Investigating the operations and maintenance strategy of solar photovoltaic plants in South Africa

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ABSTRACT

The REIPPPP (Renewable Energy Independent Power Producer Procurement Program) was introduced in South Africa (SA) in August 2011. By the end of 2014 more than 1000 MW was allocated to solar photovoltaic (PV) plants (Milazi & Bischof-Niemz, 2015). In Bid Windows 1, 2, 3 and 4, 45 solar PV projects were part of South Africa's REIPPPP (Department of Energy, 2014).

The engineering and construction of utility scale solar PV plants was led by foreign companies since SA has never owned or operated a utility scale solar PV plant previously. The amount of installed PV globally has increased tremendously since 2010. In September 2013 the first solar PV IPP (Independent Power Producer) was synchronised onto the South African national electricity grid. Therefore, operation and maintenance (O&M) of solar PV plants is a relatively new area for owners of PV plants. Naturally, owners of solar PV plants will want to maximise energy yield of the plant, and this is only possible by having a skilled maintenance team which follow a maintenance strategy. Solar PV plants are not maintenance free, resulting in fulltime staff performing corrective and preventative maintenance in utility scale PV plants. In this research study a review of current practices of solar O&M world-wide and in SA is discussed.

Recommendations are provided to owners and O&M managers of solar PV plants on issues such as staffing requirements based on DC (Direct Current) capacity, module cleaning strategies and O&M contracts. The research findings indicated that on average 1% of total modules installed are kept as replacement parts and two central inverters are kept as spare parts. Cracked glass, snail tracks and hot spots were the three most common PV module faults. The most common faults in the PV plant were related to communication networks and inverters.

Key words: Common Faults, Equipment Warranties, Eskom, Independent Power Producers, Inverters, Maintenance Strategies, Monitoring, Operations, Performance Indicators, Photovoltaic Modules, Solar, South Africa, Utility Scale

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AC	Alternating current
a-Si	Amorphous silicon
BW	Bid Window
CBM	Condition-Based Monitoring
CCGT	Combined Cycle Gas Turbine
CCTV	Closed-circuit television
CdTe	Cadmium telluride
CO_2	Carbon dioxide
COP	Conference of the parties
CSP	Concentrated Solar Power
DC	Direct Current
EL	Earth Leakage
EMEA	Europe, Middle East and Asia
EPC	Engineering, Procurement and Construction
GCC	Government Certificate of Competency
GMR	General Machinery Regulations
GPS	Global Positioning System
GWp	Gigawatt peak
HMI	Human Machine Interface
HV	High Voltage
IGBT	Insulated-Gate Bipolar Transistor
IPP	Independent Power Producer
IR	Infra-Red
Isc	Short circuit current of the PV module
JB’s	Junction Boxes
kWh	Kilowatt hour
LCOE	Levelised Cost of Electricity
LV	Low Voltage
Mt	Millions of tons
MV	Medium Voltage
MW	Megawatt

MWp	Megawatt peak
NERSA	National Energy Regulator of South Africa
OHAS Act	Occupational Health and Safety Act
O&M	Operations and Maintenance
OEM	Original Equipment Manufacturer
PLC	Programmable Logic Controllers
PR	Performance Ratio
PM	Preventative Maintenance
PPA	Power Purchase Agreement
PV	Photovoltaic
R	Rands
REIPPPP	Renewable Energy Independent Power Producer Procurement Program
SA	South Africa
STC	Standard Test Conditions
SCADA	Supervisory, Control and Data Acquisition
sms	short message service
US	United States
Voc	Open circuit voltage of the PV module

CHAPTER 1: NATURE AND SCOPE OF THE STUDY

1.1 Introduction

In January 2008 the power utility, Eskom, had to implement load shedding in order to prevent a national blackout. Eskom, which provides at least 95% of South Africa's electricity, could not meet energy demand at that time. Load shedding affected the economic growth of the country and revealed that South Africa was facing an energy crisis. In order for South Africans to have a sustainable energy source and to address supply security, the South African government introduced the REIPPPP in August 2011. By the end of 2014 more than 1000 MW was allocated to solar PV plants (Milazi & Bischof-Niemz, 2015). All successful Independent Power Producer (IPPs) who had signed power purchase agreements (PPAs) with Eskom were contracted to feed energy into the grid for twenty years. Ninety IPP's had been added to the South African grid by October 2015 (ESI Africa, 2015).

Solar PV plants are designed to operate for a minimum of 25 years. A basic representation of the levelised cost of electricity (LCOE) for a power plant is shown below (Cambell, 2008):

$$\text{LCOE} = \frac{\text{Total Life Cycle Cost (R)}}{\text{Total Life Time energy production (kWh)}} \qquad (1.1)$$

The total life time energy production is the estimated amount of energy in kilowatt hours (kWh) expected over 25 years. The total life cycle cost comprises the capital cost and the total cost of operations, maintenance and insurance for the 25 year period. In order for solar PV plant to be sustainable in terms of profits, the revenue from energy sales (R/kWh) is required to be higher than the LCOE value. The unit for LCOE is (R/kWh) as shown in Equation 1.1. Although the capital cost of a solar PV plant is high, it's O&M cost is relatively low compared to traditional forms of power generation. However, in order for a solar PV plant to be financially viable for its lifetime, it is vital to keep O&M costs to a minimum. Therefore, the development and implementation of an O&M strategy is a key factor in the success of a solar PV plant. The O&M of solar PV plants is relatively new in SA and therefore many contractors from all over the world are providing these services for solar PV plants in SA. This is a new skill that requires to be learnt, since the construction and operation of renewable power plants is a new market in SA. Solar PV plants are here to stay since the costs of modules are decreasing annually and manufacturers are performing research in order to increase efficiencies of the PV modules. The global community wants environmentally friendly solutions for power generation, so that we do not destroy the world for future generations. The game changer in the energy sector will be battery storage. If energy can be stored and dispatched economically then base load stations, such as coal fired or nuclear power stations, will not be as necessary and common, as they are now in SA. Furthermore, end users of electricity in the residential sector may not require grid connection if battery technology advances drastically and becomes cheaper.

Eskom has an aging fleet of power stations as shown in Figure 1-1. Most of Eskom's coal-fired power stations are planned to be decommissioned by the year 2030 since by then they have would have been in operation for longer than 40 years (Independent Entrepreneurship Group, 2015) (Figure 1-1). By 2030 Kendal 4116MW, Matimba 3990MW, Lethabo 3708MW, Tutuka 3654MW, Dhuva 3600MW, Matla 3600MW, Kriel 3000MW, Arnot 2352 MW, Grootvlei 1200MW, Camden 1510MW and Hendrina Power Station 2000MW would have been in operation for at least 40 years. The operational costs of these aging power stations will rise and become uneconomical to run. Therefore South Africa will need to construct new power stations in the future in order to meet demand.

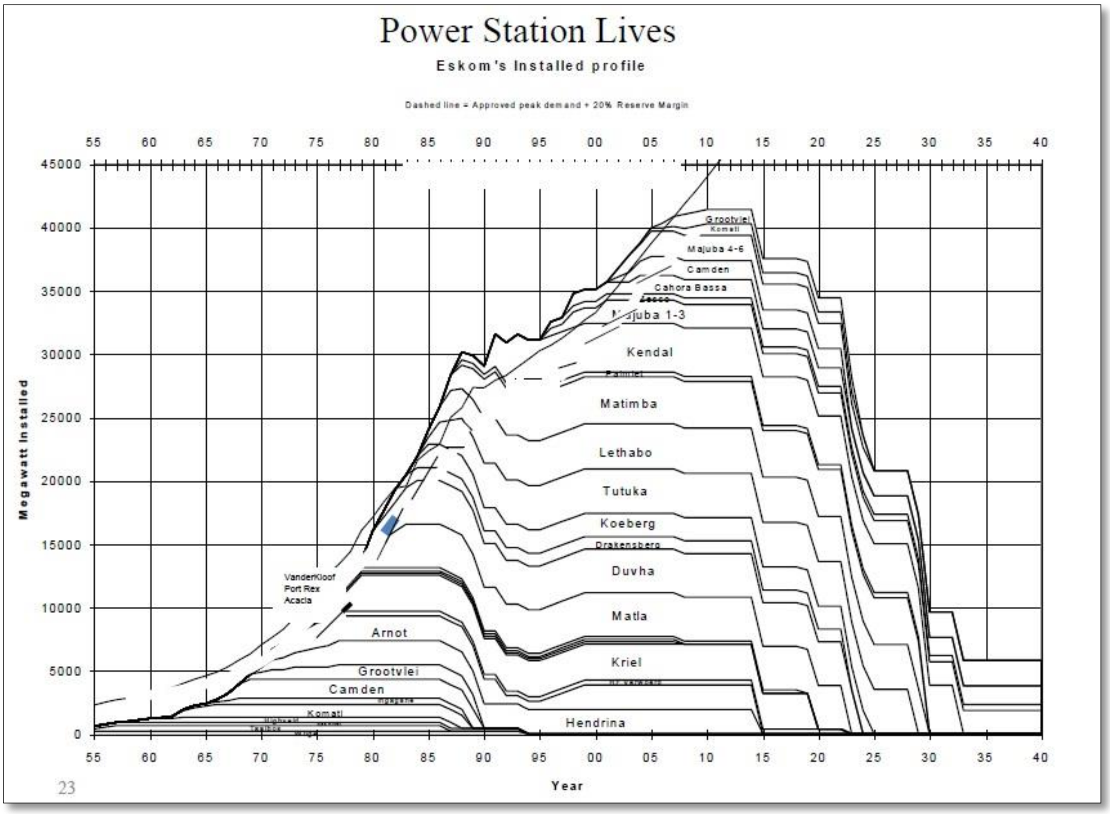

Figure 1-1: Eskom's aging power stations

Source: Independent Entrepreneurship Group (2015)

According to the Conference of the Parties (COP) 22 South Africa will not be allowed to increase emissions after 2025 (Eskom, 2016). By 2050 Eskom will not be able to emit more than 90 Mt to 190 Mt of carbon dioxide (CO_2) annually. Eskom currently emits 518 Mt of CO_2 (Eskom, 2016). Therefore, Eskom has to build emission free power plants such as hydro, nuclear and renewables, in order to meet the demand after 2025. Currently the intermittency of renewable power (solar and wind) and the high cost of battery storage limits the amount of renewable power allowed onto the South African grid. The capacity factors of renewable plants (solar and wind) are low compared to fossil fuel and nuclear power stations. The capacity factor for Koeberg Nuclear Power Station is 83.1% (Madhlopa *et al.*, 2013). The average capacity factor of renewable plants in SA is 25% for solar PV and 31% for wind (National Energy Regulator of South Africa [NERSA], 2016). Nonetheless generation capacity of the future electrical grids will be met by a combination of nuclear and renewable energy technologies.

1.2 Problem statement

The amount of installed PV globally has increased tremendously since 2010 as shown in Figure 1-2. In September 2013 the first solar PV IPP was synchronised onto the South African national electricity grid. Therefore O&M of solar PV plants is a relatively new area for owners of PV plants. Owners of PV plants are challenged with the following:

- What are the best strategies for O&M?
- What spares are required to keep availability of the plant above 98%?
- When will the inverters start to fail?
- What skills are required?
- What are the staffing requirements for a typical utility scale solar PV plant?
- What preventative maintenance needs to be performed and how often in a utility scale solar PV plant?

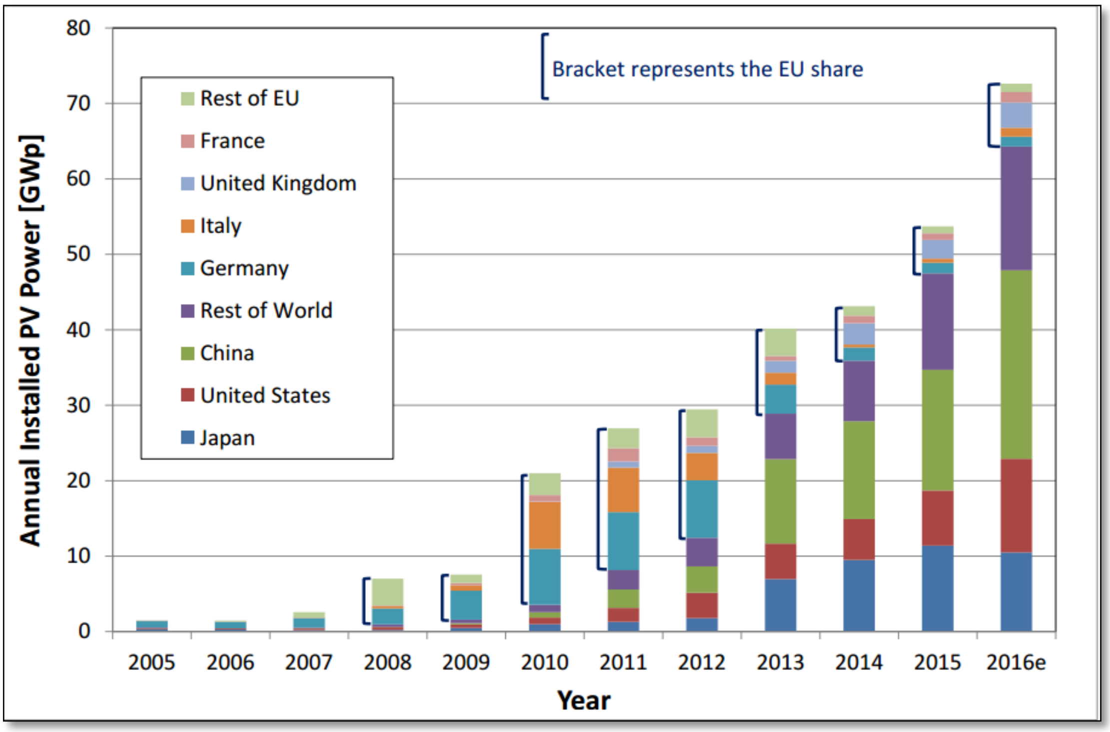

Figure 1-2: Annual PV Installation from 2005 to 2016 (GWp)

Source: European Commission (2016)

Solar PV plants in Sub-Saharan Africa are financed partly by debt and partly by investors. The debt to equity ratio is typically 70:30 (Norton Rose Fullbright, 2015). In order to increase profits, operational costs have to be kept at a minimum without sacrificing the health of the plant. Like any other industry, key success factors are required to be known in order for the owner to maximise profits and ensure that the plant has a high availability throughout its lifetime.

1.3 Objectives of the study

The following section of the dissertation outlines in brief the key objectives that were identified for the analysis of the study. The objectives were derived from the challenges mentioned in Section 1.2.

1.3.1 Primary objective

The primary objective of this study was to investigate the O&M challenges which need to be understood in order to develop and implement a successful O&M strategy for solar PV plants. This study will benefit owners and O&M managers of solar PV plants. It will also increase the knowledge base of technical personnel involved in the operations and maintenance of solar PV plants. The intention of the study is to ascertain the maintenance activities and knowledge required to operate and maintain a utility scale solar PV plant in SA.

1.3.2 Secondary objective

The secondary objective of this study is to establish what the current best practices are for solar PV O&M worldwide. The amount of solar PV installed worldwide has increased more than 10 times in the last 10 years (Jager-Waldau, 2016). Prior to the boom in solar PV installations globally, O&M for PV plants was typically a monthly visit to check if everything is in order and to perform vegetation control. Presently, due to the ‘internet of things’, solar PV plants are monitored offsite and fulltime staff perform O&M in order to increase the viability of the plant. The world is no longer concerned about whether solar PV works, that is now accepted. Now it is about PPAs and increasing energy yield of the plant through an effective O&M plan.

1.4 Scope of the study

The scope of this study is to determine the O&M strategies of solar PV IPPs operating in SA. The location of solar PV IPPs in SA is shown in Figure 1-3. As can be seen from the figure, the majority of solar PV IPPs are located in the Northern

Cape. The Northern Cape has the highest level of solar irradiation in SA as shown in Figure 1-4. Irradiation is a measure of the sun's power per a unit area. Therefore, the Northern Cape is well suited for the generation of electricity using solar modules.

