed into electricity panels and password then in the electric network to the nearest city. Like in any power plant, a solar power plant in operation requires maintenance. As the solar power plant becomes older, operation and maintenance (O&M) becomes more and more important for improving the performance of the plant. Most of the

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solar power plants are located in remote places with unreliable communication infrastructure [1]. Most of the remote monitoring systems need an Internet connection, and in the absence of a reliable connection, there could be problems of lack of data logging for long periods of time [6]. This makes it very difficult to diagnose and rectify problems in a timely manner. System O&M is a broad area and is the continuing focus of several industry/government/national laboratory working groups. These groups will better define the issues and develop consensus O&M approaches over the next few years. In this, chapter is assembled and collected into different kinds of operations and methods to maintain solar power plants existing in literature and notices of manufacturers.

2 Concentrating Systems

The most part of the techniques for generating electrical energy to warm water or another fluid requires high temperatures to reach rational efficiencies. The produced temperatures of non-concentrating sun collectors are restricted to temperatures below 250 °C. Consequently, concentrating systems should be used to generate higher temperatures. Due to their higher expenses, lenses and flaming glasses are not generally used for large-scale power plants, and more lucrative alternatives are used, as well as reflecting concentrators.

The reflector, which concentrates the rays to a focal row or central point, has a parabolic profile; such a reflector should perpetually be tracked. In common terms, a difference can be accomplished between one-axis and two-axis tracking: One-axis tracking systems focus the solar light onto an absorber cylinder in the focal row, while two-axis tracking systems do so onto a quite undersized absorber area close to the central point. The theoretical highest concentration issue is 46,211. It is prearranged since the sun is not truly a spot emission source.

The highest theoretical absorption temperature that can be achieved is the sun's surface temperature of about 5,800 °C; if the focus ratio is lower, the highest reachable heat decreases. On the other hand, genuine systems do not achieve these speculative maxima. This is because, on the one hand, it is not feasible to build an extremely accurate system, and on the other, the practical systems that transfer heat to the consumer also decrease the recipient temperatures. If the temperature transfer process stops, while, the recipient can attain significantly elevated temperatures [11].

3 Solar Thermal Power Plant

Parabolic ditch power plant is the only type of solar thermal power plant technology presented as viable working systems until 2010. In power terms, approximately 350 MWe of electrical power are installed in California, and a large amount of new plants are at present in the scheduling process in further places.

The parabolic ditch collector comprises a large shapely mirror, which concentrate the sunlight by a factor of 70 or more to a focal point. Parallel collectors make up a 250–600-m lengthy collector line, and a huge amount of parallel lines form the solar collector field. The two-axis tracked collectors pursue the sun.

The collector field can be produced from very lengthy lines of parallel Fresnel collectors. In the central line of these is a metal absorber cylinder, which is typically implanted in an evacuated glass cylinder that reduces temperature sufferers. A particular high-temperature, resistive discerning covering, moreover, reduces energy warm losses [11].

In the Californian systems, thermo-oil flows through the absorber cylinder. This tube heats up the oil to nearly 400 °C, and a heat exchanger transfers the heat of the thermal oil to a water steam cycle (also called Rankine cycle). A feed water pump then puts the water under pressure. Finally, an economizer, vaporizer, and super heater together produce superheated steam. This steam expands in a two-stage turbine; between the high-pressure and low-pressure parts of this turbine is a reheater, which heats the steam again. The turbine itself drives an electrical generator that converts the mechanical energy into electrical energy; the condenser behind the turbine condenses the steam back to water, which closes the cycle at the feed water pump.

It is also possible to produce superheated steam directly using solar collectors. This makes the thermo-oil unnecessary and also reduces costs because the relatively expensive thermo-oil and the heat exchangers are no longer needed. However, direct solar steam generation is still in the prototype stage.

3.1 Storage Capacity

In contrast to photovoltaic systems, solar thermal power plants can guarantee capacity. During periods of bad weather or during the night, a parallel, fossil fuel burner can produce steam; this parallel burner can also be fired by climate-compatible fuels such as biomass, or hydrogen produced by renewable. With thermal storage, the solar thermal power plant can also generate electricity even if there is no solar energy available.

A proven form of storage system operates with two tanks. The storage medium for high-temperature heat storage is molten salt. The excess heat of the solar collector field heats up the molten salt, which is pumped from the cold to the hot tank. If the solar collector field cannot produce enough heat to drive the turbine, the molten salt is pumped back from the hot to the cold tank and heats up the heat transfer fluid.

4 Solar Power Plants

The operation of solar thermal power plants is based on the following steps: (1) mirrors capture solar radiation at a point so as to generate very high temperatures (400–1,000 °C). (2) The obtained heat transforms the water in a steam boiler.

(3) Pressurized steam rotates a turbine which drives an alternator. (4) The generator produces an alternating electrical current [11].

There are three types of solar plants, according to the method of focusing the solar rays: Central cylindrical collectors: long mirrors rotate about a horizontal axis to follow the sun's path. The rays are focused on a tube in which the fluid used to transport the heat to the center. The central tower: fields of steerable mirrors located on the ground reflect the sun rays on a boiler at the top of a tower. Central parabolic collector: solar radiation is focused on the focal length of parables in which directional mini power station is. There are also other systems quite surprising to see incredible create electricity from solar energy, for domestic and industrial applications.

5 Trough Power Plant Efficiencies

The efficiency of a solar thermal power plant is the product of the collector efficiency, field efficiency, and steam-cycle efficiency. The collector efficiency depends on the angle of incidence of the sunlight and the temperature in the absorber tube and can reach values up to 75 %. Field losses are usually below 10 %. Altogether, solar thermal trough power plants can reach annual efficiencies of about 15 %; the steam-cycle efficiency of about 35 % has the most significant influence. Central receiver systems such as solar thermal tower plants can reach higher temperatures and therefore achieve higher efficiencies [11].

6 Solar Thermal Tower Power Plants

The solar power tower, also known as "central tower" power plants or "heliostat." In solar thermal tower power plants, hundreds or even thousands of large two-axis tracked mirrors are installed around a tower. These slightly curved mirrors are also called heliostats; a computer calculates the ideal position for each of these, and a motor drive moves them into the sun. The system must be very precise in order to ensure that sunlight is really focused on the top of the tower. It is here that the absorber is located, and this is heated up to temperatures of 1,000 °C or more.

Hot air or molten salt then transports the heat from the absorber to a steam generator; superheated water steam is produced there, which drives a turbine and electrical generator, as described above for the parabolic trough power plants. Only two types of solar tower concepts will be described here in greater detail. The potential for solar thermal power plants is enormous: For instance, about 1 % of the area of the Sahara desert covered with solar thermal power plants would theoretically be sufficient to meet the entire global electricity demand. Therefore, solar thermal power systems will hopefully play an important role in the world's future electricity supply [11].

7 Open Volumetric Air Receiver Concept

The first type of solar tower is the open volumetric receiver concept. A blower transports ambient air through the receiver, which is heated up by the reflected sunlight. The receiver consists of wire mesh or ceramic or metallic materials in a honeycomb structure, and air is drawn through this and heated up to temperatures between 650 and 850 °C. On the front side, cold incoming air cools down the receiver surface.

Therefore, the volumetric structure produces the highest temperatures inside the receiver material, reducing the heat radiation losses on the receiver surface. Next, the air reaches the heat boiler, where steam is produced. A duct burner and thermal storage can also guarantee capacity with this type of solar thermal power plant [11].

8 Pressurized Air Receiver Concept

The volumetric pressurized receiver concept offers totally new opportunities for solar thermal tower plants. A compressor pressurizes air to about 15 bars; a transparent glass dome covers the receiver and separates the absorber from the environment. Inside the pressurized receiver, the air is heated to temperatures of up to 1,100 °C, and the hot air drives a gas turbine. This turbine is connected to the compressor and a generator that produces electricity. The waste heat of the gas turbine goes to a heat boiler and in addition to this drives a steam-cycle process. The combined gas and steam turbine process can reach efficiencies of over 50 %, whereas the efficiency of a simple steam turbine cycle is only 35 %. Therefore, solar system efficiencies of over 20 % are possible [12].