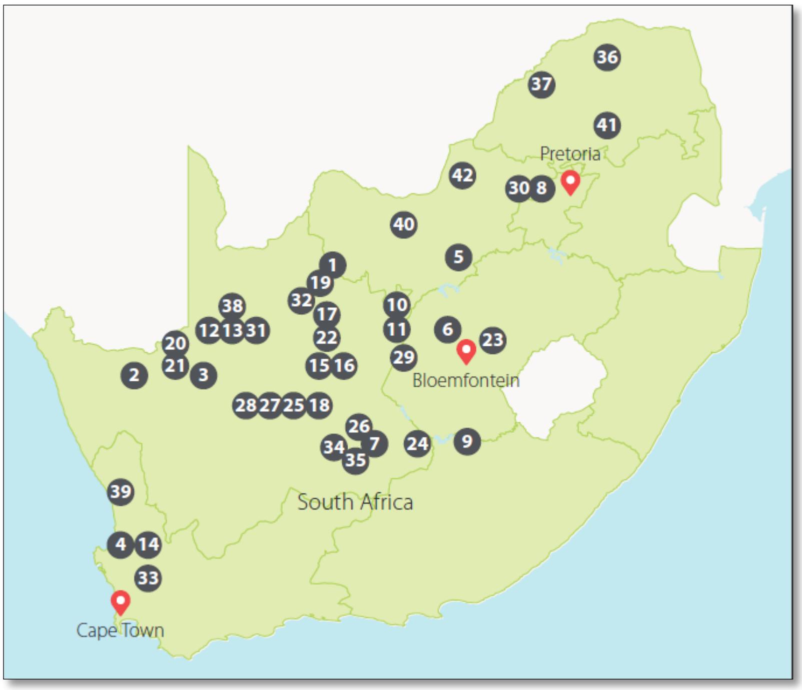

Figure 1-3: Location of solar PV plants in South Africa
Source: PV Insider (2016a)

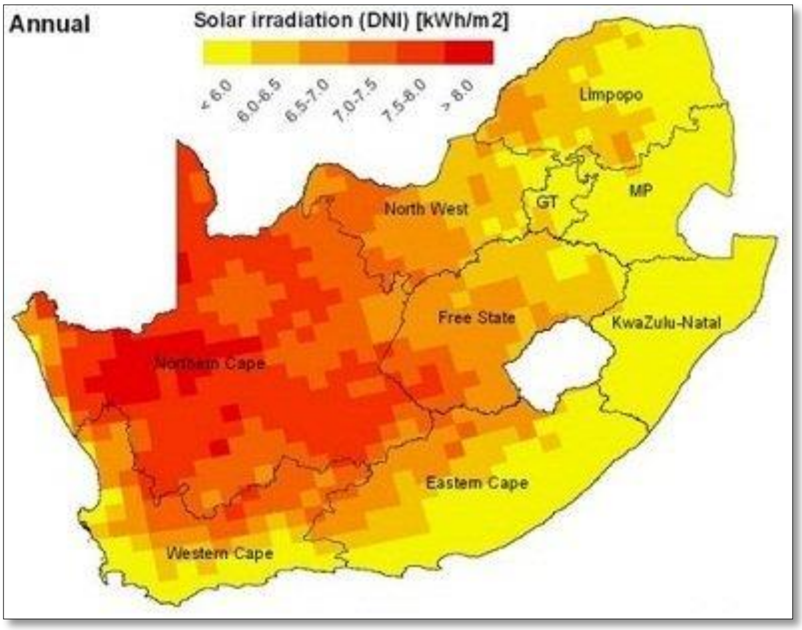

Figure 1-4: Solar radiation in SA
Source: Quinton Green Freak (2012)

1.5 Research methodology

The research methodology consisted of a literature review of current O&M practices in utility scale solar PV plants in the world and the analysis of questionnaires completed by O&M managers of solar PV plants operating in SA.

1.5.1 Literature/theoretical study

Information pertaining to the O&M of solar PV plants was obtained from the internet, journal articles, magazines, presentations and manuals.

1.5.2 Empirical study

The empirical study is on the O&M strategies of utility scale solar PV plants. Chapter 3 includes the statistical analysis of questionnaires obtained from PV O&M managers.

1.6 Limitation of the study

This study is limited to the O&M plans and practices of utility scale Solar PV plants in SA. Only activities performed by maintenance staff and equipment requiring maintenance located in utility scale Solar PV plants have been researched. The questionnaires were sent to solar PV plants that were in operation for five years or less.

1.7 Layout of the study

Chapter 1 Introduces the subject of solar PV IPPs in SA.

Chapter 2 Presents a literature review of current practices of operations and maintenance in solar PV plants.

Chapter 3 Presents and discusses the results of the empirical study.

Chapter 4 Presents the conclusion and recommendations.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter includes a discussion of current O&M practices globally for solar PV plants. The failures experienced with modules and inverters are also reviewed. South Africa's REIPPPP is discussed to show how IPP's came into existence. Staffing, manufacturer's warranties, budgeting and contractors are also explained.

The main components in a PV plant are the solar modules and inverters. In a solar PV plant modules are connected in series to form a string. These strings are paralled in combiner boxes. The combiner boxes are then connected to the input (DC side) of the inverter. The AC side of the inverter is then connected to a step up transformer. A photovoltaic cell is an electrical device that employs a photovoltaic effect and converts the light energy directly into electricity (Ameta & Ameta, 2016). A PV panel or module comprises a number of individual photovoltaic cells sandwiched between layers of glass and packaged together with a plastic or metal backing and edging. A PV array (also called a solar array) consists of multiple PV modules that are strung together. The modules in a PV array are first connected in series (like a chain) to obtain the desired voltage. The individual strings are then connected in parallel to generate more current, if required.

There are three types of PV panels: monocrystalline, polycrystalline and amorphous thin film (Solar Choice, 2009). Monocrystalline are the most expensive type of PV panel, but they are also the most efficient (15-20%). Polycrystalline are less expensive but are slightly less efficient (13-16%). Therefore, more polycrystalline PV panels are required for the same wattage compared to the monocrystalline type. Amorphous thin-film is the least expensive and the least efficient (6-8%), requiring approximately double the number of panels compared to the polycrystalline type (Maehlum, 2015).

PV inverters convert the DC voltage and current generated in the PV panels into alternating current (AC) voltage and current. PV modules for utility scale applications are either ground mounted, fixed tilted, or tracking. For the fixed tilt application, the

PV modules are arranged to face north in the southern hemisphere. When tracking technology is used the PV modules follow/track the sun from the east to west or east/west and north/south simultaneously in the case of dual axis tracking. The east/west tracking application produces the most annual energy yield compared to any other single axis application or fixed tilt application.

2.2 Operation and maintenance strategies

Solar PV plants have low maintenance requirements compared to other technologies employed to generate power such as coal fired and nuclear power stations (Miller & Lumby, 2012). The O&M of solar PV plants must be considered during the design of the PV plant. Low or no maintenance options, office space for the required number of staff, size of warehouse for spares, water requirements, control room size, level of monitoring, etc. can be decided during the design, with O&M in mind. Preventative maintenance is required for the following reasons:

1. To maximise energy yield of the plant.
2. To extend lifetime of the plant.
3. To maintain warranties of components.

Preventative maintenance lowers the risk of unplanned/corrective maintenance. Preventative maintenance is scheduled maintenance and must be done according to manufacturer's recommendations. Corrective maintenance limits the downtime of the plant in the case of faults or equipment failure. Condition based monitoring is where the plant is monitored using a supervisory, control and data acquisition (SCADA) system to detect possible failures and low performance. Maintenance is then planned accordingly.

Every utility scale solar PV installation must have a maintenance schedule as shown in Table 2-1 below, which is the maintenance schedule of a typical unstaffed PV plant. Unstaffed PV plants are usually less than 5 MW in capacity. It is recommended that every utility scale installation must have a task manual that describes the procedures for maintenance and operating activities and a strategy document that details the schedule of maintenance and the modes of failure, for the various equipment installed. Appendix 1 shows a detailed maintenance plan per component for a utility scale PV plant.

Table 2-1: Frequency of Preventative Maintenance Inspections

Apparatus	Activity	Frequency
Inverter	Inspection and cleaning Electrical connection checks Functional checks Dust filters of inverters located in polluted environments	6 months 1 month
PV Modules	Inspection Verifications of connections Electrical verification, Voc and Isc Cleaning	1 month 6 months 12 months Twice in winter
Electrical JB's	Mechanical inspection, door level/catch mechanism Corrosion, labelling, electrical connections, earthing	6 months
Structures	Inspection	6 months
Pyranometers/Reference cells	Cleaning	Weekly
SCADA System	Remote monitoring, Status of plant & sensors	Daily
Pyranometer silica-gel desiccant	Replace when desiccant changes colour to clear. Inspect weekly	Weekly
Auxiliary Supply	Inspection and electrical connection checks	6 months
Control room Containers and Prefabs	Inspection and cleaning	6 months
Weather station	Verification of connection	1 month
Transformers	Inspection	12 months
Trackers	Functioning	Weekly

Source: Naicker (2015)

The frequency of component failures in solar PV plants and their related energy loss is shown in Figure 2-1 below. Figure 2-1 shows the relative impact of component failures on downtime experienced at solar plants managed by Sunedison in 2008 and 2009. By 2009 Sunedison had constructed over 300 solar PV plants (REW, 2009).

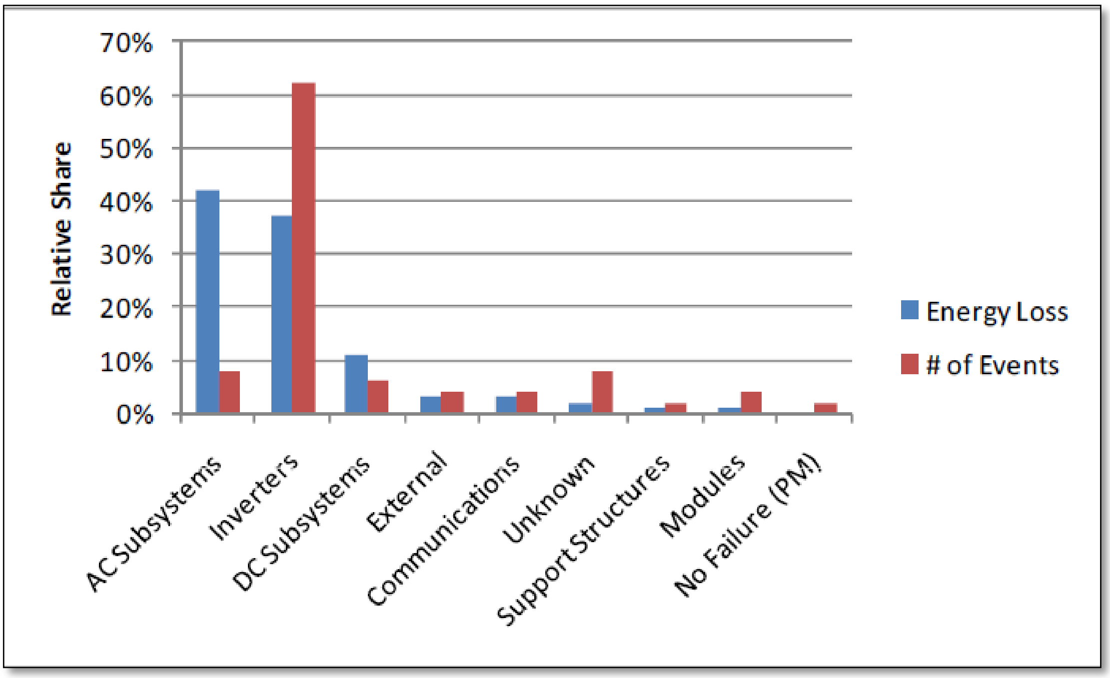

Figure 2-1: Relative frequency of failure of PV components

Source: Enbar & Key (2010)

The O&M function at a utility scale solar PV plant must achieve the following goals:

1. Monitor the plant to ensure maximum generation.
2. Ensure that safety regulations are adhered to.
3. Record all preventative and corrective maintenance done.
4. Record and store plant data.
5. Maintenance is performed according to manufacturer's recommendations.
6. Assist the owner with warranty claims.
7. Keep a list of critical spares and maintain the level of stock.
8. Maintain the security system and the grounds.
9. Reduce the risk of the plant being unavailable.

According to Williams (2010), solar PV maintenance is more about analysis of data, possible failure of plant components and management of contracts. In order to ensure that the plant is operational it is vital for the solar PV plant to be monitored daily. Figure 2-2 illustrates the difference between maintenance and operational activities and all the activities required to be performed by the O&M department of a utility scale solar PV plant. The O&M department is expected to perform asset management as well.

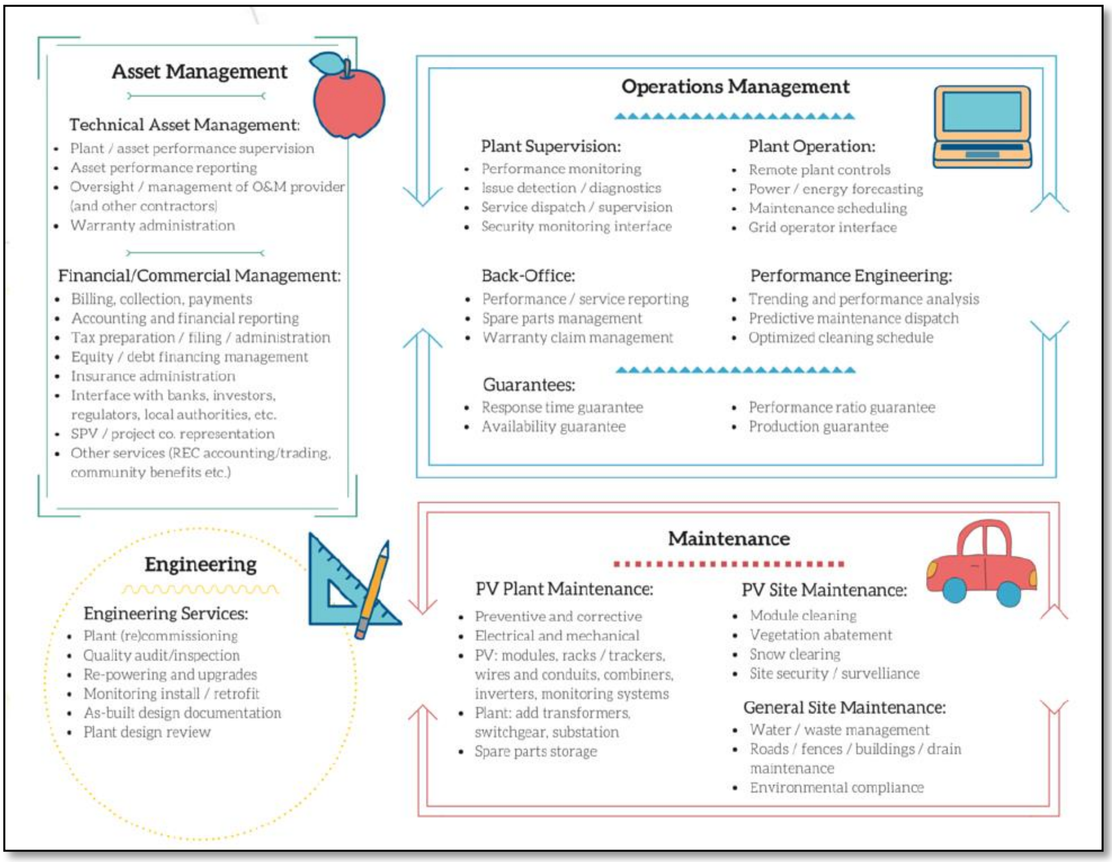

Figure 2-2: O&M responsibilities

Source: Solar Power Europe (2016)

2.2.1 Infra-red thermography

In order to locate defective panels and hot spots quickly in large solar plants, a thermal imaging camera mounted on a drone can be used. A cracked panel is hotter than the other surrounding undamaged panels. The cracked panel can be seen easily using an infra-red (IR) camera as shown in Figure 2-3. With an IR camera, large areas can be scanned quickly. Handheld IR cameras are also employed in solar PV plants. However, using handheld IR cameras is labour intensive and time consuming. Therefore, in a typical utility scale PV plant, only a portion of modules is inspected each year. Using an IR camera to locate defective panels takes significantly less time than using an IV curve tracer. An IV curve tracer measures the current and voltage of a PV module from the short circuit condition to the open circuit condition. The corresponding graph obtained from an IV test is used to determine if there are any defects in the module. The IR camera picks up hot spots caused by damaged bypass diodes, cracked cells and failed solder joints (Brearley, 2016).

Failures of modules almost always release heat, since defective modules that are not converting the rated percentage of irradiance into electricity will invariably get hotter than modules that are converting the rated percentage of irradiance into electricity. Once the IR camera has identified a defective panel, the IV curve tracer can be used to analyse the degradation of the module. According to Rob Andrews from Heliolytics, assessment for a 10 MW PV plant can be completed in 20 minutes using aerial thermal imagery (Brearley, 2016).

Figure 2-3: IR Thermography

Source: Multirotor (2017)

2.2.2 Tracker maintenance

Solar PV tracker systems require periodic maintenance. Tracker systems may consist of components such as motors, hydraulic systems, actuators, PLCs, control systems, inclinometers, relays and global positioning system (GPS) devices. Moving parts will have to be greased and the operation of the trackers must be checked daily. A single axis tracker fixed facing the East direction will provide significantly less energy yield than a fixed system facing North in SA. Therefore, all trackers must be operational to maximise energy yield.

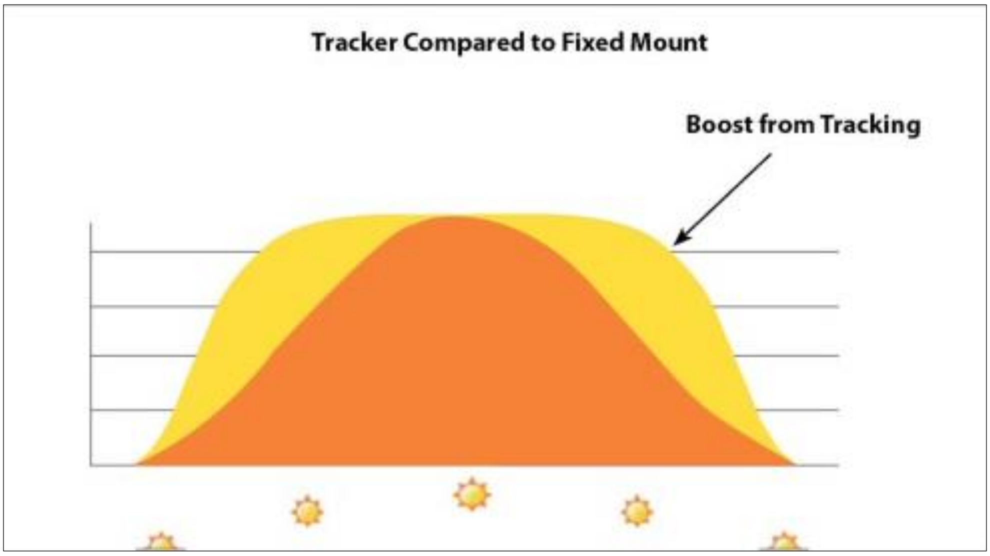

Figure 2-4: Tracker vs Fixed
Source: Missouri Wind and Solar (2017)

Figure 2-4 above shows the additional energy harnessed from a tracker system compared to a fixed system. This additional energy is prevalent only when the sun is high in the sky from spring to summer to autumn. Trackers must be checked to see if they are colliding with the fixed part of the structure or the junction box. Some components may require calibration. Tracker systems may be single axis or dual axis. Figure 2-5 shows a single axis tracker.

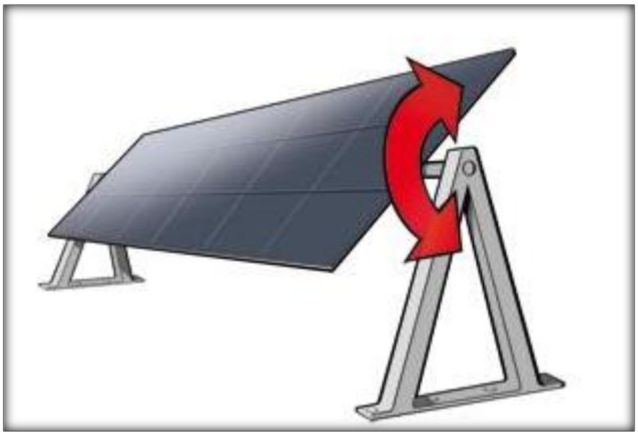

Figure 2-5: Horizontal single axis tracker
Source: Home CSP (2017)

2.2.3 Spares

In order to limit downtime of the plant and to maintain high availability spare part management is critical. It is the responsibility of the O&M function to keep inventory of critical spare parts. In SA utility scale solar PV plants are usually located hundreds of kilometres away from major cities and manufacturers. Furthermore, some manufacturers have to import spare components into the country such as control cards used in inverters, monitoring cards used in combiner boxes and tracker controls. Table 2-2 shows a list of minimum spares required at a solar PV plant. The list of minimum spares must also include consumables such as cable ties, nuts, bolts, screws, lugs (insulated and uninsulated), panel wire, etc., since they will be required when replacing/repairing electrical equipment.

Table 2-2: List of spares

Fuses used in inverters, combiner boxes, control circuits and SCADA system
PV Panels with MC4 connectors and solar cable
Spares for inverters (cards, contactors, MCB's and power stacks)
Spare UPS
Fuses and fuse holders for MV/LV voltage transformers
SCADA spares such as protocol converters
Junction boxes
Inclinometers and cards for tracker controls
Motors and oil for tracker system
Inclinometers
Spares for the security system
Pyranometers, rain gauges, anemometers and reference cells.
Spare inverters
Trip coils, under-voltage and closing coils for LV and MV circuit breakers

2.2.4 Module cleaning

Washing/cleaning panels is an extremely important task that requires to be done at most solar PV Plants. This is location and consequently weather dependant. Soiling on PV panels affects the energy yield of the PV plant. In the Highveld of SA peak power can decrease 30% to 40% due to the accumulation of dust over a period of three months, when there is no or little rain, and when module cleaning is not performed. The accumulation of dust is more severe on panels that have low tilt angles. The degree of soiling depends on environmental conditions such as dusty conditions, mining activities and agricultural activities, dew, etc. Soiling is now a crucial part of research for owners and operators to increase performance in solar PV plants (Rochas, 2016). Furthermore, there is a growing concern amongst PV plant owners/operators that if soiling is allowed to accumulate it may damage the panel by causing shading which could lead to hotspots, or the chemical composition of the dirt/dust itself may corrode/tarnish the glass. Modules can be cleaned manually with a squeegee and water or with a tractor that has an attachment for cleaning. The tractor will have a trailer or some arrangement to carry the water. These tractors could also be used to cut grass. A tractor equipped with attachments for cleaning is shown in Figure 2-6. PV module robots can also be used to perform waterless cleaning of modules. Pressurised air or dust brooms can also be used to clean panels. Borehole water can be used to clean panels. Typically, three litres of water is required to clean 1m^2 of PV panels (EDP Renovaveis, 2013). If there is no water on-site then water must be trucked in for module cleaning. This can be very costly.

Figure 2-6: Tractor with module cleaning attachments

Source: Timperley (2016)

A cost benefit analysis must be conducted to determine the frequency of cleaning. If cleaning staff are permanently employed and water is available onsite cleaning can be as frequent as every month during the season when there is no rain. Reference cells used to measure the irradiance of the sun can be used to verify whether cleaning is required. As shown in Figure 2-7 below, this involves cleaning one cell daily and not cleaning the other cell. The measured irradiance from the reference cell that is not cleaned will give an indication of the soiling on the PV modules. Typically, if there is a constant difference of greater than 50 W/m^2 measured between the two reference cells then cleaning is required. However, the plant manager must calculate the loss in revenue versus the cost of cleaning. The 50 W/m^2 (difference in irradiation measurement between reference cells) indicates the irradiance loss due to soiling. From the irradiance loss the energy loss can be calculated. Before authorising the washing of panels the plant maintenance manager must check the weather forecast to verify that there is no rain predicted for the next few days. In SA where the solar resource is high the benefit of cleaning can be quickly realised, since soiling decreases the amount of irradiation reaching the solar cells. Another method for checking the power loss due to soiling is to use an IV-curve tracer to measure the peak power of a soiled panel vs the peak power of a cleaned panel or a short circuit test (Shrestha & Taylor, 2016).

Solar panels should ideally be washed in the early morning or late afternoon in order to prevent thermal fractures of the modules. Chemicals used in the cleaning process should not cause harm to the glass of the panel nor the environment. Although the use of de-ionised water is recommended by some panel manufacturers for washing panels, the following sources of water can possibly be used for cleaning in SA:

1. Borehole water;
2. Borehole water with reverse osmosis plant;
3. Municipal water; and
4. Municipal water with reverse osmosis plant.

Recommendations for cleaning solar PV modules by various manufacturers are shown in Appendix 2.

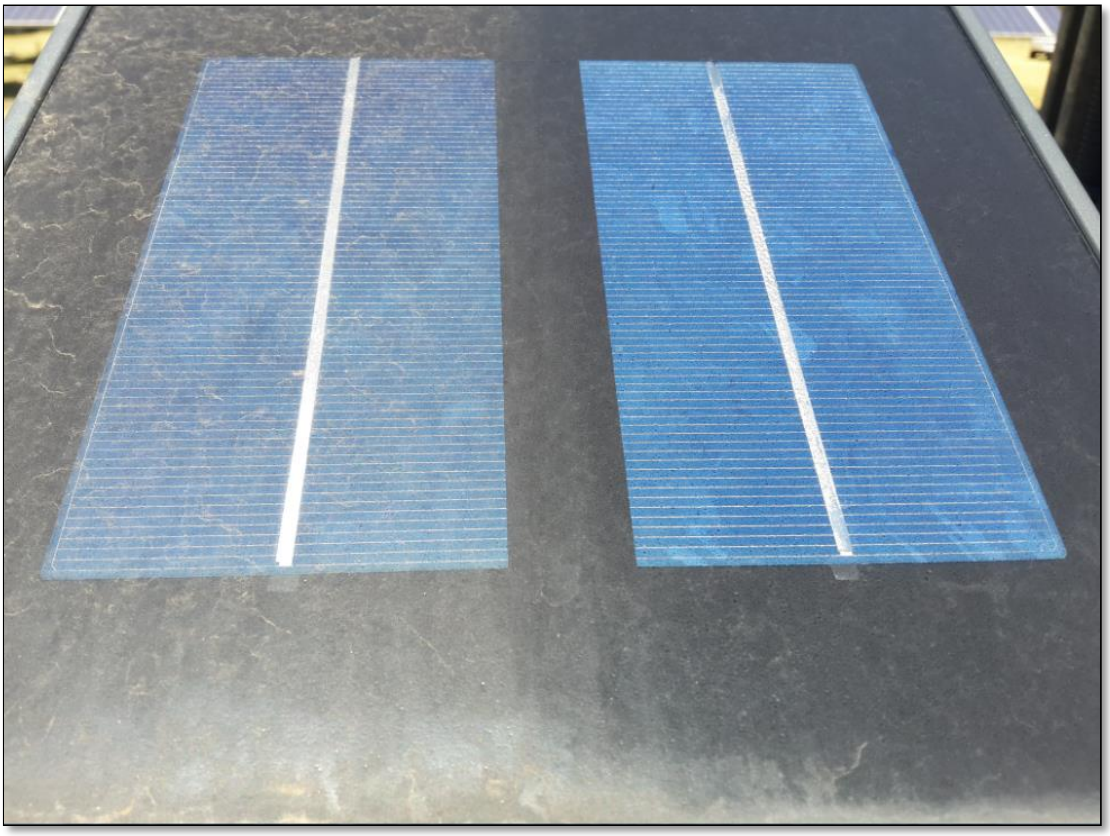

Figure 2-7: Reference cells
Source: Naicker (2015)

2.3 South Africa's REIPPPP

South Africa's REIPPPP started in August 2011. The process was supervised by the Department of Energy, NERSA and Eskom's single buyer office. Twenty-year PPAs were awarded to successful bidders. In Round 1 there was no power volume cap and the ceiling price was disclosed (International Renewable Energy Agency, 2013). This resulted in Eskom paying high prices per kWh for solar PV as shown in Figure 2-8 in red. In Round 2, a volume cap was introduced and the ceiling price was not disclosed to bidders. This created competition which resulted in much lower prices. Table 2-3 shows the average rates offered to IPPs for the five bid windows.

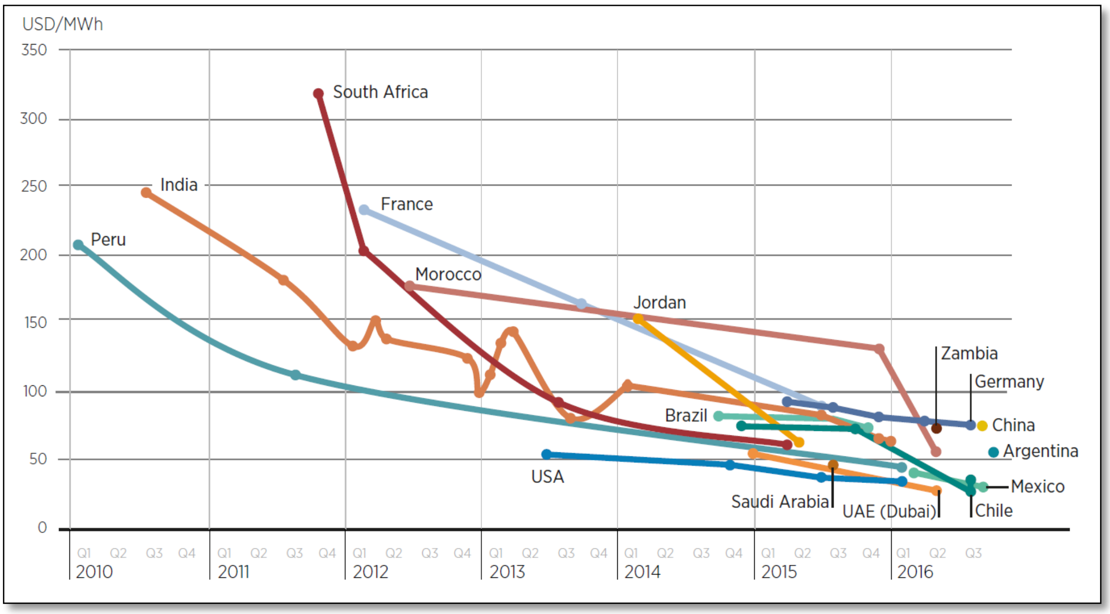

Figure 2-8: Utility scale solar PV bid prices from around the world

Source: International Renewable Energy Agency (2017)

2.4 O&M budgeting

According to Enbar and Weng (2015), O&M practices in the solar PV industry are not standardised. This has resulted in budgets for O&M being highly inconsistent. In the United States (US) the current cost for constructing a utility scale solar PV installation is $1.69/W (Enbar and Weng, 2015). Therefore, the cost per MW installed in the US is $1.69 M. This value has decreased 80% in six years from 2008 to 2014. With an exchange rate of R14.00 to the US dollar this cost is R23.66 M. In SA the average price per kWh offered for solar PV in round 1 compared to round 4 had dropped by 75% (Department of Energy, 2014). Table 2-3 below shows the average rates offered to IPPs from bid windows 1 to 4. Therefore O&M cost becomes a critical factor to realise profit if the price per kWh offered to IPPs gets lower at each successive bid window. According to Enbar and Weng, (2015) there is no “one size fits all” method to create an O&M budget; however, a wide structure exists to create one. The reason for this is that plants vary in installed capacity, tracking vs fixed, design, PPAs and O&M agreements, etc. O&M service providers generally inflate costs whilst engineering, procurement and construction (EPC) contractors tend to lower the costs of O&M, in order to attract business.

Table 2-3: Average price in South African rand per PPA – Bid windows 1 to 4

	BW1	BW2	BW3	BW3.5	BW4
Onshore Wind	1.36	1.07	0.78		0.68
Solar PV	3.29	1.96	1.05		0.82
Solar CSP	3.20	3.00	1.74	1.62	
Landfill Gas			1.00		
Biomass			1.49		1.45
Small Hydro		1.23	1.49		1.12

Source: Department of Energy (2014)

It is envisioned that well maintained central inverters with some component replacement will last the life time of the solar PV plant. However, most inverter manufacturers state that it is more cost effective to replace the inverter completely after 15 years (Briones & Blasé, 2011). Replacement of string inverters is most likely to take place after 10 years in operation. Failure of an inverter will definitely happen sooner or later (Williams, 2010); therefore a reserve fund must be set aside for inverter corrective maintenance after the warranty period. Abakus Solar USA allocates 5% of its annual revenue to a reserve fund for inverter replacement (PV Insider, 2016b). The world has seen a significant growth in the deployment of utility scale plants in the last seven to eight years (Enbar & Weng, 2015), but inverters only need to be replace after 15 years so there is no data yet on inverter replacements.

2.5 O&M contracts

O&M contracts are most likely to be designed as either fixed price or pay per task. Fixed priced contracts are usually more expensive if the PV plant is staffed daily. Pay per task contracts would ideally suit roof top installations (<1 MW), where physical plant inspection is usually performed once a month. Fixed price contracts are usually in place for utility scale PV plants, where the equipment warranties are still valid. Outside the warranty period given by the EPC contractor and/or equipment manufacturer, the O&M service provider tends to increase the price of his/her services. After the warranty period has elapsed the owner also bears the cost of replacing components upon failure. Performance guarantees such as availability, performance ratio and sometimes specific yield are included in fixed term contracts. Availability guarantees are usually set at 98%. In order to increase availability of the solar plant some maintenance activities can be performed at night. O&M contracts can also include penalties for not meeting performance guarantees or rewards for exceeding the energy yield. The contract must also include the frequency of preventative maintenance to be performed on all components. The EPC contractor usually performs O&M for the first two or three years of operation, since this coincides with the defects warranty period. Short term contracts (one to three years) are encouraged for solar PV plant owners to take advantage of the possibility of O&M costs decreasing and the knowledge gained from operating and maintaining a specific solar PV site.

According to Enbar and Weng (2015), the O&M (preventative and corrective) cost per kW/year is between $20 and $22 in the US, for fixed tilt systems. Therefore, for a 10 MWp the O&M cost per year will be between $200,000 and $220,000. However, O&M costs per kW/year will decrease as the size of the increase of PV plants. This is because the fixed costs will be shared between the increasing number of solar modules and inverters. When budgeting, at least 10% to 20% of yearly O&M costs should be reserved for corrective maintenance. For corrective maintenance in inverters and communication networks it is expected that some new components have to be procured. Figure 2-9 below shows the percentage of total maintenance cost of key components over the 25-year life time of a solar PV plant.