9 Tower and Trough Systems

In contrast to the parabolic trough power plants, no commercial tower power plant exists at present. However, prototype systems—in Almería, Spain, in Barstow, California, US, and in Rehovot, Israel—have proven the functionality of various tower power plant concepts. The minimum size of parabolic trough and solar tower power plants is in the range of 10 MWe. Below this capacity, installation and O&M costs increase and the system efficiency decreases so much that smaller systems cannot usually operate efficiently. In terms of costs, the optimal system size is in the range of 50–200 MWe [4].

10 Dish–Stirling Systems

A parabolic concave mirror (the dish) concentrates sunlight; the two-axis tracked mirror must follow the sun with a high degree of accuracy in order to achieve high efficiencies. In the focus is a receiver which is heated up to 650 °C. The absorbed

Fig. 1 Solar oven, diameter 50 m, 3,000 °C (Algiers)

heat drives a Stirling motor, which converts the heat into motive energy and drives a generator to produce electricity. If sufficient sunlight is not available, combustion heat from either fossil fuels or biofuels can also drive the Stirling engine and generate electricity. Dish–Stirling systems can be used to generate electricity in the kilowatts range.

The system efficiency of Dish–Stirling systems can reach 20 % or more. Some Dish–Stirling system prototypes have been successfully tested in a number of countries. However, the electricity generation costs of these systems are much higher than those for trough or tower power plants, and only series production can achieve further significant cost reductions for Dish–Stirling systems (Fig. 1) [4].

11 Solar Chimney Power Plants

A solar chimney power plant has a high chimney (tower), with a height of up to 1,000 m, and this is surrounded by a large collector roof, up to 130 m in diameter, that consists of glass or resistive plastic supported on a framework (see artist's impression). Toward its center, the roof curves upward to join the chimney, creating a funnel. The sun heats the air inside the greenhouse, so the air rises up through the shaft. The turbine starts spinning, generating electricity for a nearby town. The excess heat is absorbed by the water within the dark solar panels (built on the floor of the greenhouse). During the night when there is no sun shining, the water releases the heat keeping the turbine spinning.

The sun heats up the ground and the air underneath the collector roof, and the heated air follows the upward incline of the roof until it reaches the chimney. There, it flows at high speed through the chimney and drives wind generators at its bottom. The ground under the collector roof behaves as a storage medium and can

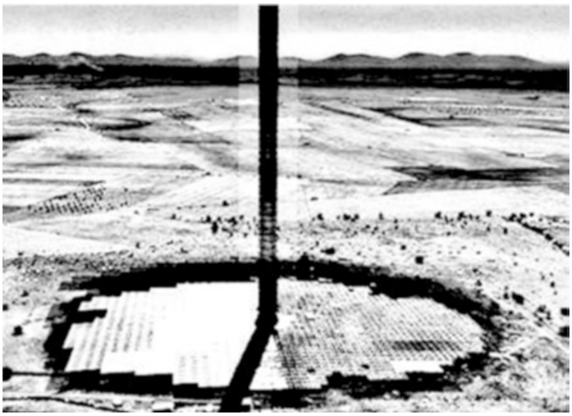

Fig. 2 Sketch of a solar chimney power plant

even heat up the air for a significant time after sunset. The efficiency of the solar chimney power plant is below 2 % and depends mainly on the height of the tower, and so these power plants can only be constructed on land which is very cheap or free. Such areas are usually situated in desert regions (Fig. 2).

However, the whole power plant is not without other uses, as the outer area under the collector roof can also be utilized as a greenhouse for agricultural purposes. As with trough and tower plants, the minimum economical size of solar chimney power plants is also in the multi-megawatt range[5].

12 Electricity Generation Costs

Due to the reduced part-load conduct of solar thermal power, plants should be installed in regions with a minimum of around 2,000 full-load hours. This is the case in regions with a direct normal irradiance more than 2,000 kWh/m^2 or a global irradiance more than 1,800 kWh/m^2. These irradiance values can be found in the earth's sunbelt; however, thermal storage can increase the number of full-load hours significantly. The specific system costs are between €2,000 and €5,000/kW depending on the system size, system concept, and storage size. Hence, a 50 MWe solar thermal power plant will cost €100–250 million. At very good sites, today's solar thermal power plants can generate electricity in the range of €0.15/kWh, and series production could soon bring down these costs below €0.10/kWh [10].

13 Qualified Personnel

The staffs are competent as "One who has expertise and knowledge related to the construction and operation of the electrical equipment and installations and has acknowledged security instructions to distinguish and keep away from the hazards

Fig. 3 Qualified person in maintenance activities

involved." Technicians can be experienced for some maintenance and service tasks but still be incompetent for others. Whether someone is a "qualified person" habitually depends on the specifics of the task at hand. Qualification is produced by both direct on-the-job training under qualified supervision and through instruction programs offered by certified educational establishments or manufacturers.

Many testing and maintenance activities necessitate two people to be completed safely and efficiently. An employee, who is being trained for a task, demonstrates the ability to perform duties related to that task safely and is under the direct supervision of a qualified person who is usually considered to be a qualified person (Fig. 3).

Additionally, in order to be considered a qualified person for solar power plant service and maintenance, a person must be trained in and familiar with: the skills and techniques necessary to identify exposed live parts from other parts of electrical equipment, the skills and techniques necessary to determine the nominal voltage of exposed live parts, the clearance distances specified by OSHA in the code of federal regulations (CFR) Part 1910.333(c) ("working on or near energized parts") and the corresponding voltages to which the qualified person will be exposed, the pertinent sections of the *NEC*, the characteristics of photovoltaic sources and hardware typically used in PV systems, and the characteristics of the hardware used in the photovoltaic system the person is working on [4, 7].

It is strongly recommended that anyone working around energized PV systems completes a minimum of the 20-h construction industry training program. Local jurisdictions may specify the necessary training, skills, certifications, or licenses required to perform the work in solar power plant area. One indicator that a person may be qualified to work on many types of photovoltaic systems is to confirm that the person is a certified energy practitioner who has met the qualifications for and passed a certification exam.

14 Safety Necessities

Safety initiates with tolerable scheduling and research. Valuable safety strategies must be in state, human resources and contractors have to be familiar with (and devoted to) safety procedures in order to avoid accident or damage. Most important safety necessities during solar power plant operating consist of the proper use of Lockout/Tagout procedures, the exploit of personal protective equipment (PPE) procedures for securely disconnecting live paths, and appropriate examination and in conformity with the entire solar power installations specific system signage and warnings.

14.1 Lockout/Tagout Procedures

Lockout/Tagout procedures are designed to ensure safe working practices and must be strictly followed whenever systems are de-energized prior to servicing. Lockout/Tagout procedures are covered by CFR, under 29 CFR 1910.147. Lockout/Tagout procedures are required when energized equipment is serviced or maintained; safety guards are removed or bypassed; a worker has to place any part of his or her body in the equipment's point of operation, or hazardous energy sources are present.

Lockout/Tagout procedure steps include: notify others that the equipment will be shut down, perform a controlled shutdown to power down the equipment, open all of the energy isolating devices identified on the equipment's specific procedure, lock and tag all energy isolating devices, dissipate or restrain stored or residual energy, verify that the equipment is completely de-energized by attempting to cycle it, and verify that the equipment is completely de-energized by testing for voltage with a voltmeter.

Proper procedure labeling includes: name of the person placing the procedure and the date placed, details regarding the shutdown procedure for specific equipment, a list of all of the energy sources and isolating devices, and labels indicating the nature and magnitude of stored potential or residual energy within the equipment.

The lock placed on equipment during servicing should be removed only by the person who placed it. The lockout devices, such as padlocks, shall be approved for Lockout/Tagout procedures applications. OSHA provides variations in Lockout/Tagout procedures that may be used depending on an approved energy control program. Safety protocols need to be followed when re-energizing equipment, including notifying others that the system is about to be energized [5].

14.2 PPE and Other Safety Equipment

Service personnel must know what PPE is required for a specific task and wear it while completing the task. PPE includes fall protection, arc flash protection, fire-rated clothing, hot gloves, boots, and protective eyewear, among other items. PPE is designed to help minimize exposure to inherent system hazards. Identification of potential hazards is crucial to the process of selecting the appropriate PPE for the task at hand. All personnel working on or near photovoltaic systems should be trained to recognize hazards and choose the appropriate PPE to eliminate or reduce those hazards.

Rubber-insulating gloves, often referred to as "hot gloves," are the first line of defense against electric shock. They should always be worn with protective leather gloves over them and inspected before each use. Additionally, OSHA requires the gloves to be re-certified or replaced at regular intervals, beginning 6 months after they are placed in service. Insulated hand tools provide an additional layer of shock protection.

As solar power plant systems get larger and direct current operating voltages up to 1,000 V become increasingly common, arc flash requirements are a growing concern and it is more common to see arc flash warning labels on combiner boxes and disconnects. Unfortunately, for maintenance personnel, many existing solar power systems have been installed without labels warning of arc flash hazard.

Service personnel needs to be able to perform on-site evaluations to determine when a higher category of PPE is required to perform the work. Tasks such as performing thermal imaging on operating inverters with opened coverings or doors or verifying voltages in switchgear commonly require arc flash-rated PPE.

Even when not required by statute or regulations, general industrial safety equipments such as hardhats, safety glasses, boots, fire-rated clothing, and safety vests are strongly recommended when working on construction sites or around live electrical equipment. The jobsite also must be equipped with appropriate fire extinguisher sand first aid supplies, and all personnel must have proper training in their use. Lastly, at least two qualified people trained in cardiopulmonary resuscitation (CPR) should be on-site at all times [10].

14.3 Safe Operation of Electrical Disconnects

Switching on or off an electrical contactor or disconnect is a process often taken for granted as safe, but it can be one of the more dangerous tasks involved in maintaining a photovoltaic system. Workers must wear proper PPE when operating disconnects, and care should be taken to use the proper technique for throwing switches.

Some of the switches used to control the dc circuits of photovoltaic systems are not rated for load-break operation. Non-load-break-rated switches, which must be labeled as non-load-break-rated, must never be opened while the system is operating. Before opening a dc switch that is not rated for load break, the system should be shut down by turning off the connected inverter.

The pivots of most disconnect switches are on the left side of the switch, and the handles are on the right. A recommended safety protocol is to follow the left-hand rule, which involves standing to the right side of the switch and using the left hand to throw the switch. This ensures that the worker's body is not in front of the switch should an arc flash occur.

The proper technique for safely throwing an electrical disconnect includes: wear proper PPE, shut the system off at the inverter, stand to the right of the switch, grab the handle with the left hand, turn body and face away from the switch, close eyes, take a deep breath and hold it (to avoid breathing in flames if an arc flash occurs), throw (operate) the disconnect lever, use a properly rated voltmeter to confirm that no voltage is present on the disconnected circuit, and use Lockout/Tagout procedures methods to ensure the switch remains off.

15 PV-Specific Signage and Warnings

Article 690 of the *NEC* [8, 9] covers the requirements for PV-specific signage and warnings that must be present on every solar power system. Additional signage may also be required by the local jurisdiction or utility. These placards and warnings need to be visible to those working on or near the systems and should never be covered or painted over.

Early solar power systems often operated with maximum system voltages less than 50 Vdc. Today, 600 Vdc systems are common, and 1,000 Vdc systems are allowed by code in commercial and large-scale installations. Qualified personnel must use properly rated equipment and be trained for servicing the higher voltage systems.

Particular care must be taken to observe and follow warning labels reading "DO NOT DISCONNECT UNDER LOAD" located on module connections, combiner boxes, disconnects, and some inverter switches not designed as a load-break switch. Failure to heed these warning labels can lead to instrument malfunction, arcing, fires, and personnel injuries.

Although it is impossible to compile a list of universally applicable safety guidelines, the authors suggest the following steps as crucial to safe work: Before operating the solar power system, read all instructions for each product. All system components must be assumed to be energized with maximum dc voltages (up to 1,000 V) until personnel verify that the voltage has been removed. All enclosure doors should remain closed with latches tightened, except when they must be open for maintenance or testing.

Only qualified personnel who meet all local and governmental code requirements for licensing and training for the installation of electrical power systems with alternating current (ac) and dc voltages up to 1,000 V (or 600 V, when applicable) should perform solar power system servicing. To reduce the risk of electric shock, only qualified persons should perform servicing other than that specified in the installation instructions [4]. In order to remove all sources of voltage from the inverter, the incoming power must be de-energized at the source. This may be done by opening the ac disconnect and the dc disconnect.

Follow manufacturer guidelines for specifics of how to de-energize the inverter. In addition, allow a minimum of 5 min for the dc bus capacitors to discharge after disconnecting the power, always testing that voltage is reduced to touch-safe levels (30 Vdc) before working on the system. Always follow Lockout/Tagout procedures. Always check for ground faults. If there is a ground mistake, there may be a voltage potential between the inverter and ground. Further, check that the normally grounded pole is properly grounded and has not been energized by a fault.

Do not work alone when servicing solar power equipment. A team of two is required until the equipment is properly de-energized, locked out, and tagged out. Verify with a meter that the equipment is de-energized. Do not open a string (also known as a source circuit) combiner fuse holder without first confirming that there is no current flowing on the circuit. Do not disconnect (unplug) module leads, jumpers, or home run wires under load.

16 General Site Annual Inspections

Preventive maintenance is the planned maintenance of plant infrastructure and equipment with the goal of improving equipment life by preventing excess depreciation and impairment. This maintenance includes, but is not limited to, adjustments, cleaning, lubrication, repairs, replacements, and the extension of equipment life. At least once a year, O&M personnel should conduct a general inspection of the solar power installation site. During this inspection, technicians should: Ensure roof penetrations are watertight, if applicable, ensure roof drainage is adequate, roof drains are not clogged, and confirm that there are no signs of water pooling in the vicinity of the array, check for vegetation growth or other new shade items such as a satellite dish, check for ground erosion near the footings of a ground mount system, confirm proper system signage is in place, confirm appropriate expansion joints are used where needed in long conduit runs, confirm electrical enclosures are only accessible to authorized personnel who are secured with padlocks or combination locks and have restricted access signage, check for corrosion on the outside of enclosures and the racking system, check for cleanliness throughout the site—there should be no debris in the inverter pad area or elsewhere, check for loose hanging wires in the array, and check for signs of animal infestation under the array.

17 Detailed Visual Inspection

The installation should be inspected regularly for issues that impact the physical integrity or performance of the PV system. A visual inspection should include the following actions: inspect the inverter/electrical pad to make sure it does not show excessive cracking or signs of wear. The inverter should be bolted to the pad at all mounting points per the manufacturer installation requirements. Depending on the size, location, and accessibility of the system to unqualified personnel, the inverters, combiner boxes, and disconnect switches should require tools or have locks to prevent unauthorized access to the equipment.

Look for warning placards including arc flash or PPE requirements for accessing equipment. Be sure to comply with all warning placards. If no placards are present, or if some placards are missing, make a note of it and install the missing placards during the maintenance visit. Consult the *NEC* and Underwriters Laboratories (UL) standards as well as the site host to determine signage requirements [4]. Inspect PV modules for defects that can appear in the form of burn marks, discoloration, delamination, or broken glass.

Check modules for excessive soiling from dirt buildup or animal droppings. Ensure that the module wiring is secure and not resting on the roof, hanging loose and exposed to potential damage, bent to an unapproved radius, or stretched across sharp or abrasive surfaces. Inspect racking system for defects including rust, corrosion, sagging, and missing or broken clips or bolts. If sprinklers are used to spray the array, check that the water is free of minerals (demineralized) as these minerals can cause gradual performance degradation. Inspect conduits for proper support, bushings, and expansion joints, where needed. In roof-mounted systems, check the integrity of the penetrations. In ground-mounted systems, look for signs of corrosion near the supports. Open combiner boxes and check for torque marks on the connections. Torque marks are made when lugs have been tightened to the proper torque value.

Ideally, they are applied during initial installation, but if not, the technician can mark the lug after torquing during a maintenance visit. A proper torque mark is made with a specialized torque marking pen. The mark is a straight line through the lug and the housing.

Over time, if the line separates between the lug and the housing, it shows that the lug has moved and needs to be retorqued. Look for debris inside the boxes and any evidence of damaging water intrusion. Look for discoloration on the terminals, boards, and fuse holders. Open the door to disconnect and look for signs of corrosion or damage. Check to make sure whether cabinet penetrations are properly sealed and there is no evidence of water ingress. Check for torque marks on the terminals. Perform a visual inspection of the interior and exterior of the inverter. Look for signs of water, rodent, or dust intrusion into the inverter. Check for torque marks on the field terminations.