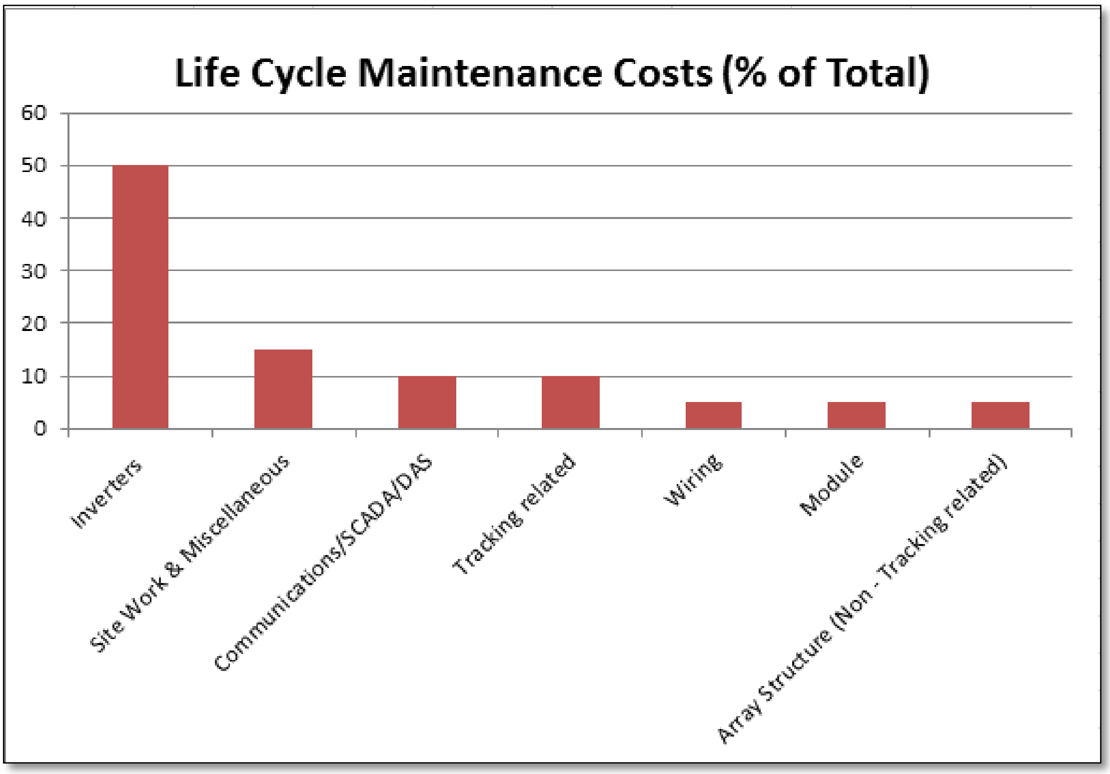

Figure 2-9: Life cycle maintenance costs (% of total)

Source: Enbar and Key (2010b)

Table 2-4 below shows total O&M costs together with reserve amount for inverter replacement and fixed overheads, for a 10 MW plant in the US. As can be seen for fixed tilted modules, the costs for preventative maintenance are greater for thin film modules (CdTe and a-Si) compared to crystalline modules (c-Si). This is because thin film modules have a lower efficiency than crystalline modules and thus more thin film modules will be installed per MW when compared to crystalline modules. Tracking systems require more maintenance than fixed systems. This is because tracking systems may have motors and hydraulics. Furthermore, inclinometers could fail periodically.

Table 2-4: Utility-scale solar PV plant O&M estimates

O&M costs ($/kW-yr)	Fixed Tilt c-Si	Fixed Tilt CdTe	Fixed Tilt a-Si	Tilted Single Axis Tracking c-Si	Single-Axis Tracking c-Si
Scheduled maintenance/cleaning	$20	$25	$25	$30	$30
Unscheduled maintenance	$2	$2	$2	$5	$5
Inverter replacement reserve	$10	$10	$10	$10	$10
Subtotal O&M	$32	$37	$37	$45	$45
Insurance, property taxes, owner's cost	$15	$15	$15	$15	$15
Total O&M	$47	$52	$52	$60	$60

Source: ScottMadden (2010)

An O&M contract must state in detail the following (Miller & Lumby, 2015):

- Activities to be performed;
- Owner's responsibilities;
- Standards, legislation and guidelines that will be applicable at that site;
- Conditions of payment;
- Performance guarantees;
- Formula used to calculate performance ratio, availability and specific yield;
- Formula used to calculate penalties due to under performance;
- Legal aspects; and
- Terms and conditions.

Most utilities are outsourcing O&M to third party contractors (Stolte, 2010). However, as the installed capacity of solar increases, the utility will tend to employ in-house staff. By using in-house staff, the familiarity of the staff with regards to PV maintenance will increase and quality of the work should increase. Alternatively, O&M contracts for the initial three to five years must stipulate training of the utility's staff by the O&M contractor. Performance guarantees can only be contested when reliable data is available. Clauses in the agreed upon PPAs allow IPPs to claim revenue lost from the grid operator when the grid is not available. Without data this claim would not be honoured. Therefore, the upkeep of the communications system and data storage is crucial for solar PV plants. Labour cost for a PV plant is generally a fixed cost, which accounts for the bulk of O&M expenses (Stolte, 2010).

2.6 Staffing

The area required to install a ground mounted PV plant comprising crystalline modules in SA varies between 0.9 and 1.4 hectares per MWp installed (Miller & Lumby, 2015). Thus, a 5 MWp PV plant will occupy a maximum area of 7 hectares. According to Relancio and Recuero (2010) two full time persons are required for O&M at plants employing tracking technology and one full time person is required for fixed systems having an installed capacity of 5 MW. They also state that for each additional 5 MW added, two more people are required for tracking systems and one more person is required for fixed systems.

However, in line with good work safety practices, at least two persons should be present when work such as isolation of plant is required. At least two technical controllers should be employed full time. Their duties will include O&M activities. Another two personnel should be employed to perform vegetation control and module washing. Therefore, for plants having an installed capacity between 5 MW and 10 MW at least four persons should be employed full time. With two technical controllers and two general workers, the taking of leave by employees can be accommodated by the O&M manager. For every additional 10 MW at least one more technical controller should be employed. The technical controller must be multi-skilled and have the expertise shown in Table 2-5.

It is now a general practice to share technically competent staff between various installations. Furthermore, it is economical to have one O&M manager for many sites. A skills matrix for O&M staff is shown in Appendix 3.

Table 2-5: Technical controller skills

DC systems	CCTV systems
Inverter commissioning	Transformer maintenance
Inverter fault finding	MV switchgear
SCADA systems	LV switchgear
UPS systems	Report writing
AC electrical protection	HV switchgear
Metering	PV systems

2.7 Equipment warranties

The section reviews the warranties of solar modules and inverters.

2.7.1 Solar modules

Manufacturers of solar modules provide both a product warranty and a performance guarantee. A product guarantee protects the buyer of these modules against manufacturing defects. Most module manufacturers provide a product warranty of 10 years. Manufacturing defects covers faults that are caused by poor quality products used during manufacturing and poor workmanship such as diode failures, hot spots and delamination, etc.

A performance guarantee is the guarantee given by the module manufacturer that the degradation in terms of power output of the panel will not be lower than a stated percentage of rated power. Guaranteed power output of PV modules is usually 90% of rated power after 10 years and 80% of rated power after 25 years. The guaranteed output power is what is expected at standard test conditions (STC) in a lab. In reality STC conditions are rarely duplicated under field conditions. Polycrystalline modules typically degrade 3% during the first year of operation and then 0.7% per year for the next 24 years, which results in approximately 20% degradation over 25 years.

Table 2-6 below shows the product and performance warranties provided by some manufacturers of solar PV modules.

Table 2-6: Module product and performance warranty

Manufacturer	Duration of Product Manufacturer Warranty				25-Year Performance Warranty
	5 years	10 years	12 years	25 years	
Amerisolar			X		80.6%
Axitec			X		85.0%
Canadian Solar		X			83.0%
Centrosolar		X			80.2%
China Sunergy		X			80.7%
ET Solar		X			81.9%
Green Brilliance	X				80%
Hanwha SolarOne			X		82.0%
Hyundai	X				80.0%
Itek		X			80.0%
Kyocera Solar		X			80.0%
LG			X		83.6%
REC Solar		X			80.2%
ReneSola		X			80.0%
Renogy Solar		X			80.0%
Seraphim		X			80.7%
Silevo		X			80.2%
Silfab			X		92.0%
SolarWorld		X			86.85%
Stion		X			80.0%
SunEdison/MEMC				X	80.0%
Suniva		X			80.2%
SunPower				X	87.0%
Trina Solar		X			82.5%

Source: Energy sage (2015)

The following must be noted regarding product and performance warranties of solar modules (Whaley, 2016):

- A warranty will be cancelled if the modules are not handled properly or if the instructions or conditions of the warranty are not carried out (for example, modules cannot be stored outside with their packaging in the rain).
- Module manufacturers may go out of business.

- To prove degradation (power loss) of the module is costly since each module must be sent to an accredited lab for testing.
- Warranty does not cover the shipping of faulty modules to the manufacturer and the shipping of the replacement modules.

Since module costs account for the biggest slice of the capital expenditure for a solar PV plant (see Figure 2-10), investors and financers limit risk by using Tier 1 manufacturers of modules. This tier system is not a clear indication of module quality but rather shows the operations of the manufacturer as shown in Figure 2-11. The tier system is simply an indication of investors' approval of module manufacturers. According to Sandia National Laboratories, 0.05% of PV modules fail annually. This is however based on PV plants that are relatively new in operation. Failure rates of modules late in their expected lives are not available as yet (Rycroft, 2016). However, it is expected that the failure rate will increase as modules age in the field. A literature search conducted by Tamizhmani and Kuitche (2013) concluded that failure rates range from 0.005% to 0.1% annually, based on exposure in the field. According to Tamizhmani and Kuitche (2013), crystalline silicon modules have an insignificant number of failures and warranty returns.

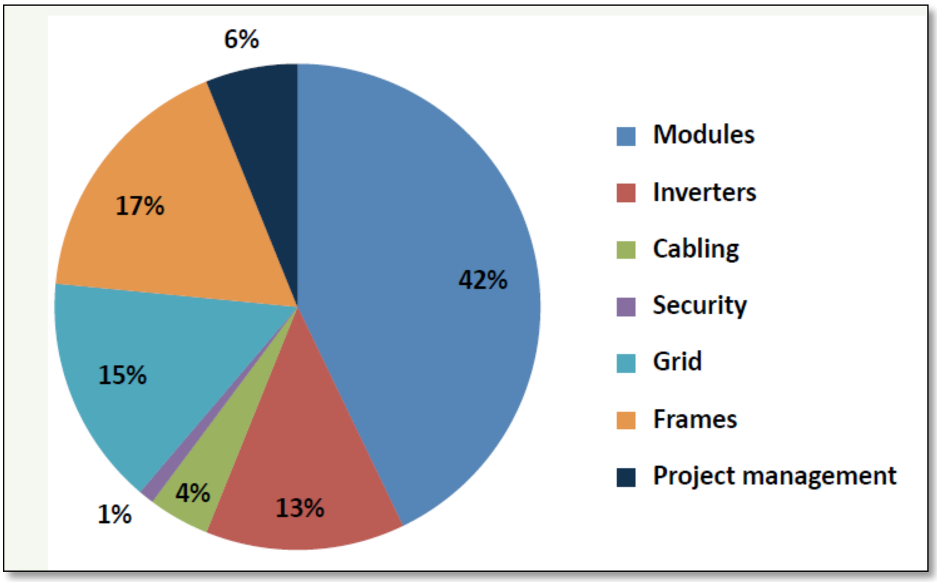

Figure 2-10: Average breakdown costs for a solar PV project – ground mounted
Source: Miller & Lumby (2015)

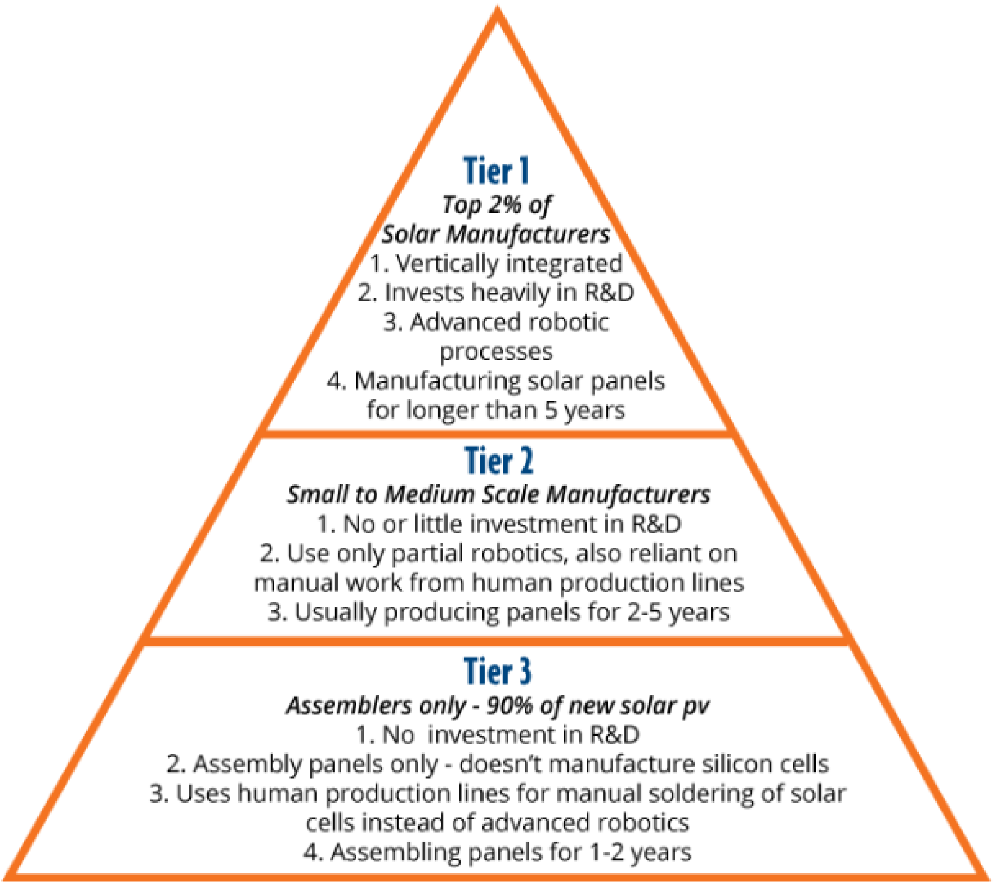

Figure 2-11: Tier system

Source: Infinite Energy (2016)

Failure modes that could initiate a claim against the product warranty and degradation modes that could initiate a claim against the performance warranty are shown in Table 2-7. It should be noted that other than poor quality management during manufacturing, PV modules can also fail prematurely due to poor handling during installation. Micro-cracks in PV modules later cause hot spots. These micro-cracks are usually identified using electroluminescence (EL) imaging (Brearley, 2016).

Table 2-7: Failure and degradation modes of crystalline-silicon PV modules

Failure modes	Degradation modes
Broken interconnection – this causes arcing, burns on the backing sheet, cracking of glass or power loss exceeding limits in the warranty	Incremental cracking of interconnections (resulting in power degradation)
Solder bond failure (resulting in burns on the backing sheet, or cracking of glass)	Incremental solder bond failure (resulting in power degradation)
Severe corrosion (resulting in burns on the backing sheet or power loss exceeding limits in the warranty)	Incremental corrosion (resulting in metallization discoloration and degradation in power)
Chipped cells (resulting in hotspots or power loss exceeding limits in the warranty)	Incremental cracking of cells (resulting in power degradation)
Encapsulant delamination (causes power loss exceeding limits in the warranty)	Incremental encapsulant discoloration (causes power loss exceeding limits in the warranty)
Cracked glass (this is a safety issue)	Incremental warping of the backsheet (resulting in power degradation)
Hotspots (resulting in burns on the backing sheet, is a safety issue or causes power loss exceeding limits in the warranty)	Incremental rise of module mismatch (resulting in power degradation)
Ground faults (this is a safety issue or causes power loss exceeding limits in the warranty)	
Junction box failures (this causes arcing, open circuits or ground faults)	
Connector failures (this is a safety issue)	
Structural failures (this is a safety issue)	
Bypass diode failures (this is safety issue, resulting in a hot spot or power loss exceeding limits in the warranty)	

Source: (Tamizhmani and Kuitche, 2013)

Figure 2-12 illustrates picture of a bypass diode failure resulting in the burning of the junction box.

Figure 2-12: Bypass diode failure

Source: Naicker (2015)

Figure 2-13 shows a picture of a burnt connector at a combiner box. As shown in Figure 2-14 most faults in PV strings are due to faults in the strings themselves such as blown connectors/fuses (open circuit), rather than due to module related faults.

Figure 2-13: Burnt connector

Source: Naicker (2015)

The most common module related fault according to Grenko from Amplify Energy is junction box failures, followed by cracked panels (Brearley, 2016).

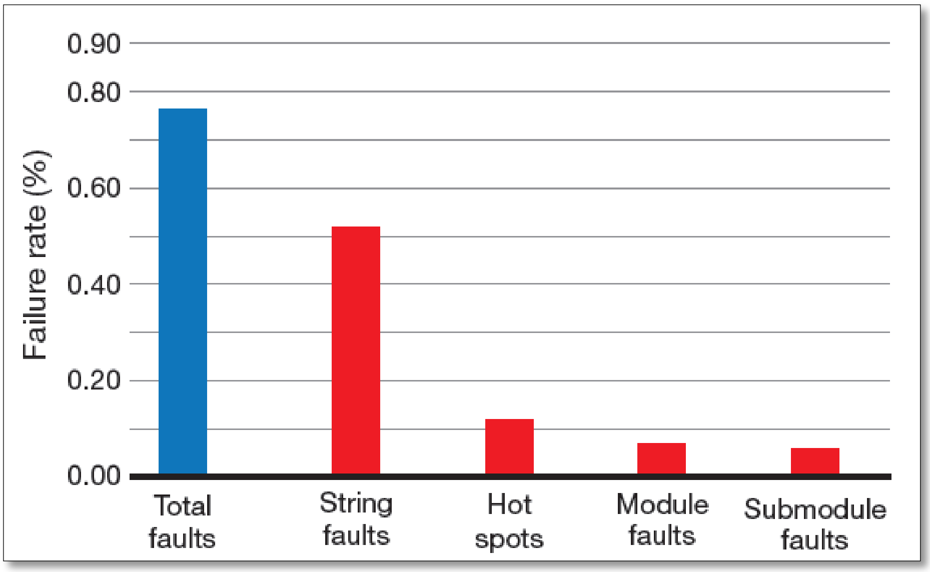

Figure 2-14: Failures in PV strings

Source: Brearley (2016)

2.7.2 Inverters

Inverters are major components in a solar PV plant. Of the total amount of reported failures in a PV plant, 51% are due to hardware or software problems in inverters, as shown in Figure 2-15. Inverters are the most common device inclined to fail in a solar PV plant (Thompson, 2011). Therefore, reliability of inverters and the years of warranty provided by the manufacturer are crucial for the functioning of the PV plant. An inverter is an electronic device and components such as capacitors are prone to failure. Figure 2-16 shows the proportion of inverter components that fail. Considering that the design life of a solar PV plant is 25 years it is expected that some components in the central inverter will have to be changed during that time. According to Golnas (2011), 57% of all inverter failures are caused by failure of parts and materials.