If a weather station is present, ensure that the sensors are in the correct location and at the correct tilt and azimuth. A global horizontal irradiance sensor should be flat, and a plane of array irradiance sensor should be installed to the same pitch and orientation as the array. Irradiance sensors should be cleaned to remove dirt and bird droppings.

18 Manufacturer-Specific Inverter Inspection

Each inverter manufacturer will have specific requirements for inspection, testing, services, and documentation to meet its warranty obligations. Typical requirements for inverter inspections include: Record and validate all voltages and production values from the human machine interface (HMI) display, record last logged system

Fig. 4 Inverter inspection

error, clean filters, clean the inside of the cabinet, test fans for proper operation, check fuses, check torque on terminations, check gasket seal, confirm warning labels are in place, look for discoloration from excessive heat buildup, check integrity of lightning arrestors, check continuity of system ground and equipment grounding, check mechanical connection of the inverter to the wall or ground, check internal disconnect operation, verify that current software is installed, contact installer and/or manufacturer about any issues found, document findings for all work performed (Fig. 4) [4].

19 Manufacturer-Specific Tracker Inspection

Tracker manufacturers will have specific requirements for inspections, testing, service, and documentation to meet their warranty obligations. Typical maintenance or startup requirements for tracker systems include: lubricate tracker by inserting grease with grease gun into appropriate grease caps per manufacturer maintenance recommendation, check voltages inside the controller box, use a digital level to check the calibration and positioning of the inclinometers, check array for signs of parts hitting or rubbing other parts, remove vegetation that is near the drive shaft or moving components, check wind-stow operation [2].

Use appropriate (volt, ohm, dc clamp-on) meters to test: continuity of the equipment grounding at the inverter, combiner boxes, and disconnects, continuity of all system fuses at the combiner boxes, disconnects, and inside the inverters, open-circuit voltage (Voc) of all strings with the inverter off, and maximum power current (Imp) of all strings with the inverter on and at specified or recorded levels of power.

Additional testing (used when problems are identified or required by contract terms) may include: thermal images of combiner boxes (opened and closed), disconnects, inverters (external and internal at a specified operating point for a specified period of time), and modules, short-circuit (Isc) testing of strings, current-voltage (IV) curve testing of strings, insulation resistance tests of conductors at specified voltage, and comparison of a weather-corrected performance calculation of expected output to actual output of the system.

20 Manufacturer-Specific Data Acquisition System Inspection

Data acquisition system (DAS) manufacturers will have specific requirements for inspections, testing, service, and documentation to meet their warranty obligations. Typical maintenance or startup requirements for DASs include: taking voltage readings of power supplies, validating current transducer readings by comparing to calibrated equipment, and validating sensor reading by comparing to calibrated equipment. To confirm proper functionality of the DAS, the values measured by the DAS must be verified against values from devices with traceable calibration records.

Comparing the irradiance, temperature, and power measurements recorded by the DAS to values obtained from calibrated instruments will help identify sensor calibration issues that could result in the DAS data being incorrect.

The solar power industry as a whole is getting better at DAS installation and documentation, but it is still typical for DAS plans to be omitted or insufficiently detailed. As a result of such an omission, plan checkers often do not check for errors in the DAS design and inspectors have nothing to compare the as-built with for compliance. If the DAS will be tied into the building information technology system, O&M personnel should be aware that building networking upgrades or routine maintenance can cause connectivity issues.

21 General Isolation Procedures

21.1 Energized Components

Some testing and maintenance activities may require the system to be energized while workers are working on or near the equipment—string current testing is one example. Another common testing practice is to use an insulation resistance meter to induce voltage to wiring or other components in an effort to identify signs of damage to insulation or resistance/leakage from other sources such as loose connections.

Guidance for what must be done in order to work safely on energized systems is as follows: Only qualified employees can work on electric circuits or equipment that has not been de-energized using Lockout/Tagout procedures, qualified employees must be able to work safely on energized circuits, the qualified employee must be familiar with the proper use of special precautionary techniques, PPE, insulating and shielding materials, and insulated tools. Employees working in areas where there are potential electrical hazards must be provided with and use electrical protective equipment that is appropriate for the specific parts of the body to be protected and for the work to be performed.

21.2 Inverter Pad Equipment

Use the following procedures for disconnecting a single inverter from the grid: If applicable, follow the inverter manufacturer guidelines for a controlled shutdown using the HMI keypad to pilot and select a shutdown, if the inverter has an on/off switch, turn it to off, turn the ac disconnect switch on the inverter off, turn the dc disconnect switch on the inverter off, turn any remaining external disconnect switches connected to the inverter off, install lockout devices on all disconnects, locking them in the open or off position, and repeat for all inverters and switches to completely isolate the entire solar power system from the grid and the inverters from the solar power source.

21.3 Transformer Isolation

Use the following procedures for transformer shutdown: For inverters connected to the transformer, turn the on/off switch to off, turn the ac disconnect off for the inverters connected to the transformer, turn the dc disconnect off for the inverters connected to the transformer, install lockout devices on the disconnects, turn off the transformer switch, which is either a dedicated stand-alone switch or is located in the switchgear, install a lockout device on the transformer switch, repeat for all transformers to completely isolate them from the switchgear.

22 Failure Response

22.1 Emergency Shutdown

In an emergency situation: If the inverters have Emergency Stop buttons, push them in on each inverter; if the inverter has an on/off switch, turn it to the off position (this may require a key). Each inverter should be manually turned to the off position. This will immediately open the internal ac and dc contactors (if present) inside the inverter. Note that some inverters do not have an on/off switch or an Emergency Stop button. For these inverters, it will be necessary to turn the systems off using the disconnect switches attached to or located near the inverters. Do not open switches that are specifically labeled “Do not disconnect under load” until a load-break switch has been opened and current flow is stopped.

Generally, the first available upstream load-break ac switch or circuit breaker is safer to operate first (before the dc switch), because the inverter instantly shuts down the transistor bridge when ac voltage is removed. Once the system is off, the remaining switches can be opened, and the system can be locked out until the fault condition is repaired or it is safe to turn it back on.

22.2 Isolation Procedure: Inverter Pad Equipment

To isolate the inverter pad safely: Shut the inverters off through a controlled shutdown, turn off all dc and ac disconnects that feed the pad, follow the procedure in the Lockout/Tagout section for opening electrical disconnects, use Lockout/Tagout procedures to ensure the system remains off, always wear appropriate PPE and test for voltages with a properly rated meter to confirm the system is completely isolated.

22.3 Isolation Procedure: Field Combiner Box

To isolate field combiner boxes: Turn off the inverters as described above, operate the switch of the combiner by turning the handle to the off position, use a dc clamp on the meter to confirm there is no current passing through the ungrounded conductors in the combiner box, and then open all of the fuses, if further isolation of the box is needed, use the string diagrams to locate the homeruns (end connectors of the PV strings), use a clamp-on dc current meter to confirm that the homerun does not have any current passing through it, and then disconnect the string by opening the homerun positive and negative connectors and putting caps on the source circuit connectors, go back to the combiner box and use a voltmeter to confirm that each string has been successfully disconnected [7].

22.4 Isolation Procedure: Modules and String Wiring

After turning off the inverter, switches, and combiner boxes and isolating the combiner boxes from the array, disconnect individual modules from the string: Before disconnecting any string, use a dc clamp-on meter to confirm there is no current passing through the string, use the appropriate connector unlocking tool to disengage the module connector, repeat for each module to be isolated from the system, if modules are removed from a system, even temporarily, technicians must ensure that the equipment grounding system remains intact for the remaining modules.

23 Inverter Troubleshooting and Service

There is an understandable focus on maximizing return on investments and system production. System uptime and availability is a key objective of O&M. Inverters that are offline can have a dramatic negative impact on the return on investments of a PV installation. Inverter failure rates are important to return on investments, but even more important than how often an inverter goes offline is how quickly it can be placed back into service.

The type of inverter fault often dictates how quickly it can be placed back into service. Inverters with known failure modes need a failure response procedure. This may include stocking critical parts that have long supply lead times so that the system is not left offline because of a lack of spare parts.