Support provided by manufacturers of inverters is important so that breakdown time can be kept at a minimum. Manufacturers should also provide a list of critical inverter spares that are likely to fail. Cost, years of warranty and performance are some of the most important factors to consider when choosing an inverter. Most manufacturers of inverters provide extended warranties as an option of up to 20 years. However, the cost of an extended warranty must be compared to the actual failure rate and cost of components in inverters. Once onsite O&M personnel figure out what components fail after some time and how to replace them, and perform preventative maintenance, less support will be required from inverter manufacturers.

Since an inverter is essentially an electronic device, the method of cooling employed will affect the life time of the inverter. Furthermore, electronic devices require a dust free environment. The design of the inverter cabin should be such that the forced heat extraction from the inverter must be vented directly outside the cabin. The inverter cabin must have an air-conditioning unit to cool the cabin in Southern Africa.

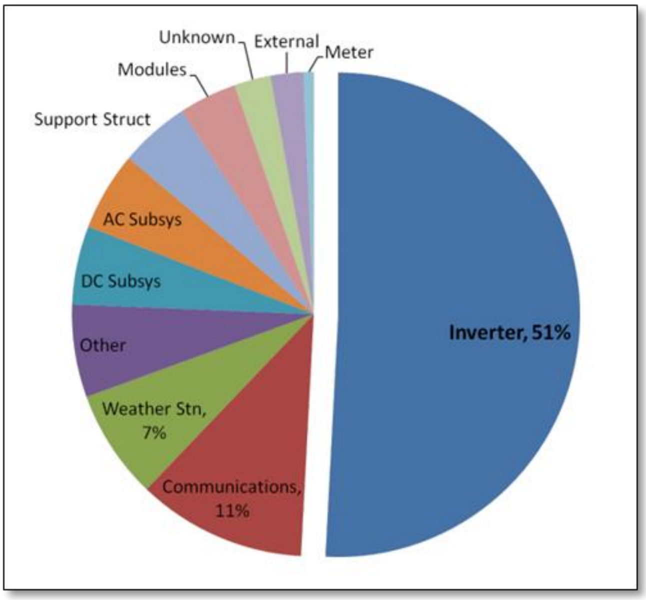

Figure 2-15: Failures in SunEdison operated and maintained PV plants (2008 to 2010)
Source: Golnas (2011)

The creation of site specific maintenance and start-up procedures is crucial for an effective O&M strategy at solar PV plants. Most central inverters are equipped with an automatic start after a successful fault clearance. Central inverters have many protection settings which tend to operate frequently as the inverters age. Enabling the automatic start after a transient fault will limit downtime of the inverter. However, every trip of the inverter must be thoroughly investigated and documented so that planned maintenance can be performed to investigate the faulty component. Original equipment manufacturers (OEMs) do not openly communicate failures of inverters at various sites (Williams, 2010). For this reason, most learning about inverter failures occurs on site. According to Solarpraxis and Sunbeam (2013), solar inverters on average experience failures between the 10^{th} and 12^{th} year of operation and inverters will not outlive the PV panels installed on site, without some component replacements. Remote reset and restart of inverters will increase availability of the inverters.

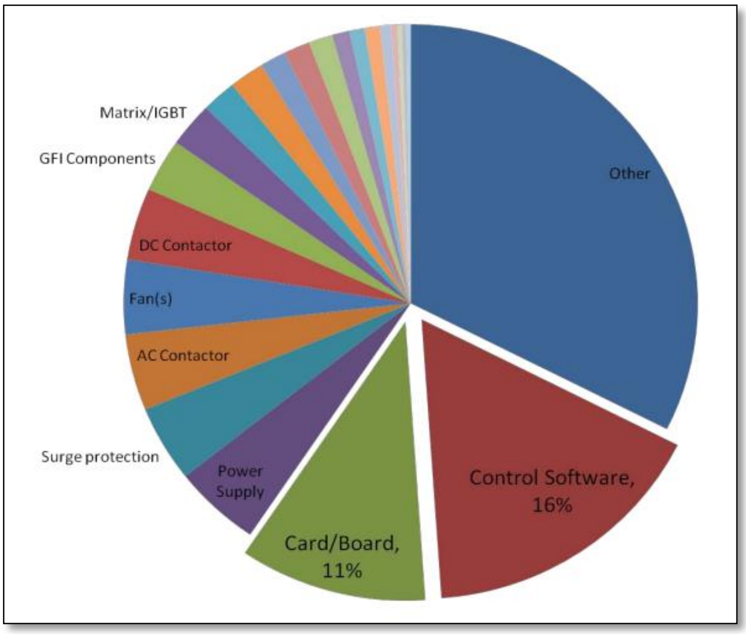

Figure 2-16: Affected inverter component

Source: Golnas (2011)

Documents such as warranty certificate, invoice, commissioning report, serial number of inverter, and proof of preventative maintenance performed on inverter is important when making a warranty claim against the manufacturer. After the warranty period the owner of the PV plant must bear the cost of replacing inverter components that have failed. Most warranties provided by central inverter manufacturers will replace or repair the faulty component within the central inverter. Most inverter manufacturers provide a standard warranty of five years. The standard warranty comes with the product at no extra cost. It should also be noted that most inverters will have an event recorder to record events and operational conditions which can be used by the OEM when a claim is lodged against them.

2.8 Insurance

Insurance is extremely important for solar PV plants. The capital costs of solar PV plants are very high, which has resulted in single PV plants in SA usually having more than one financial investor. Insurance is taken out in order to guard against natural disasters, theft, force majeure, failure of critical equipment, etc. Insurance premiums account for roughly 25% of the total yearly O&M expenses of a PV plant in the US (Spear *et al.*, 2010). Figure 2-17 below indicates the causes and percentage of total claims for commercial rooftop solar PV plants in Germany, between 2003 and 2008. Figure 2-17 indicates that storms and lightening accounted for 44% of claims. In Figure 2-17 3% of claims were due to small fury animals called martens which cause damage by biting equipment. Lightening and storms can also cause damage at utility scale PV plants. In 2014, 60% of the world's installed PV systems were installed on roofs (Patel, 2016).

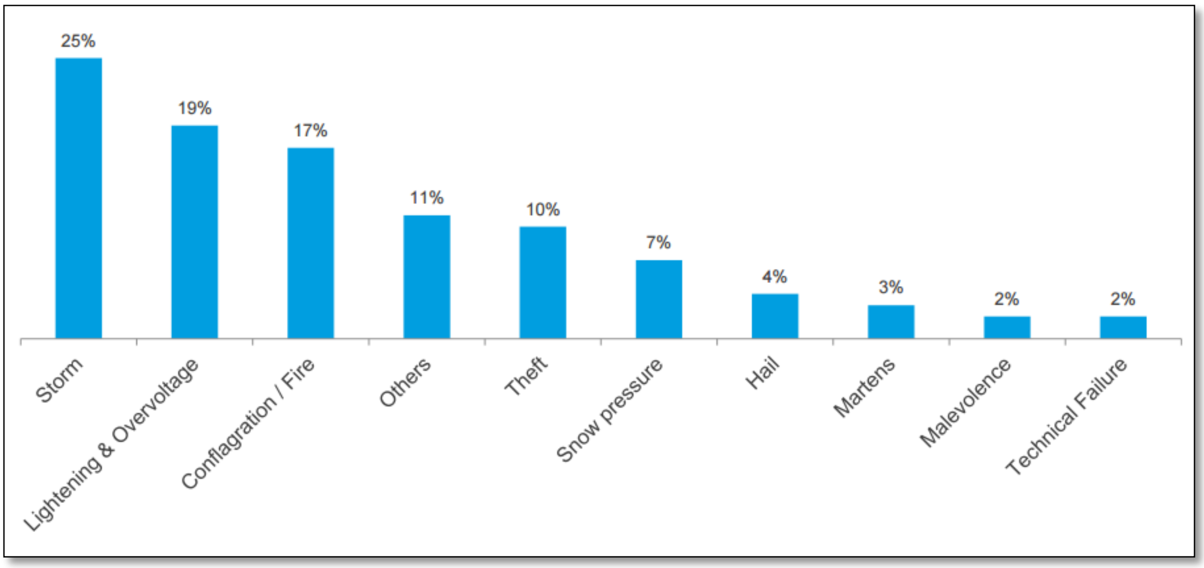

Figure 2-17: Causes of insurance claims – Germany 2003 to 2008

Source: Moses *et al.* (2015)

2.9 Levelised cost of electricity

The LCOE equation for a power plant was represented by Equation 1.1. This calculated value represents the breakeven point between all costs and expected revenue. The LCOE value depends on the following factors (Wirth, 2014):

- Construction and installation costs;
- Life time of plant, interest on loans and return on investment for owners;
- O&M and insurance costs;
- Irradiance expected; and
- Annual degradation of PV modules.

The LCOE for renewable plants is reducing whilst the LCOE for fossil fuel plants are increasing (Beetz, 2015). Grid parity is a phrase used to describe the occurrence when the price of generating electricity using solar PV matches, or is less than, the price of electricity generated by conventional sources. Grid parity has been achieved in several countries in the world (Solar century, 2014). The above inflation increases in grid electricity, high solar irradiation, and the decreasing costs of solar panels has resulted in solar PV achieving grid parity in SA. The economics of solar PV has attracted many investors. A solar PV plant has no fuel costs whereas for a conventional fossil fuel plant the price of coal can only be expected to rise. Table 2-8 below shows the average LCOE for different power generation technologies in Europe, Middle East and Africa (EMEA) for 2015. The average exchange rate for the South African rand to the US dollar in 2015 was R13.28 (Internal Revenue Service, 2017).

Table 2-8: LCOE's for EMEA

Technology	LCOE (R/MWh)
Onshore Wind	1208
Solar PV	1687
Coal	1394
CCGT	1567
Nuclear	2098

Source: Chestney (2015)

The LCOE of a solar plant is influenced by the total life time expected production. The capacity factor of solar plants and thus energy produced can be increased by using trackers and higher efficiency solar modules. The expected years of operation, discount rate, annual degradation of modules and annual O&M will also affect the LCOE value (Cambell, 2008).

2.10 Monitoring of solar plants

Utility scale solar PV plants are usually staffed Monday to Friday. The control room should be equipped with a Human Machine Interface (HMI) that displays various live parameters and performance elements of the plant. Offsite monitoring and alarming via sms is recommended to increase availability of the solar plant. If an inverter or a circuit breaker trips the operator needs to be alerted immediately so that technicians can be sent out to perform corrective maintenance. The SCADA system provides the status and performance of the plant in real time (Reaugh *et al.,* 2017). A historian is normally used to store the data that the SCADA system retrieves from the inverters, combiner boxes, weather stations, transformers, etc. In order for IPP's to connect to the national grid they are required to meet the SCADA requirements of the grid operator. The grid operator requires certain parameters from an IPP in order to balance the load requirements of the national grid. Data is required to calculate availability and performance ratio, etc. Appendix 4 shows the SCADA system of a typical utility scale power plant.

2.11 String level monitoring

String level monitoring measures the current of every string. Whenever any string is not producing any current an alarm is illuminated on the HMI to alert the operator. String level monitoring takes place in the combiner box. A combination of RS485 and fibre optic networks is usually used to communicate the string currents and voltage from the combiner box to the SCADA system. Without string level monitoring or array level monitoring it is very difficult for the operator to see if one string is not producing from the central inverter data. The alternative to string level monitoring is for the maintenance staff to measure the current of each string manually with a clamp-on current meter. This is a labour intensive exercise.

2.12 Inverter monitoring

Most utility scale solar plant plants have central inverters. There are some manufacturers of inverters that recommend string inverters for utility scale applications. Most central inverters have the ability to communicate live parameters to the SCADA system. Common live parameters that are displayed on the HMI are shown in Table 2-9. These parameters inform the operator about the health of the inverter and its state of operation. The operator can compare the measured values of one inverter to another inverter, in order to verify deviations. This is condition-based monitoring (CBM). Furthermore, the SCADA system can be programed to give an alarm when certain live measured values are not within range, such as high IGBT temperature.

Table 2-9: Inverter monitoring - live parameters

DC Power	**Inverter & Energy Metering**
AC Power	Input Power 315.0 kW
DC Voltage	Input Current 507.0 A
AC Voltage	Input Voltage 624.0 V
MWh (day)	Output Power 308.0 kW
IGBT temperature	Output Current 559.0 A
AC Current	Output Voltage 314.0 V
DC Current	Temperature 92.0 °C

Table 2-10 shows the advantages and disadvantages of the different levels of monitoring. Module level monitoring is usually done in relation to micro-inverters or DC power conditioners (Paul & Bray, 2012).

Table 2-10: Levels of monitoring

	Inverter	String	Module
Benefits	Convenience Low cost Track inverter condition and efficiency	Moderate resolution and precision Identify root cause of problems to the string	Highest resolution and precision Identify root cause of problems to the module Monitor individual panels Efficiency benefits* Improved inverter reliability**
Drawbacks	Poor resolution Inability to identify string or module problems	Analytics required Cost Increased points of failure	Analytics required Cost Increased points of failure
* When combined with DC power optimiser or micro inverter			
**Only for DC power conditioner			

Source: Paul and Bray (2012)

2.13 Layout of solar PV plant

A solar PV plant normally consists of the following buildings:

1. Main control room building consisting of offices and ablution facilities.
2. Switchgear rooms, where one switchgear room will typically house two to four inverters, a step-up transformer and MV switchgear.
3. Storage and workshop facility.

The solar PV plant should also have a source of water and security fencing. The layout of the solar PV plant is usually designed in 1 MW (or greater) array blocks as shown in Figure 2-18. The 1 MW of PV panels are connected to the inverters located in the switchgear room. Appendix 5 shows the typical electrical apparatus found in a switchgear or inverter cabin room. In Figure 2-18 the white cabins located at the edge of each array block are the inverter cabin room. The inverter cabin usually consists of two to four inverters. A single inverter could have a rating of 1 MW. Recently inverter manufacturers are providing a complete inverter station which comes with the inverters, MV/LV transformer and MV switchgear, housed in a weather resistant container.

Figure 2-18: Array blocks
Source: Solar Server (2013)

2.14 Performance Indicators

Plant performance indicators such as availability, performance ratio, energy output, capacity factor and specific yield are used to measure the status and health of a PV plant. Many of these indicators are stated in O&M contracts. For example, an owner of a PV plant may want a guaranteed availability of 98% for the PV plant and an annual performance ratio of 78%. The availability of a PV plant is a measure of whether the inverters are online, connected to the grid and ready to deliver power based on the current irradiation levels. Basically, it is the ratio of how many hours the inverter was synchronised and how many hours the inverter should have been synchronised. Certain events/situations such as force majeure, grid failure, etc. must not be considered when calculating availability. The events/situations that will not affect the availability calculation must be agreed upon between the owner and O&M contractor.

The performance ratio (PR) of a solar PV plant is an assessment of the efficiency of the plant in converting solar irradiation into electrical energy. The PR can be used to compare different utility scale plants irrespective of orientation and location. For the first five years of operation it is typical to have O&M teams contracted to deliver a PR between 75% and 80% per annum. Due to the degradation of solar panels where the modules lose a certain percentage of their power output/annum, it is expected that the PR of the plant will gradually decrease. During the initial years of operation, it is common for plants to have an annual PR greater than 80%. Table 2-11 shows the degradation rate of different modules per year. According to Jordan and Kurtz (2012), the average module degradation rate per year is 0.8%.

Table 2-11: Degradation rate of modules

PV Module Type	Degradation Rate per Year (%/year)
Amorphous silicon (a-Si)	0.87
Monocrystalline silicon (sc-Si)	0.36
Multicrystalline silicon (mc-Si)	0.64
Cadmium telluride (CdTe)	0.4
Copper indium gallium diselenide (CIGS)	0.96
Concentrator	1.00

Source: Jordan and Kurtz (2012)

2.15 Safety at PV plants

All personnel required to operate on or to perform work in a PV plant must be trained, and found competent, on the dangers of a solar PV installation. The ‘permit to work’ system shall be enforced to ensure employee safety and prevent unauthorised operation of electrical apparatus. Personal protection equipment shall be used according to the hazards of the tasks being performed at the PV plant. Staff must be educated on the fact that the PV panel is a generator of electricity and will be electrically alive as long there is light. The Occupational Health and Safety (OHAS)

Act requires employers to create and maintain a safe working place for their employees. Hazards in a PV plant applicable to employees, PV system and aviation are shown in Appendix 6. Although the owner/employer is ultimately responsible for ensuring that health, safety and environmental regulations are abided by, the O&M manager of the solar PV plant is usually responsible for the implementation of the OHAS Act.

2.16 Training and documentation

Usually the EPC contractor is responsible to compile a maintenance manual and to train staff that will perform O&M activities after the end of the EPC contract. The maintenance manual must consist of the following:

a) A detailed description of the purpose of all major components in the PV plant.
b) A maintenance plan/schedule detailing frequency of preventative maintenance.
c) Procedures to perform maintenance tasks.
d) Procedures to perform operating tasks.
e) Description of failure modes and the corrective actions required.
f) Check lists.
g) A detailed chapter on the SCADA system which explains the communication networks, and how to troubleshoot the system.
h) List of spares with ratings.

Apart from operator and maintenance training, the owner of the plant must ensure that software training is provided for the SCADA system, security, UPS and the inverter. Technicians must be able to communicate with these devices using their PCs to diagnose faults. The level of training should be such that the technicians must be competent to commission inverters and add new devices to the SCADA system. The following documentation should be provided by the EPC contractor to assist O&M staff in performing their tasks (Seaward Solar, 2012):

a) Permits and licenses.
b) Existing contracts.
c) Installed/Designed AC and DC power ratings of major components.
d) The manufacturer’s name, model and number of PV modules, central inverters, transformers, batteries, SCADA and all other major components.

e) Commissioning reports and test data.
f) The names and contact numbers for the customer/owner, network operator, system designer, EPC contractor and sub-contractors.
g) A site layout map showing equipment locations.
h) Schematic drawings of all components and for the entire plant.
i) The types, sizes and ratings for all components (data sheets).
j) O&M documentation specific for items of plant such as inverters, trackers, etc.
k) Operating guidelines, safety procedures and maintenance plans.
l) Warranty information for major components such as panels and inverters and the SCADA system.
m) Software manuals.

Every solar PV plant must have a document management system for the safe keeping and easy retrieval of as-built documentation, reports and records. All preventative and corrective maintenance performed on the plant must be recorded and stored. It is recommended that records be archived both electronically and physically.

2.17 Summary

Preventative maintenance is required to maximise the energy yield and to extend the lifetime of the solar PV plant. Inverters must be maintained according to the manufacturer's requirements in order to maintain the warranties. Maintenance schedules ensure that all equipment in a PV plant is inspected periodically. The component that fails the most often in a PV plant is the inverter. The inverter itself consists of various components and most of the time a simple "reset" gets the inverter back into operation. Infra-red cameras can be used to detect defective modules. Large areas can be scanned relatively quickly compared to visibly checking if panels are cracked. Trackers are required to be maintained periodically and should be monitored daily.

One of the O&M functions is to keep an inventory of critical spare parts, especially if the solar PV plants are located in remote areas hundreds of kilometres away from major cities and spares manufacturers (as is the case with IPPs in the Northern Cape). Spare parts are necessary in order to limit downtime of the plant. The cleaning frequency of modules depends on where the PV plant is located and the local weather conditions. O&M budgets are not standard, varying according to installed capacity, tracking vs fixed design, PPA and O&M agreements, etc. Inverter manufacturers claim that the most cost-effective way to maintain a central inverter is to replace the inverter completely after 15 years. O&M contracts are usually awarded to the EPC contractor for the first two or three years of operation, since this coincides with the defects warranty period.

Manufacturers of solar modules typically provide a 10 year product warranty and a 25 year performance warranty. Most inverter manufacturers provide a standard warranty of five years but this can be extended up to 20 years. Storms and lightening are most likely to cause the biggest damage in PV plants resulting in insurance claims. Grid parity had been achieved in several countries in the world including SA. O&M of solar PV plants comprises corrective maintenance, preventative maintenance and condition based monitoring.

CHAPTER 3: EMPIRICAL STUDY

3.1 Introduction

In this chapter the sample population size and unit of analysis will be explained. The survey results will be presented and analysed, focusing on the following O&M topics related to solar PV plants:

1. Personnel requirements;
2. Common faults;
3. Panel washing, vegetation management and pyranometer cleaning;
4. Staff working hours; and
5. Other O&M practices.

The responses to the 34 questions answered by the respondents will be discussed within the five topics mentioned above. According to Energyblog, (2017) 31 solar PV IPPs are fully operational out of 45 PV projects. The remaining projects are either being constructed or awaiting PPAs from Eskom. Table 3-1 below shows the number of fully operational solar PV IPPs per province.

Table 3-1: Number of operational solar PV plants

Province	No. of Solar PV Plants
Eastern Cape	1
Free State	2
North West	1
Limpopo	3
Northern Cape	19
Western Cape	5

Source: Energyblog (2017)

3.2 Gathering of data

The questionnaire (see Appendix 7), the consent cover letter (Appendix 8) and ethical clearance letter (Appendix 9) were sent via email to O&M managers of solar PV IPPs. The questionnaire was designed to collect information on the O&M practices at that particular PV plant. Eleven completed questionnaires in total were received. The questionnaire was sent to 31 operational Solar IPPs. The DC capacities of the solar PV plants surveyed are shown in Figure 3-1. Three of the plants surveyed had a DC capacity between 70 MW and 80 MW. No plant surveyed had a DC capacity between 60 MW and 70 MW. The largest size of any single solar PV IPP is currently 75 MW. Four plants employed tracking technology and seven plants employed fixed technology. Most O&M contractors declined to complete the survey as the industry is very protective of individual practices.

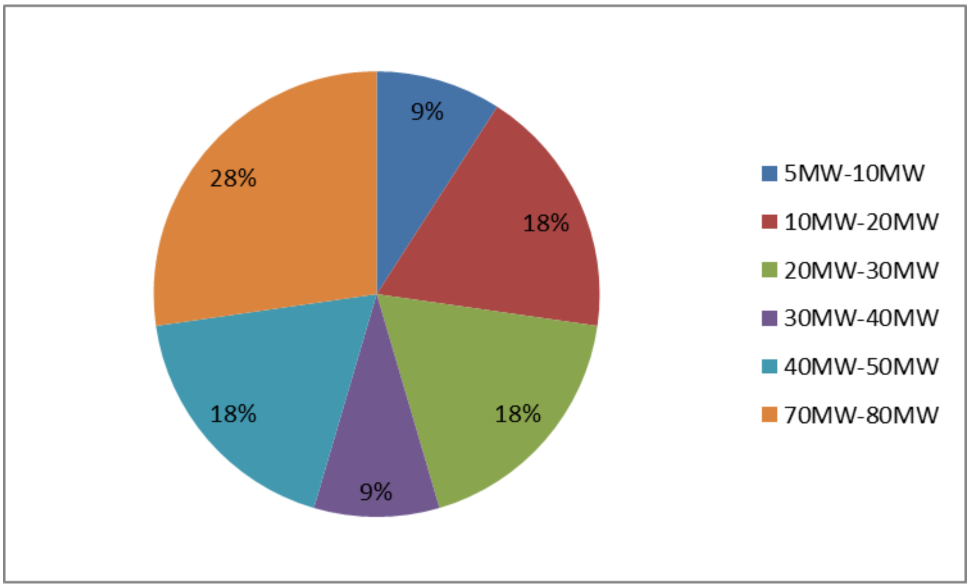

Figure 3-1: DC Capacities of solar PV plants surveyed

3.3 Results and discussion

In this section the results of the survey will be presented and analysed.

3.3.1 Manpower requirements at solar PV plants

In SA a single renewable power producing company can own and operate various sites within the same province or across provinces. Consequently, certain staff are shared across sites. For example, the O&M manager, skilled technicians and GMR2.1 (General Machinery Regulations) appointee, can be shared across sites which will reduce O&M costs. Some sites indicated that they contract general workers seasonally to perform vegetation management and/or to wash panels. In these cases the number of permanent general workers employed was zero.

Table 3-2 shows the number of persons employed at the various sites surveyed based on the DC capacity of the plant. The total amount of persons on site excludes security staff. All plants had security staff on duty 24-hours a day. The number of employees employed full time varies according to the plant size and whether general workers are contracted or not.

Table 3-2: Personnel requirements at solar PV plants

DC Size	70MW-80MW	70MW-80MW	70MW-80MW	40MW- 50MW	40MW – 50MW	30MW – 40MW	20MW – 30MW	20MW – 30MW	10MW – 20MW	10MW – 20MW	5MW – 10MW
Total amount of employees for O&M	25	25	50	8	8	25	9	9	10	4	3
Electricians	5	5	3	4	4	3	2	3	2	2	2
Technicians	5	5	12	4	2	8	1	0	2	1	0
Plant controller/operators	4	3	2	0	2	1	0	0	2	1	1
General workers	5	5	33	0	0	13	6	6	4	0	0

A good industry standard is one permanent person employed for every 3 MW DC installed. For plants smaller than 50 MW staff tend to be more multi-skilled. For example, an electrician can maintain the DC plant, HV plant, SACDA systems, compile reports and even operate in a 5 MW to 10 MW plant.

All eleven solar PV plants surveyed had contracts for O&M. This means that owners of PV plants had contracts in place with experienced O&M providers rather than employing and managing their own O&M personnel. Six of the solar IPPs surveyed shared the GCC (Government Certificate of Competency) engineer between sites.

3.3.2 Common faults at utility scale PV plants

Respondents were asked to choose three of the most common faults experienced on the solar PV plant. The results (Figure 3-2) indicate that 28% of the faults experienced were communication problems between devices and 23% of faults were due to inverters. Although four of the 11 Solar PV plants had trackers, none of these plants reported that faulty inclinometers are common faults, and only one reported on the tracker system itself being a common fault. The AC system was not reported as a common fault.

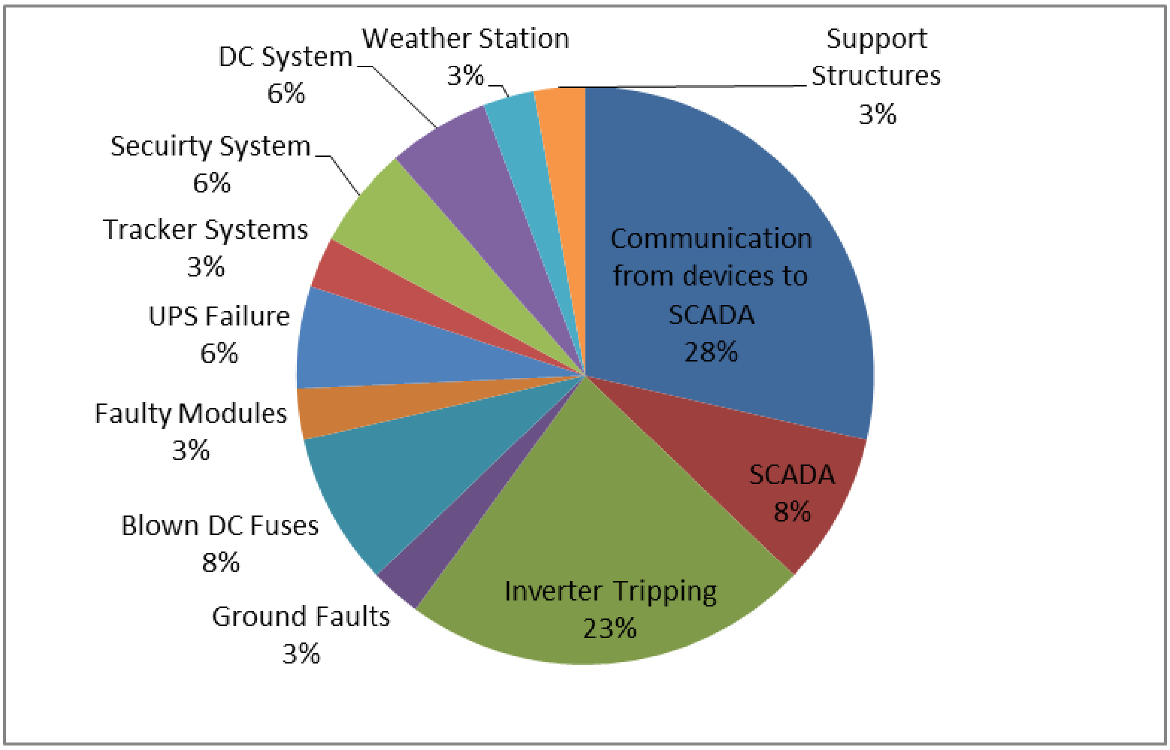

Figure 3-2: PV plant common faults

Figure 3-3 indicates that the most common defects experienced with solar modules were cracked glass, hot spots and snail tracks.

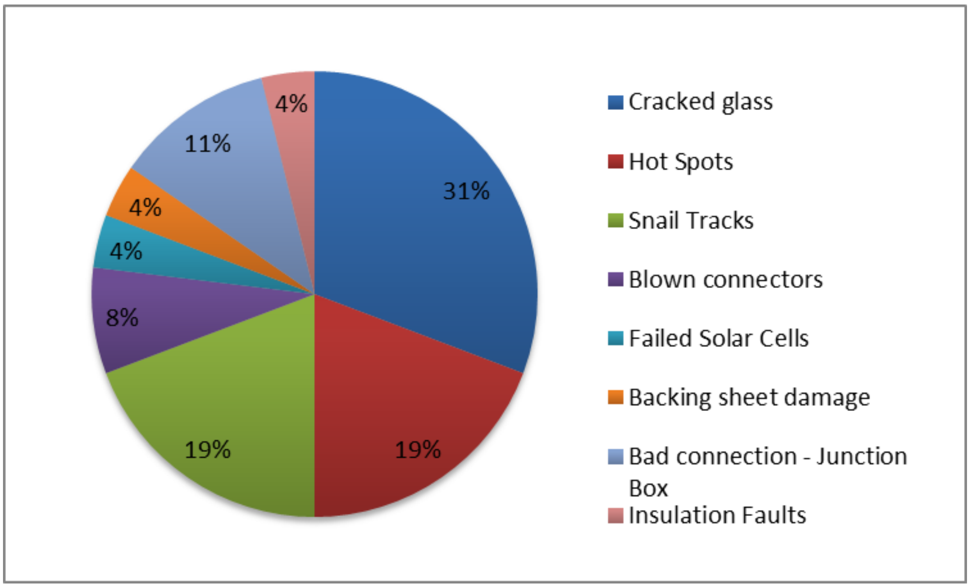

Figure 3-3: PV module defects

To mitigate long down time, 10 of the participating IPPs keep between 0.06% to 2.5% of total modules installed as spare parts. The average percentage spare modules kept for the 10 plants (that responded to this question) is approximately 1% as shown in Figure 3-4. Because module manufacturers could go out of business, a stock of spares is necessary to ensure that the plant remains in production for at least 25 years. None of the 11 IPPs that participated reported that blown diodes or delamination was a common defect. One participant reported that blown diodes in the junction box was a problem in a commercial-scale fixed ground-mounted PV plant where the modules were placed in landscape rather than in the usual portrait orientation. In this case, dirt accumulated at the bottom of the panel due to the panels not being washed during the dry autumn to winter months on the Highveld. Due to the presence of the dirt accumulation at the bottom of the panel, only one diode permanently conducted within the junction box, which resulted in its failure.

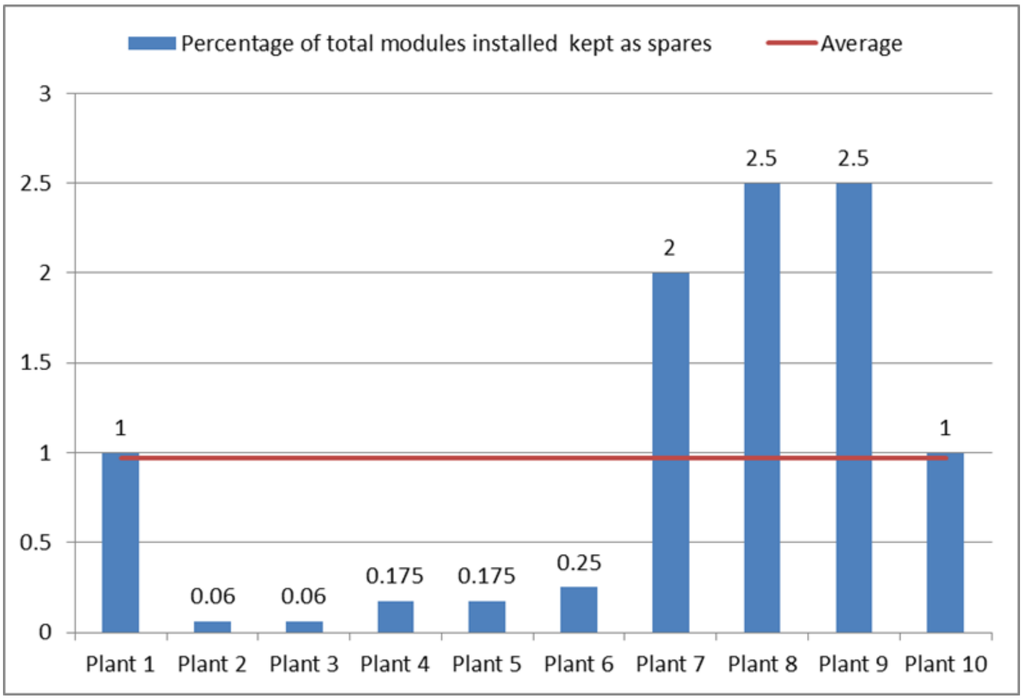

Figure 3-4: Percentage of total modules installed kept as spares

Snail tracks were reported as a common defect of the solar modules. According to Witte (2013), snail tracks occur commonly on monocrystalline and polycrystalline modules. Experiments performed on silicon modules by Meyer *et al.* (2013) concluded that snail tracks developed along micro-cracks and cell edges. Meyer *et al.* (2013) further stated that snail tracks did not appear for every micro-crack. Snail tracks cause power degradation (Yang *et al.*, 2015). Figure 3-5 shows snail tracks on a solar PV module.