23.1 Inverter Troubleshooting

When an inverter goes offline, technicians must determine why and correct the error as quickly as possible. They can check the HMI for reported errors and then follow the actions noted in the table jointed. Some inverter faults will clear automatically when the fault condition returns to normal, but some fault conditions require a manual reset of the inverter. The ground fault fuse and even AC fuses can be nonstandard items that are difficult to purchase. Keep replacements on hand, especially if there are multiple inverters of the same size on site or in the portfolio. Having qualified technicians available and properly equipped with common replacement parts helps maximize system uptime [4].

23.2 Inverter Service Procedures

Some inverter service actions require that the system be shut down for safe inspection. Always begin with an examination of the equipment as described in the routine scheduled preventive maintenance table and further inspect subassemblies, wiring harnesses, contacts, and major components.

The following sample inverter service checklist applies to larger inverters in industrial scale and is not intended to be complete for all models from all manufacturers: Check insulated gate bipolar transistors and inverter boards for discoloration. Use inspection mirror if necessary. Check input dc and output ac capacitors for signs of damage from overheating, record all voltage and current readings from the front display panel, check appearance/cleanliness of the cabinet, ventilation system, and insulated surfaces, check for corrosion/overheating on terminals and cables, torque terminals, connectors, and bolts as needed, record ambient weather conditions, including the temperature and whether the day is cloudy or sunny, check the appearance of both the ac and dc surge suppressors for damage or burn marks, check the operation of all safety devices (emergency stop devices, door switches, ground fault detector interrupter), inspect (clean or replace) air filter elements, correct any detected deficiencies, complete maintenance schedule card, complete written inspection report, if manufacturer-trained personnel are available on-site, install and perform any recommended engineering field modifications, including software upgrades [3].

24 Diagnosing and Testing for Low Power Production

Low power production also impacts return on investment, and O&M personnel need effective strategies for identifying and correcting problems quickly. System operators or owners may become conscientious of a PV installation's underperformance through one of the following means: A predefined DAS alert, which may be weather-related, a result of comparison with other systems in the range, or a result of comparison with other monitored parts of the system at a site with multiple inverters, a manual review of the DAS data through online gateway that indicates performance anomalies, a comparison of present performance with performance test results from preceding maintenance visits, and customer or external individual reports of a potential problem, often because of an unexpected boost in a monthly schedule.

24.1 Diagnostic Overview

Once the underperformance is confirmed, personnel must determine what is causing it. Steps to diagnosing power production deficiencies include: During routine maintenance and when diagnosing an underperforming system, the first and most important components to check are the fuses. Fuses generally must be removed from their holders to determine whether they have blown, perform a system performance data review using the DAS or a program such as the PV Watts calculator [10] to calculate the expected system output based on weather conditions and system size to compare actual to modeled systems production, dispatch a field technician to the site to do the following: Check that on-site performance meters have similar values.

Often systems will have revenue grade performance monitoring that can be compared against the inverter display totals, if there is a difference in the values, then ideally the technician can log into the DAS system (when available) to investigate, a phase that has a different output than the others could be the result of a bad current transformer or a blown fuse in the current transformer circuit (i.e., an instrumentation problem), if there is no difference in recorded values, then use the inverter operator display/interface to identify the inverter error log. See inverter diagnostics for errors that may have caused the inverter to perform at less than 100 % power [1].

Verify that the array maximum power point voltage is in the maximum power point tracking window of the inverter, using an IV curve tracer on a sample string or group of strings. Modules will degrade over time and an array that begins service at the lower end of the inverter maximum power voltage window may degrade until its maximum power voltage no longer falls within this range, further compounding the effects of module degradation.

Look for external causes of the production drop, such as unexpected shade on the array. Vegetation growth is the most common form of shading, but it is not unusual to find a satellite dish or other object shading the array that was not present when the system was built.

Take photographs of the installation during commissioning and keep a visual record of any noticeable differences during maintenance visits. Perform general system checks as necessary to identify problems by to: Check all fuses at the inverter and work out to the combiner boxes, perform Voc string testing, perform Imp string testing, validate weather sensors, look for soiling. If soiling might be the problem, test an individual string (Voc, Imp, IV curve) and then clean the string and retest, perform IV curve tracing, take infrared (IR) images of the PV cells [3].

24.2 Diagnostic Testing

Operation and maintenance staff can exploit a number of diagnostic procedures to determine the causes of power deficiencies in a PV installation as:

24.2.1 Infrared Image Procedure

This procedure describes how to properly achieve field diagnostics of a PV installation using an IR camera to detect abnormal heat signatures, within the test conditions as: IR imaging should be completed with the system operating at peak levels if possible, do not open or work in electrical boxes, during rainy or wet conditions under safety considerations: Ensure all OSHA and environmental health and safety requirements are met, especially if working on angled roofs and/or at heights greater than 6 ft, safety precautions should also be taken when working near active high voltage systems or near surfaces that may be very hot to the touch, contact local health, security, safety, and environment personnel for questions and access to pertinent documentation [3].

24.2.2 Infrared Imaging Procedure

Prior to opening the IR scan, verify that the PV array is working, because temperature differences in modules are not apparent when the system is not operational, check inverter display for instantaneous kilowatt output, check current on each string in combiner box to ensure that it is operational, if the inverter or any of the strings are not operational, these must be corrected before the test can be conducted [3].

24.2.3 Infrared Camera Settings

Set the IR camera to "auto-scaling" rather than manual scaling. This will allow for automatic adjustment of the temperature scale. The IR camera does not capture shiny surfaces such as polished metals well due to their low emissivity value. However, for most active components on a solar module such as cells, J-Box, and cables, a value of 0.95 will be sufficient. Set temperature units to Celsius. Set color palette to Iron or Rainbow. "A thermal imager interprets IR-radiated or reflected heat by assigning a visible graduated color or gray scale to a radiated portrait of the scene. The color palette displays hot spots as white with diminishing temperatures through red-orange-yellow-green-blue-indigo-violet to black being cold" [3].

24.2.4 Infrared Inspection

When sunlight is present and camera settings are properly set, point the lens at the object of interest. In the case of solar modules in operation, looking through the glass onto the active cells is the most common inspection technique. Ensure that the picture is focused, either manually or automatically. For best results, position the camera as close to the module as possible without shading it or creating a reflection in the glass surface. If possible, the distance between the camera and the surface to be measured should not exceed 3 m [3].

This will depend on the camera's minimum focal distance and other specifications. Some temperature differences will not be picked up if the camera is too far away from the module. For best results, position the camera as perpendicular as possible to the object being measured. Hot spots will be easier to see if the image is taken perpendicular to the module surface. Image quality will degrade at camera angles other than normal (i.e., perpendicular) incidence. Care should be taken to avoid shading any part of the module while capturing images. Record module serial number, time, date, picture number, and module location in the array for all issues.

24.2.5 Infrared Testing Procedure

Turn system off at the inverter, post "High Voltage," "Testing in progress," "Stay clear of photovoltaic array!" signs around all entry points to array, use LOTO procedures, record test conditions including ambient temperature and irradiance, open disconnect switch on combiner box. If there is no switch at the combiner box, open the applicable disconnect or fuse at the inverter to isolate the combiner box circuit. Isolate the output-circuit-grounded conductor (negative in a negative-grounded system, positive in a positive-grounded system) by removing the cable from its termination, remove any surge protection devices from circuits being tested (if testing at more than 50 Vdc).

Visually inspect box for signs of damage, as heat discoloration, corrosion, water intrusion, and conductors rubbing against metal in enclosure or other insulation damage. Use dc current meter to confirm there is no current present in the combiner box, open all fuse holders, and use ohmmeter to verify continuity of the box enclosure to ground.

If enclosure is not metal, verify ground wire connection to ground, test Voc of all strings to confirm proper polarity and voltage of each string [3].

24.2.6 Megohmmeter Testing

Megohmmeter or "megger" testing is a valuable way to identify weakened conductor insulation and loose wiring connections. These tests are often used in system acceptance and commissioning procedures but not often used in general maintenance unless a scrupulous troubleshooting of a fault condition is needed. The insulation resistance tester (IRT) applies a voltage to the circuit under test and measures return current to determine the insulation resistance and reliability. IRTs have various test voltage settings, such as 50, 100, 250, 500, and 1,000 V.