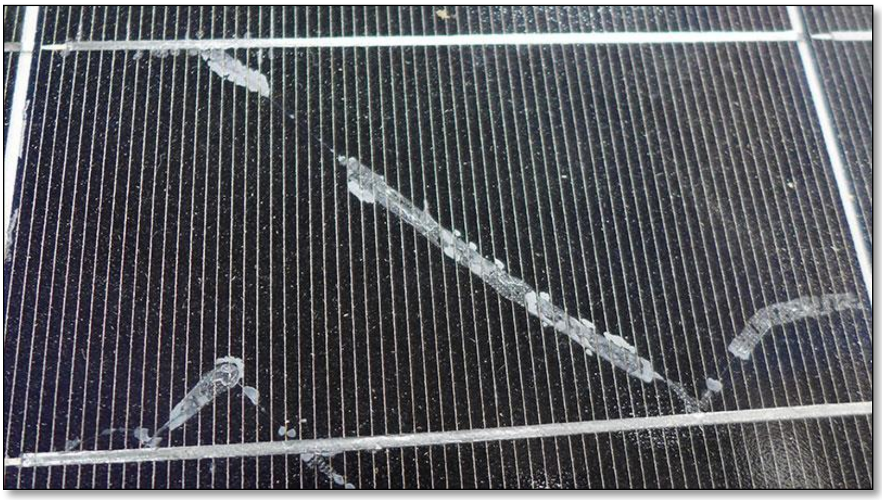

Figure 3-5: Snail tracks
Source: Bimble Solar (2012))

The 11 respondents reported that the most common faults on the central inverters were related to ‘other’, matrix/IGBT, DC contactor and power supply circuitry as shown in Figure 3-6. None of the respondents reported that cooling fans were giving problems as yet. However, according to the maintenance requirements of central inverters, cooling fans should be changed typically once every five years. The fact that most respondents selected ‘other’ as one of the most common faults in the inverter indicates that the questionnaire did not cover all the faults that can occur within an inverter. The inverter consists of many internal components, and requires a skilled inverter technician for repairs.

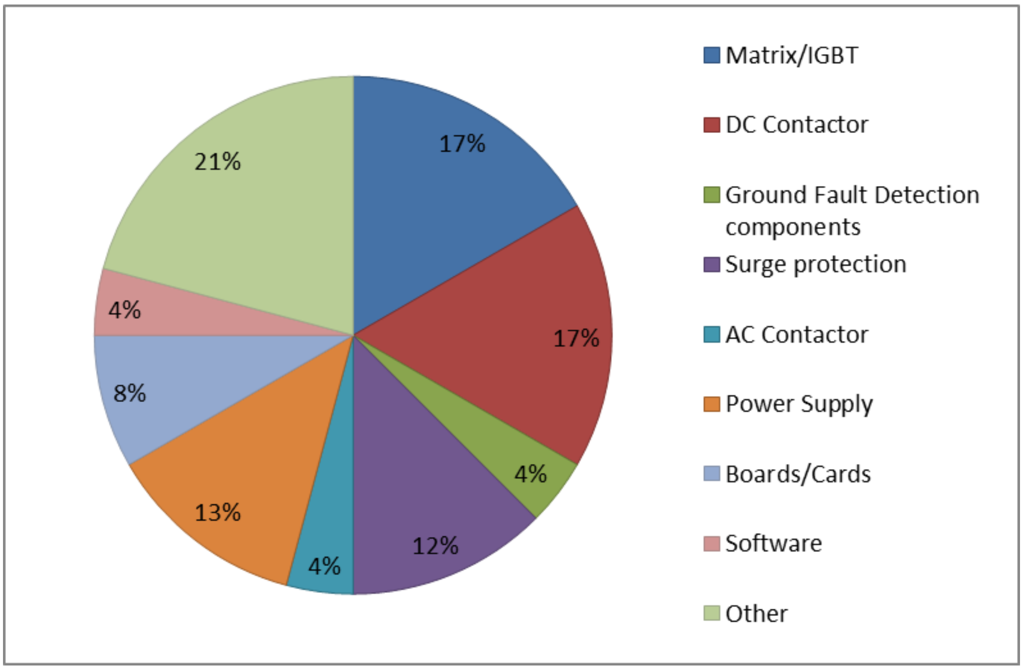

Figure 3-6: Inverter faults

The average number of central inverters kept on site was approximately two inverters as shown in Figure 3-7. Some IPPs kept four units as spares and one IPP kept no spare central inverter. Eight of the 11 IPPs have extended warranty agreements with inverter manufacturers. The standard warranty period is 5 years; owners of the IPPs in this study had extended the warranty period to 10 years or more.

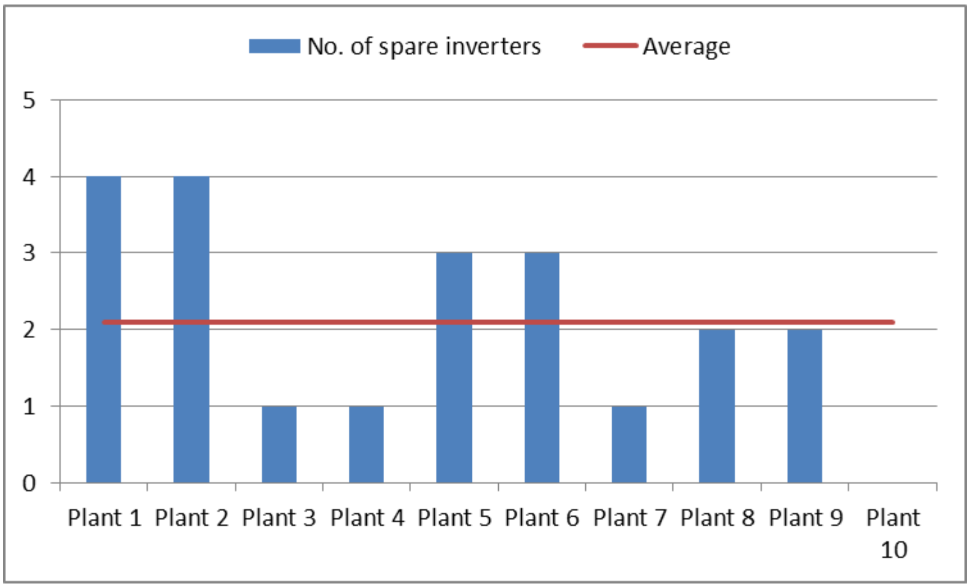

Figure 3-7: Number of spare inverters

3.3.3 Panel washing, vegetation management and pyranometer cleaning

Six of the 11 IPPs surveyed performed module cleaning one to three times a year. Module cleaning is performed when dust/dirt attaches itself to the module. In order for the dust/dirt to attach itself to the module there must be some moisture in the air. Thirty six percent of the IPPs surveyed reported that no module washing is done. In areas where it is extremely dry (no moisture in the air) soiling would not be aggressive during the dry season. Consequently, some solar IPPs do not wash panels at all but rather wait for the wet season to arrive before doing washing. In areas where there is morning dew during the dry season module cleaning may be required. With respect to annual cleaning, 9% of the IPPs surveyed washed modules at least 6 or more times per year, as shown in Figure 3-8. Therefore, the weather conditions where the solar PV plant is located affects the cleaning regime adopted.

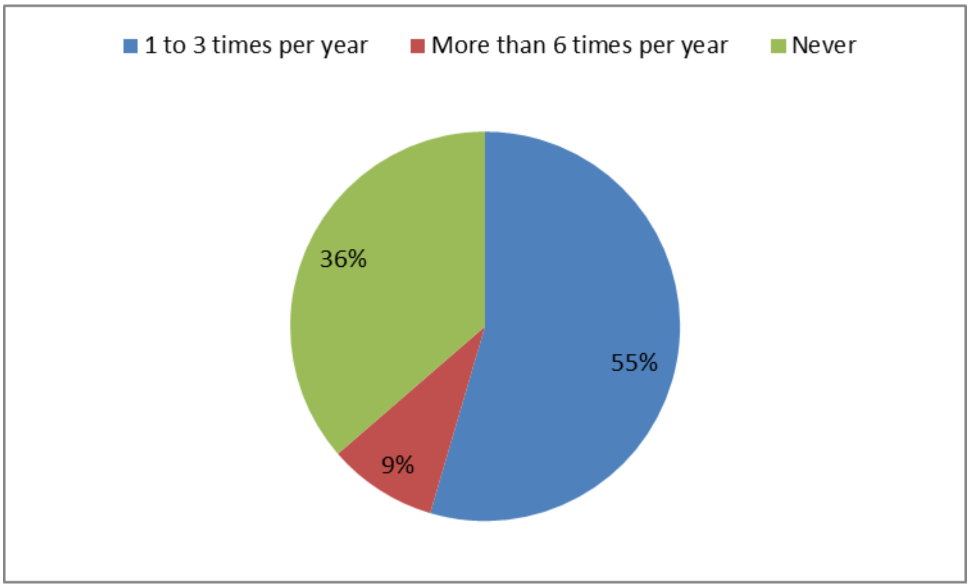

Figure 3-8: Panel cleaning frequency

Of the seven plants that perform module cleaning, six (86%) did so using a special tractor equipped with attachments for module cleaning (Figure 3-9).

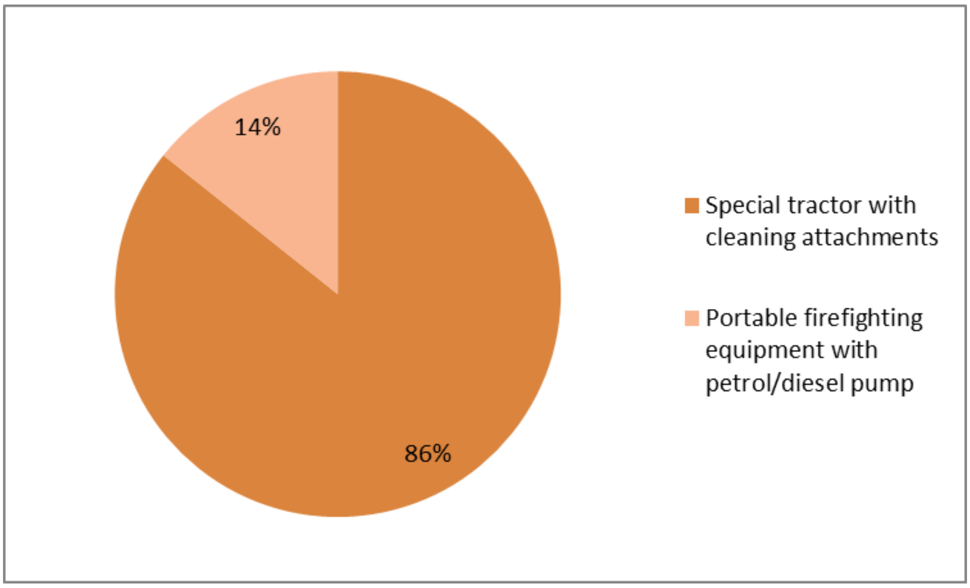

Figure 3-9: Module cleaning method

The water used for cleaning is mainly sourced from a bore hole together with a reverse osmosis plant as shown in Figure 3-10. Since most solar IPPs are located in the Northern Cape which is sparsely populated and dry, it makes sense that the source of water is bore holes. All plants surveyed made use of reverse osmosis plants whether the source was from bore holes or from municipalities. The reverse osmosis plant removes ions and particles from the water which prevents scaling and residue forming on the washed panels.

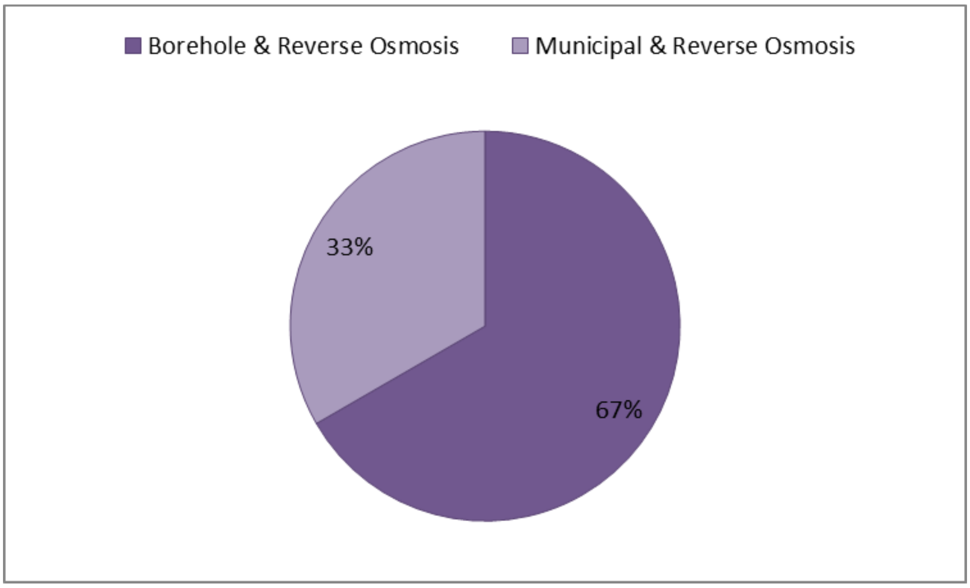

Figure 3-10: Source of water

As shown in Figure 3-11 91% of the respondents indicated that pyranometers are cleaned weekly. No respondent indicated that they clean pyranometers daily although all the plants surveyed where staffed daily. If pyranometers are cleaned daily and modules cleaned only one to three times a year the performance ratio calculated is likely to drop.

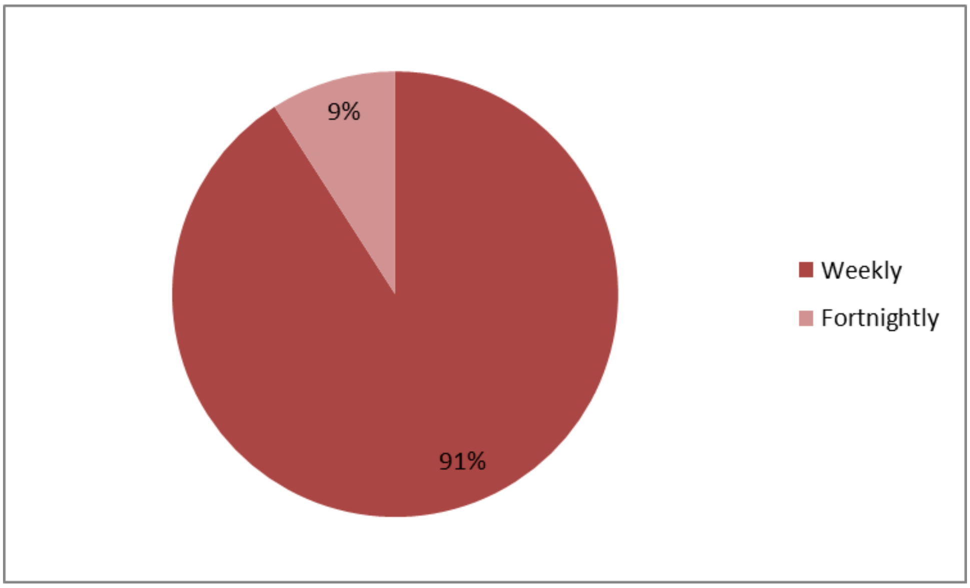

Figure 3-11: Pyranometer cleaning frequency

Vegetation control on the solar PV sites surveyed is mostly performed quarterly (see Figure 3-12). It is cost effective to contract in general workers when vegetation control is only performed quarterly.

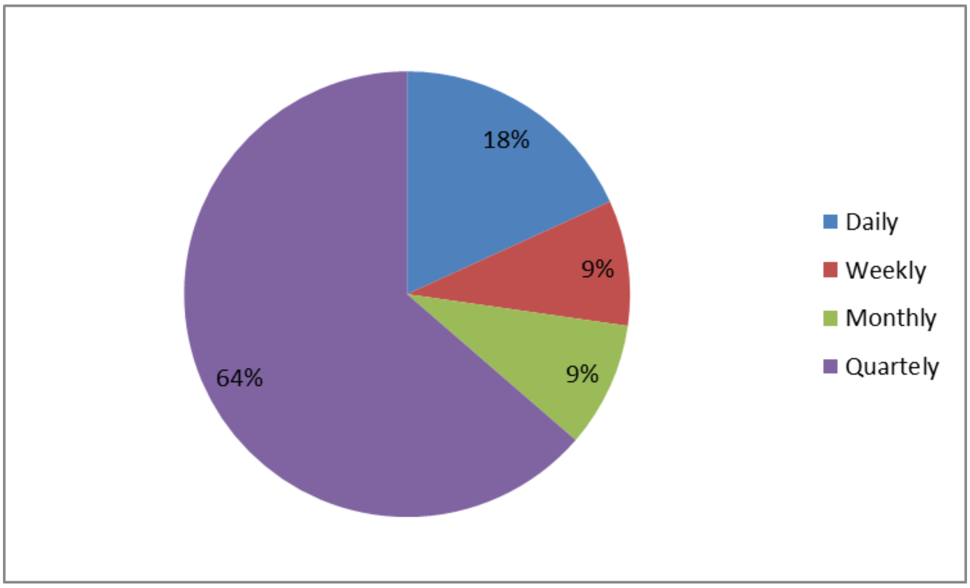

Figure 3-12: Vegetation control – frequency

In the Northern Cape where rainfall is low, vegetation growth is also slow. The terrain consists of low scrub landscape with grass as shown in Figure 3-13.

Figure 3-13: Terrain in the Northern Cape
Source: Crown (2017)

3.3.4 Staff working hours

Only two of the 11 respondents had staff on site during normal working hours on the weekend. The other nine sites had staff on standby that went to the site when they received alarms or faults via sms or telephonically via the remote control centre. When alerting staff to abnormal events six IPPs used remote control centres and seven out of the 11 Solar IPPs sent out mobile phone text messages to notify staff of alarms or trips. All plants surveyed had staff on standby daily. Figure 3-14 shows that six plants had staff working eight hours a day. No employee at any plant worked less than eight hours a day. Four plants had staff working eight to 10 hours per day. One plant had staff on site up to 12 hours per day.