Generally, the higher voltage settings are better for detecting high-impedance shorts in the wiring than lower-voltage settings. However, some newer low-voltage equipment has sophisticated filtering that enables effective measurements even on circuits with PV modules. All 600-V-rated wire and PV modules should be capable of being tested at 1,000 Vdc, because they are factory proof tested at twice the maximum rated voltage plus 1,000 V—this adds up to 2,200 V for 600 V cable and PV modules. This test is short-term and will not damage the wire or module insulation.

To test specific products, including strings of modules, it is best to confirm that the testing (high voltage) will not void the warranties of those materials. It is best to get written permission for testing procedures from the module manufacturer if they do not already have approved megohmmeter testing guidelines. Some manufacturers explicitly disallow megohmmeter testing on their modules. Although it is true that some products may not allow this testing, the most common location of ground faults in PV systems is in the module wiring and modules [7].

Testing using the 500-Vdc setting may be appropriate for some modules. Lower voltages are often necessary when the system includes surge protection devices within the combiner boxes. Insulation testers are now available with 50-Vdc settings that will not damage the surge protectors. If these are used, it is important to ensure that they have filtering capable of compensating for the array capacitance. The added benefit of a low-voltage insulation test is that it can detect problems with surge protectors. Leaking surge protectors are a common fault of older PV systems [7].

Tools used for such test include: IR tester megohmmeter, PPE rated for the appropriate voltages, screwdriver or combiner box key, dc clamp-on meter, dc voltmeter, electrical tape, system drawings—string wiring diagram, warning signs: "High Voltage—Testing in progress—Stay clear of photovoltaic array!," and recording device (pen and paper, laptop or tablet preferred).

Safety considerations and test conditions are that do not open or work in electrical boxes, in wet conditions. Also, shock hazard, live voltages present, fall hazard, combiner boxes are often elevated, need for proper PPE for electrical voltage testing, recognition that normally de-energized circuits may be energized in fault conditions, and requirement for two qualified people trained.

24.2.7 Fuse Checks

Fuses blow for a reason. Whenever a blown fuse is found, investigate why the fuse blew. When replacing fuses, it is essential to source the appropriate size, type, and rating. Do not assume that the fuse being replaced was the correct size, type, and rating, because an incorrect rating or size could be the reason the fuse blew. It may be necessary to consult the product manual to ensure the correct fuse is sourced. It is common to come across operating systems with incorrect fuses in place.

24.2.8 Fuse Testing Procedure and Safety Considerations

Confirm system is de-energized with a voltmeter, use Lockout/Tagout procedures and use an ohmmeter to test the continuity of the fuse. It may be possible to get voltage through a fuse that has not completely blown but is about to blow. For this reason, having voltage only on the load side of the fuse is not enough, set ohmmeter on a brawny surface, remove the fuse to be tested from the fuse holder unless it is clear that no alternative continuity paths can exist that would provide a false reading, use meter and test the fuse by placing a lead on each end of the fuse and listening for the meter to beep confirming continuity [3].

If the beep continuity reading is not constant while still holding the leads on each end of the fuse, then look at the ohm settings for a measurement of the resistance, make sure your fingers are not touching each end of the fuse as this will give a resistance reading for an open fuse that can be confusing, look at the fuse and confirm the size, type, and rating of the fuse. If the fuse fails the test or is not the properly rated size or type, replace the fuse with the correct fuse, always test replacement fuses before installing to confirm the fuse was good when it was placed in service, fuses should never be replaced or tested while the circuit is energized. Shut the system down prior to servicing fuses. Wear proper PPE for electrical voltage testing, at least until no voltage has been verified and the source has been locked out, if applicable.

24.2.9 DC System Voc Checks

Dc voltage checks are done with the system off, but "depending on the system size" voltages of up to 1,000 Vdc may be present. Ideally, test in stable sunlight of more than 750 W/m^2. However, stable conditions more than 200 W/m^2 still allow for simple comparisons among strings do not open or work in electrical boxes; in wet conditions, perform testing at the combiner boxes.

Safety considerations and tools include: Shock hazard, live voltages present, fall hazard, combiner boxes are often elevated, proper PPE for electrical voltage testing, recognition that normally de-energized circuits may be energized in fault conditions, and requirement for two qualified people trained to use dc voltmeter, PPE, irradiance meter, temperature sensor, screwdriver or combiner box key, and recording device (pen and paper, laptop, or tablet preferred).

Voltage testing procedure is resumed as turn system off at the inverter, use Lockout/Tagout procedures, record test conditions including ambient temperature and irradiance, open disconnect switch on combiner box, if applicable. Visually inspect box for signs of damage, heat discoloration, corrosion, water intrusion, and conductors rubbing against metal in enclosure or other insulation damage. Open all fuse holders, attach red lead to red terminal on tester, and attach black lead to black terminal on tester, use ohmmeter to verify continuity of the box enclosure to ground. If enclosure is not metal, verify ground wire connection to ground, use dc clamp-on ammeter to test for current in the equipment grounding conductor.

If current is present, stop this procedure and proceed to the ground fault troubleshooting procedure. Use voltmeter to test equipment, grounding conductor to ground. If voltage is present, find source of problem before placing combiner box back into service. Test ungrounded conductors one at a time by removing them from the bussing. Wear PPE and use insulated tools to remove ungrounded conductors under a fault condition, ideally, use an alligator clip meter cable for the black lead, connect to ground, and take the red lead and individually test from the line side of the open fuse holder for the ungrounded conductor.

Record results, making a note of voltage and polarity of each string, and if polarity is incorrect, find the source of problem before placing back into service, if reverse polarity is observed, do not just switch it without further investigation to identify the problem. Re-identify and properly label conductors if a switch is made. A change to the as-built plans may also be necessary. All voltages should be within 10 % of each other. If one string is the equivalent of the Voc of one module (roughly 30–40 V depending on the module) less than the average and one string is 30–40 V more than the average, it is a good indication that the stringing is incorrect for both strings. Given the same example of 40 Voc, if one string is 10–20 V less, then there may be an issue with one of the modules, and further investigation may be necessary (such as performing IV curve tracing).

If Imp testing is going to be carried out in the same combiner box, it is best to plan the box for the Imp testing. Ensure all terminations are properly torqued. Pull on conductors to ensure a large enough loop for the current meter to attach to. If necessary, cut zip ties, close fuse holders, close disconnect, plane of array irradiance: Ensure location is not shaded, use inclinometer and compass to ensure it is in the same pitch and orientation as the array, clean with a cloth and mild soap solution if necessary, log into DAS program, place cleaned and recently calibrated handheld sensor in same pitch and orientation, compare results, if outside of acceptable range, replace sensor, noting the serial number of the new sensor for as-built updates. For ambient temperature sensor make a same procedure as here above, rather than risk damaging the module, leave the sensor in place and install the new sensor in the middle of the next closest cell.

Also for the anemometer, current transducers, voltage reference, and revenue meter have to log into DAS program, navigate program to compare programmed CT ratio to the ratio listed on the CTs, look at power factor of all three phases to confirm it is close to one with the system operating, note that power factor may be low at startup or in low-light conditions of less than 250 W/m^2, confirm good phase rotation with system running, compare revenue grade data with inverter data, noting differences [3].

Finally, the inverter direct, the maintainer has to log into DAS program, confirm system is checking in accurately, and look at system history to confirm data is not intermittent. Intermittent data from inverters can be the result of noise induced by the inverter; thus, check that the recommended shielded cable is used for communication wiring, check route of communication wiring to ensure it is away from voltage carrying conductors, confirm shield is only landed in one spot; best to do this at the DAS enclosure, confirm appropriate resistor or termination is installed in the last inverter in the chain (if required).

24.2.10 Combiner Box Level Monitoring Procedure

Log into DAS program, confirm that all boxes are visible, compare results to Imp string test results, and confirm communication to all devices, shade individual modules to confirm module mapping is accurate. Ensure location of global horizontal irradiance sensor is not shaded, use level to make sure it is level, clean with a cloth and mild soap solution if necessary, log into DAS program, place cleaned and recently calibrated handheld sensor in same pitch and orientation, compare results and if outside of acceptable range, replace sensor, noting serial number of the new sensor for as-built updates.

24.2.11 Array Washing Procedure

Depending on the site conditions, an annual or even quarterly cleaning may pay for itself in gained production. Some sites have more accumulation of dirt and other buildup than other sites. Depending on the tilt of the array and amount of seasonal rainfall, the soiling can have a dramatic impact on the overall production of the system. Most module manufacturers have specific guidelines about how not to clean modules, such as not using high-pressure water, not using harmful chemicals, and even not using cold water when the module glass temperature is hot or using hot water to clean cold modules. Thermal shock from the difference in temperature between the glass surface temperature and the water temperature can result in fracturing or breaking of the glass [11].

Safety considerations must be taken as wear rubber sole shoes with good traction to prevent slips and falls, never walk on the modules, use non-conductive extended reach broom and hose handles to reach modules and a lift may be needed to access the array. Follow a serial lift safety procedures, including wearing a harness if required.

24.2.12 Before Washing Modules

Walk the site to confirm that there are no broken modules (shattered glass). Never spray broken modules with water. Perform a safety evaluation of the site looking for safety hazards such as trip hazards or areas that will become excessively slippery when wet, plan for water runoff. If the site has a storm water prevention plan in place, determine how the used water will be collected and disposed of. If harmful chemicals are not used during the cleaning process, drain guards can be used to filter out sediments. Be aware of trip hazards introduced by having hoses spread throughout the property, cone off area if needed. Determine whether the module cover glass is too hot and will be damaged by coming into contact with cool water.

Depending on the local climate and time of year, it may be best to limit washing activities to the morning or evening hours. Identify the water source to be used. Ideally, there will be a source of water near the array. If not, it may be necessary to bring in water from an outside source, which will involve a tank or water truck. Determine the best method of getting water to the modules. Typically, a 3/4-inch garden hose is used to connect to a spigot near the array. Set up hoses and tools. If required, block or install drain guards for filtration or water capture purposes. Take a baseline production reading of the system, noting both kilowatt-hour (kWh) output of each of the inverters and weather conditions including temperature and irradiance.

24.2.13 Washing Modules

De-ionized water is preferred to prevent spotting and calcium buildup. Normal water pressure is recommended; do not use high-pressure washers. If high-pressure washers are necessary, hold the pressure source far enough away from the modules to prevent damage. As a rule of thumb, if the stream is too strong to comfortably hold one's hand in, it is too much pressure for the modules, spray the modules with water, use a soft-bristled brush to get stubborn dirt off, if needed, use a non-damaging soap, use extensions with tools to be able to reach extended distances, if needed, squeegee modules dry.

24.2.14 After Washing Modules

After the system returns to steady-state temperature (i.e., there is no remaining impact from the cooling effect of wash water), take another production reading of the system, noting both kWh output of each of the inverters and weather conditions including temperature and irradiance, clean up tools, remove any drain guards or blocks, record the washing in the maintenance log, compare production of the clean system to the previous production values.

24.2.15 Vegetation Management

Vegetation management is particularly important in ground mount systems, but is a concern for all solar installations. Vegetation can grow into and cause problems with trackers, can cause problems with array wiring, and can cause shading, which will definitely impact production but could also cause damage to an operating system. Vegetation should also be controlled around the inverter pad and other areas where electrical equipment is present. Note: PV arrays are often home to snakes, bees, and venomous animals of all kinds. Wear protective clothing and be alert for possible encounters.

Safety considerations must be taken into account as wear rubber-soled shoes with good traction to prevent slips and falls, wear PPE to prevent bites and stings from insects, snakes, and vermin. Mowing or weed trimming vegetation around a ground mount can lead to problems if the mowing or weed trimming kicks up debris that can break the glass or cause general soiling those results in underperformance [4]. Poisoning weeds can lead to environmental and health problems.

Permanent abatement at the time of installation is the ideal way to deal with vegetation management. During inspections, note the amount of vegetation growth and document it through pictures. Work with the site owners to come up with a specific vegetation management plan that involves carefully removing or cutting back vegetation that is currently shading or will eventually grow to shade parts of the array.

24.2.16 System Warranties

It is important to know and understand the warranty requirements of the specific products used in a solar power plant. Not all warranties are created equal. The O&M personnel should have a very clear understanding of the warranty terms from the suppliers. They also need to know the type of defects or problems that are covered under warranty, the duration of the warranty and also the key personnel from the supplier with whom warranty claims can be taken up and enforced in a timely manner.

Warranty requirements not followed, including documenting regularly conducted preventive maintenance, can result in a voided warranty. Typical warranty requirements are strict regarding the tasks that must be performed. However, the tasks are often simple and serve to protect the products and ensure greater long-term reliability.

25 Solar Power Plant Monitoring

Solar power plant needs to be monitored to detect breakdown and optimize their operation. Several solar power plants' monitoring strategies are depending on the output of the installation and its nature. Monitoring can be performed on site or remotely. It can measure production only, retrieve all the data from the inverter or retrieve all of the data from the communicating equipment (probes, meters, etc.). PV monitoring is the cornerstone of the o and m of a solar power plant. Monitoring includes inspection, supervision, sending signals and messages, and receiving signals from the environment [1].

The performance of monitoring depends on the performance and availability of solar power. It is therefore essential to bring in an expert organization, human, and material resources necessary to ensure effective monitoring and appropriate quality. Monitoring tools can be dedicated to supervision only or offer additional functions. Individual inverters and battery charge controllers may include monitoring using manufacturer-specific protocols and software [2]. Energy metering of an inverter may be of limited accuracy and not suitable for revenue metering purposes. A third-party DAS can monitor multiple inverters, using the inverter manufacturer's protocols, and also acquire weather-related information. Independent smart meters may measure the total energy production of a PV array system [1].

Separate measures such as satellite image analysis or a solar radiation meter can be used to estimate total insulation for comparison. Data collected from a monitoring system can be displayed remotely over the World Wide Web. For example, the open solar outdoors test field (OSOTF) is a grid-connected photovoltaic test system, which continuously monitors the output of a number of photovoltaic modules and correlates their performance to a long list of highly accurate meteorological readings. The OSOTF is organized under open-source principles—all data and analyses are being made freely available to the entire photovoltaic community and the general public. The Fraunhofer Center for Sustainable Energy Systems maintains two test systems, one in Massachusetts, and the outdoor solar test field OTF-1 in Albuquerque, New Mexico, which opened in June 2012.

Monitoring can be performed on site or remotely. It can measure production only, retrieve all the data from the inverter, or retrieve all data communicating equipment (probes, meters, etc.). Monitoring tools can be dedicated to supervision only or offer additional features. There are several technical solutions for monitoring different photovoltaic systems, depending on the type and accuracy of the information provided as well as their prices.

The first category is the first to have emerged since it comes from one of the major players in the solar system, the inverter. These solutions have the advantage

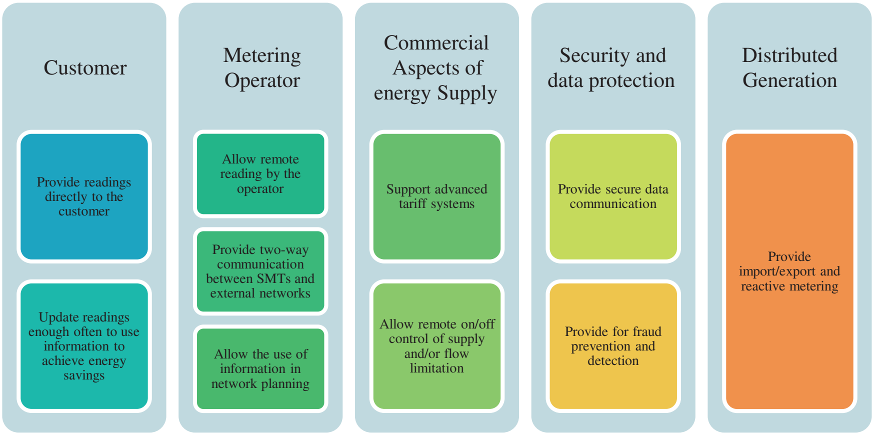

Fig. 5 Common minimum functional requirements for smart metering technologies

of back up information from the inverter and to provide a local display or transmit on the Internet, especially alerts the inverter itself (temperature, loss of connection with networks, etc.) [6]. Yet they remain expensive for single inverter, and installations are of course linked to an inverter brand. Moreover, the energy metering (kWh) is performed by the inverters more or less precise depending on the model. All major manufacturers of inverters have a data acquisition box.

The "universal" solutions connected inverters allow to overcome the major drawback of solutions inverter manufacturers, they are compatible with many brands (more or less depending on model). These data acquisition boxes connect the series connection of inverters in accordance with the protocol of each manufacturer. Universal solutions are generally more affordable than those of UPS manufacturers. The data transmission is most often an ADSL connection, but also GSM /GPRS or PSTN. According to the manufacturers, other communicating devices can be connected to these boxes. In particular, the weather sensors (cells pyranometer, anemometers, thermometers) and optionally safety devices. Note that some controllers can play the role of universal acquisition unit (Fig. 5) [2].

The last category is the most recent in the photovoltaic world. It consists of information for energy production directly back (kWh) without using the inverter. Today, there are two possibilities, each with their advantages. The first is to connect the ICT output electric meters; the second is to provide an electric meter communicating. These solutions are used to monitor production alone. To overcome the lack of information related to single monitor production, some companies offer cross-production data with a measure of sunlight (radiation in Wh/m^2) obtained by analysis of satellite images.

The measurement of radiation is essential to ensure precise control of the performance of a facility. Without this measure, impossible to verify the performance ratio (PR) of a facility. There are different solutions to track irradiance data. Either one uses one or more sensors installed adjacent photovoltaic panels or satellite data is used. With the information on the installation position, the inclination, and orientation of the panels, satellites data provide information about the radiation received by a photovoltaic system.

If these two options are compared for acquiring information, the advantage of satellite data is a lower price for sufficient accuracy. In addition, this solution requires no additional installation (and therefore no maintenance). For consequence, the data collected with pyranometers have the advantage of being more accurate. Depending on the class of pyranometer, and therefore its price, accuracy may be up to 1 % or below. Some solutions using monitoring control cells for monitoring the operation of the generator. This solution is less accurate than using a pyranometer but more economical addition as the latter [1].

Today, most monitoring systems work with photovoltaic sensors. Solutions using satellite images are fewer.

All the solutions mentioned above have either online portals or local software assigned to supervision. UPS manufacturers have almost all set up a portal data recovery, provided free with the purchase of their DAS. However, some manufacturers offer more industrial supervision software locally installed. Offer emerges publisher's specialized software for data processing, regardless of the acquisition system. These software are being developed and are beyond simple monitoring of production, should provide further diagnosis, that is to say, a more precise analysis of data. Publishers' monitoring solutions for energy meters also offer their Web software.

26 Incident Rate on Photovoltaic Installations

Think that photovoltaic installations require no maintenance over their entire life is a legend still very persistent in the solar power industry. The reality is quite different and solar power systems like any other technical equipment have abnormalities in their production and should be checked and technically framed. For this, DIN-EN standards set for regular examinations maintaining operating rules [4].

27 Efficiency Gap by Continuous Quality Assurance

Comparing the performance data of photovoltaic installations that are either collected directly on counter or recovered by a professional monitoring, we find that photovoltaic installations without blame or servicing yield losses of 5.7 %. The average ratio of performance facilities subjects to either a remote monitoring system, or a regular servicing by a technician stood at 76.8 %. Photovoltaic systems that are framed professionally by a manager or a company that specializes in solar power plant have an average ratio of performance 81.4 %.

Obviously, there are facilities that produce unframed without malfunction, but in the majority cases, small or large efficiency losses are identified much later and the operator records a decline in production. Conversely, there are facilities that despite has a performance below the average. However, this can be explained in general by major technical errors that affect negative on the performance of the installation. Most photovoltaic installations with supervision or service distinguished by the fact that the predicted total returns.

In general, it results in a difference in the PR of the order of 4.6 % and thus a relative decrease yield of 5.7 %. An operator this means that photovoltaic system that could achieve a specific annual yield of 950 kWh/kWp reached frameless an annual yield of only 896 kWh/kWp. This leads to the operator of a facility with a capacity of 10 kWc (with purchase price of 0.195 €/kWh) a financial loss of € 106 per year [10]. Individual yield loss can obviously be even higher. The research institute Fraunhofer ISE had already reached this conclusion in a study from 2008: loss of service quality performance without plants was 4.3 %.

28 Defect Classification

The defects are classified into five different categories: on the malfunctioning of the entire solar power system due to power failures or well tripping protection, decoupling of the inverter, a temporary malfunction of the UPS, a failure of the chain of modules, a problem of communication data. All events on solar power installations are based on the total number of plants examined, and then, there is an average of 5 per year reported failures that need to be analyzed systematically. Most often these are technical problems that appear on the inverter, two-thirds of malfunctions on solar power installations are assigned to the inverter.

Nearly 40 % of failures are disruptions in the operation of inverters, there are such cuts due to low insulation resistance due to cable failure or modules, or due to a shadow which leads to a decrease inverter efficiency. About a quarter of alerts are caused by failures of the inverter. Therefore, for string inverter is done in general with their replacement and central inverters to return to service is done on site by teams of specialists. Disruptions in the communication of data are about 20 % identified by the remote monitoring system errors.

These disturbances do not affect performance because only the data transfer is canceled. However, we cannot identify any failure of a technical component when perturbations in the data transmission. The judgment of the entire solar power system represents only 10 % of the cases analyzed, which is not much, but it happens more often on small plants than for large solar power plants. The reason is that, for example, in small- and medium-sized facilities, the general circuit breaker can be triggered so that the installation is disconnected from the network in case of technical problems. Failures on a single-channel module are relatively rare with only 2 % of cases and rarely contribute to the failure of solar power installations.

They represent more than 55 % yield losses. Decoupling a single inverter is about 40 % yield loss. We also note that the inverter malfunctions are the most common but they represent only 6 % of losses. It is for this reason that without a system of remote monitoring and services such failures are often not detected and lead to a long-term sensitive yield losses. Losses resulting from normal faults, in particular, failures on strings of modules do not cause major losses [1].

29 Balance Sheet

On average, a photovoltaic installation can have around 5 incidents per year that can cause a loss performance requiring detailed analysis. Operators are self-maintenance, and a permanent monitoring should expect an average yield loss 5.7 % per year. This could be avoided by the use of a service system and central station. The alerts analysis 2-year operation showed that the inverters are responsible for two-thirds of failures on solar power installations. Control both the performance of the entire system that each inverter is essential in order to identify defects before and resolve them quickly. Otherwise operator risk significant yield losses that depreciate the investment in the solar power plant.

30 Reliability in Photovoltaic Installation

As part of their marketing photovoltaic modules must be certified from standardized tests (IEC 61215 for crystalline modules, IEC 61646 for thin modules and IEC 62108 diapers modules concentration). In addition, to establish the dependability of these, the tests of IEC 61730 must also be made. However, it should be noted that the test sequences described in these standards are too short to determine the lifetime of a photovoltaic module [4].

However, manufacturers still ensure the strength of their products over a very long period (80 % of the initial power after 20 or 25 years depending on the manufacturer) only by the standards mentioned above. A reliability study would allow manufacturers to determine the warranty on their modules with more certainty and evaluate the risks they take to ensure their products as they do now. Moreover, the thermal regulation RT 2012 requires the integration of a renewable energy source. Thus, for the solar photovoltaic or a permanent solution used, it is important to understand its reliability and lifetime [11].

30.1 Potential Failures of Photovoltaic Panels

Thanks to various technical publications on the subject, possible failures of a crystalline photovoltaic module are known, and it is possible to reproduce accelerated testing. A module is considered failed when its power is less than 80 % of its original power according to manufacturers' warranties. Two failure modes have been studied in detail and highlighted, discoloration of the encapsulant which causes a significant loss of the power of the photovoltaic module and which can be reproduced by an UV exposure test, corrosion in the photovoltaic module that can be reproduced by a damp heat test. For each failure mode, an accelerated degradation test and simulation tool atmospheric conditions developed during the procedure can be used to determine the reliability curve of the photovoltaic module in real conditions of use [10].

Finally, when the reliability curve is defined for each failure mode, the total reliability of the photovoltaic module can be determined as well as its average lifespan. With this methodology, the manufacturer may specify precisely the average life of its photovoltaic modules and be able to define the proportion of modules that is likely to be defective during the warranty period.

31 Conclusions

The importance of O&M is often ignored by many developers. Considering the fact that the plant has to generate returns over a period of 25 years, a good O&M contractor, a good monitoring system and above all, a very good O&M process is very critical for the success of the solar power plant. The implementation of preventive maintenance procedures presented is a vital part of efforts promoting safe practices in the solar power plant.

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