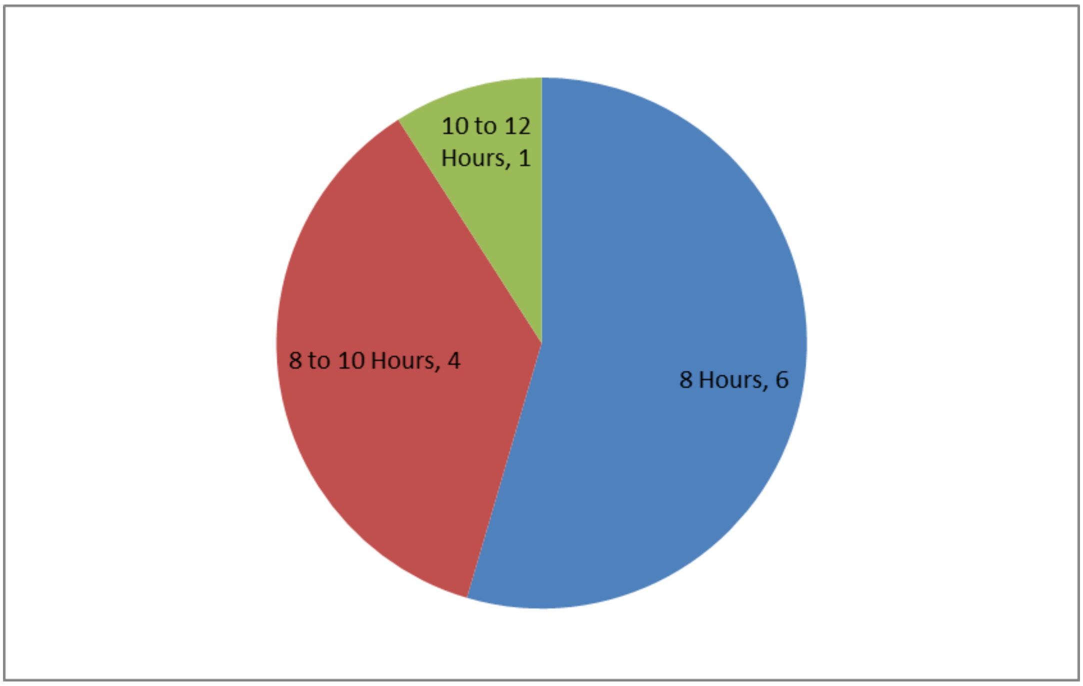

Figure 3-14: Daily working hours

3.3.5 Other O&M practices

The survey results indicated that all solar PV IPPs that participated performed infrared thermography on the solar modules. Roughly 60% of respondents replied that O&M costs per year were less than 1% of the total EPC cost for the solar PV plant (see Figure 3-15). The other 40% of respondents replied than O&M costs per annum were greater than 1% of total EPC costs.

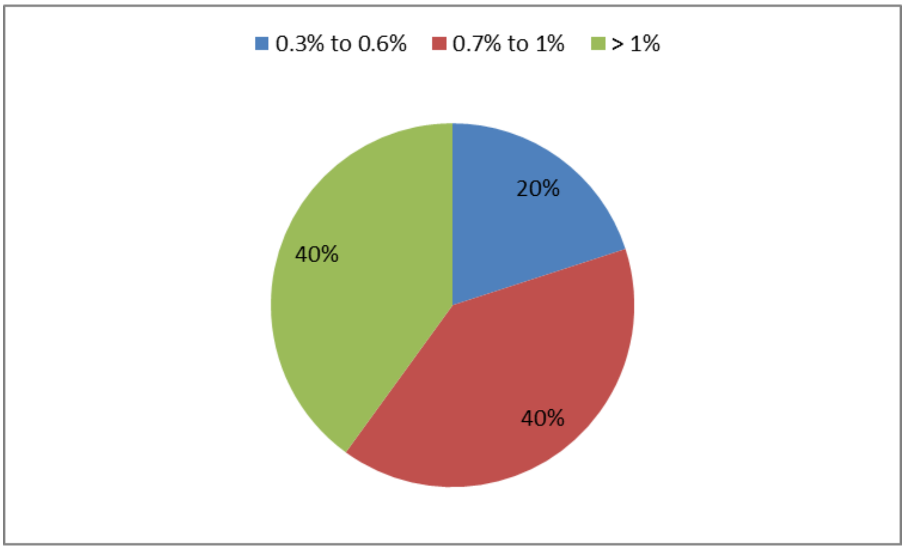

Figure 3-15: O&M costs per year – percentage of total EPC cost

Figure 3-16 shows that the price of constructing a utility scale PV plant is dropping annually all over the world. According to Wesoff and Lacey (2017), the fall in cost is due to the decreasing price of tracker systems, modules, inverters and labour costs. Since EPC costs are declining the pressure will also be on O&M costs to decline.

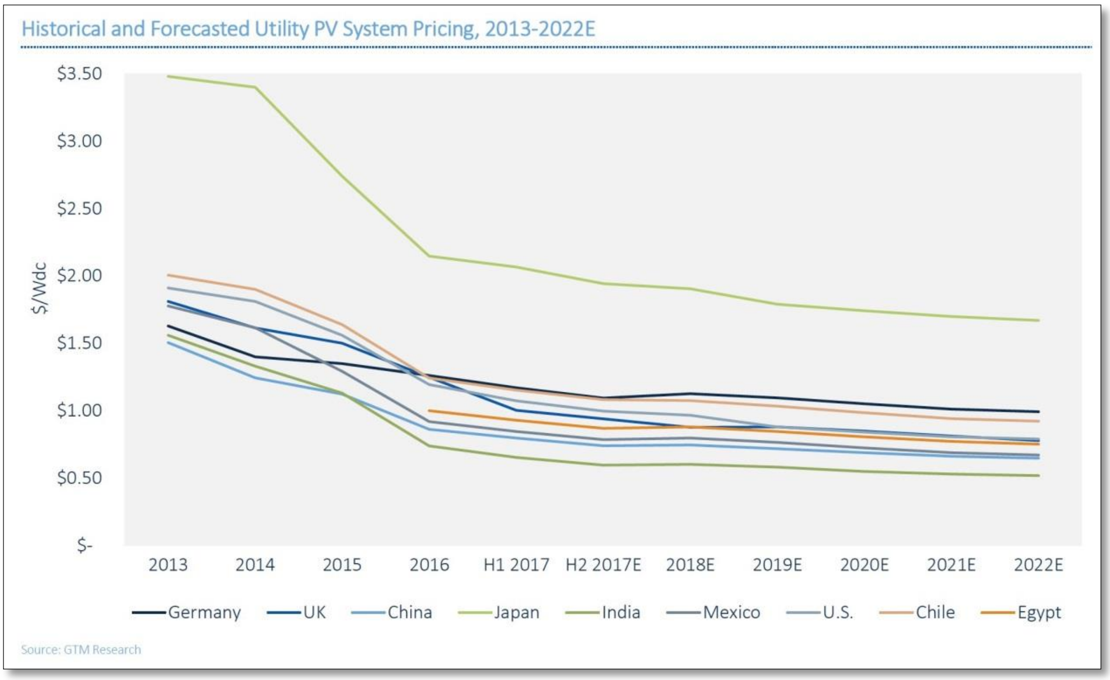

Figure 3-16: Historical and forecasted utility PV system pricing
Source: Wesoff and Lacey (2017)

As shown in Figure 3-17, 55% of the respondents indicated that the annual performance ratio of the PV plants was between 79% and 82%and 36% indicated that the annual performance ratio was greater than 82%. This indicates that 91% of the respondents have PRs greater than 79%.

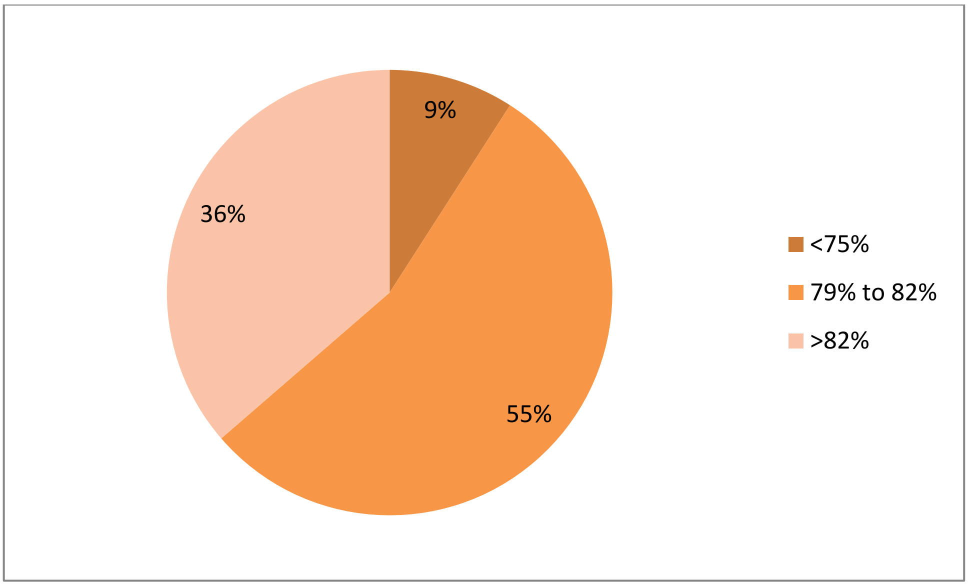

Figure 3-17: Annual performance ratio

Only two plants responded to the question “Which costs more: the property insurance against damage or the liability insurance to protect workers?” These respondents indicated that property insurance costs more than liability insurance. The reason for the poor response to this question could be because property insurance is handled by the owner/project developer and liability insurance is handled by the O&M contractors, and the surveys were issued to the O&M contractors. However, all responded to the question “What percentage of annual O&M expense do insurance premiums account for?” The results indicate that 91% of respondents incur annual insurance premium costs of between 15% and 25% of total annual O&M cost (Figure 3-18).

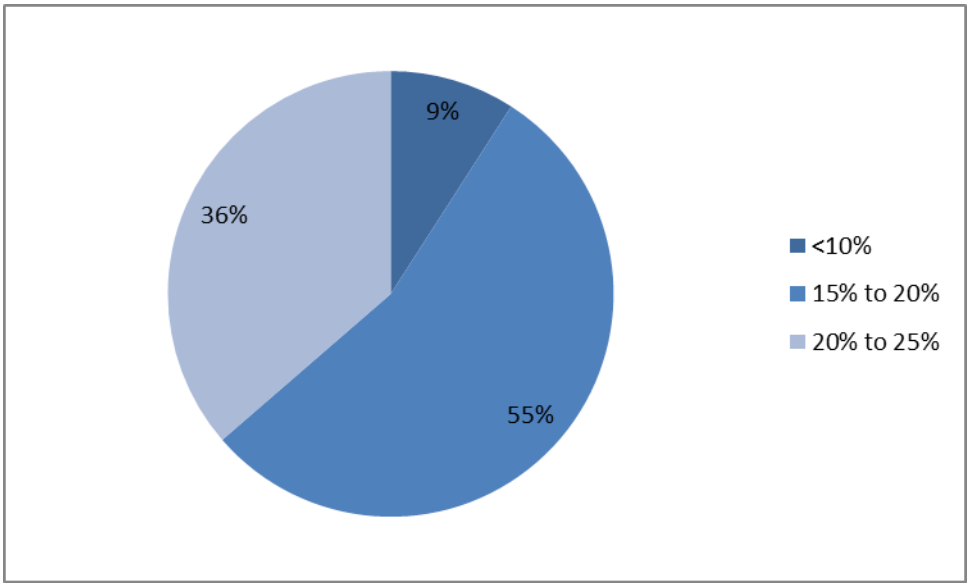

Figure 3-18: Percentage insurance annual cost of total O&M costs

Analysing all plants regarding level of plant monitoring, 73% of the respondents indicated that they employ string level monitoring at their plants (Figure 3-19). String level monitoring means that if any open circuit condition occurs in the DC plant, it will be picked up and flagged by the SCADA system. At the inverter level, it is virtually impossible to monitor and pick up if a single string is open circuited. Module current in a string is usually less than 10 Amps. For a 500 kW inverter the DC current will be in the order of few hundred amps. Thus, string level monitoring results in early detection and resolution of the problem, increasing the energy yield of the plant. An open string does not affect plant availability but an inverter that is not in operation affects plant availability. All 11 Solar PV IPPs who took part in this research indicated that the annual plant availability was greater than 98%.

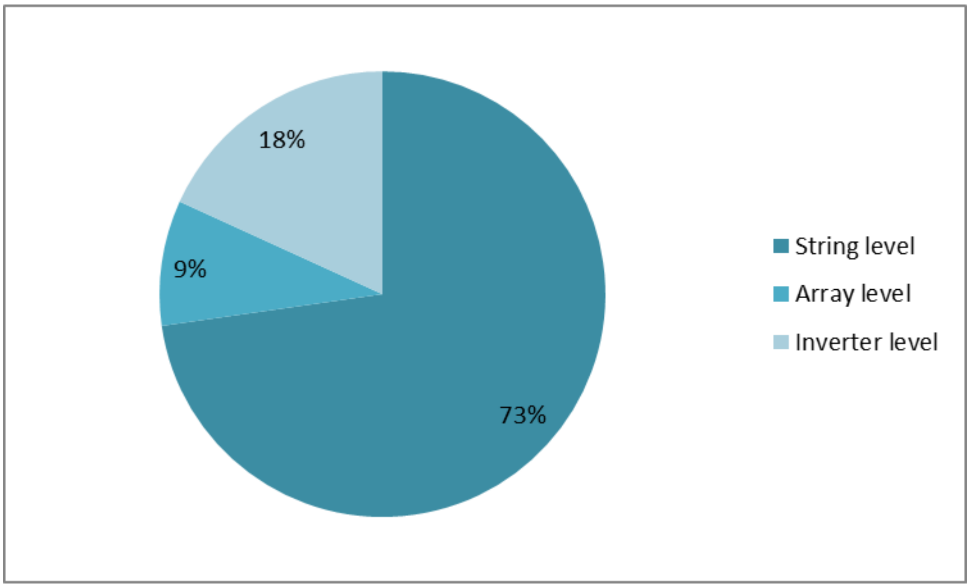

Figure 3-19: Highest level of monitoring employed

3.4 Summary

In this chapter the results were discussed and analysed. The questions were designed to gather as much information as possible about the O&M strategies implemented at solar PV IPPs. The results concluded that the number of permanent employees employed varies according to the plant size and whether general workers are contracted or not. The most common faults experienced in the PV plants were communication faults followed by inverter tripping. Defects experienced with solar modules were cracked glass, hot spots and snail tracks.

All solar PV IPPs surveyed kept on average approximately two inverters on site. Module washing was not an activity performed by all solar IPPs, although all plants had a reverse osmosis plant to purify water for washing modules. Most of the IPPs surveyed were located in areas where the rainfall is low and consequently the vegetation growth is also slow. For this reason, 64% of the IPP's surveyed reporting that vegetation control is only performed quarterly. All solar PV sites had staff on standby after normal working hours.

Utility scale solar PV plants in SA have been in operation only from 2013, therefore when this survey was performed no plant had been in operation longer than five years. Ninety one percent of the respondents reported annual PRs greater than 79%. It is expected that the PR will eventually drop as the module degrades. Annual insurance costs for the PV plant is typically between 15% and 25% of total annual O&M cost. The annual plant availability for all 11 solar PV IPPs who took part in this research was greater than 98%.

CHAPTER 4: CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusion and recommendations

Based on the results of the survey the following are best practices for O&M in SA.

1. Due to economies of scale the larger the plant the lower the O&M cost per MW installed. An O&M company that performs work at various sites can lower costs by sharing staff between sites. A GCC engineer is an expensive and statutory requirement and should be shared between sites. Multi-skilled and self-motivated staff are required for O&M activities in solar PV plants. The number of employees per site depends on the installed DC capacity of the plant. Table 4-1 shows the recommended number of employees required per site. Teams consisting of two people are recommended for rectifying faults in a PV plant. Each team must have a van for transport and to convey panels, etc. Statutory appointments must be in place. If panel washing and vegetation control is not conducted monthly, then the number of permanent general staff can decrease.

Table 4-1: Recommended number of staff per PV site

	10MW	20MW	40MW	50MW	70MW	100MW
Technical Operators	4	6	10	12	16	20
General Workers	2	3	5	6	8	10
Total	6	9	15	18	24	30

The duties of the technical operators will be as follows:

- Fault finding on all systems in a PV plant;
- Maintenance of all systems in a PV plant;
- Commissioning of equipment; and
- Report writing and operating.

The duties of the general workers will be as follows:

- Vegetation management;
- Cleaning of panels and other equipment; and
- Assisting with all other manual tasks such as panel replacement, etc.

2. The plant must have 24-hour security staff. The perimeter around the solar plant must have at least a two-tier fence. The inner fence must be an electric fence. Lighting around the perimeter will assist guards whilst doing foot patrols.

3. Owners of solar IPP PV plants should use contractors for the O&M of their plants. If a utility has more that 100MW installed DC capacity then in-house maintenance should be exercised (Patel, 2016)

4. The most common faults in the PV plant were due to communication networks and inverters. This means that electricians/technicians must be skilled in these areas. The EPC contractor will have experience in commissioning the inverters and communication systems and this make them ideal candidates for O&M contracts. The inverter OEM is also an ideal candidate for O&M contracts. Having a skilled inverter technician trained by the OEM or from the OEM is critical in operating solar PV plants. As shown in Figure 2-1, inverter faults are the most common issue in solar PV plants. Maintaining a good relationship with the manufacturer of the inverter is recommended.

5. Approximately 1% of total modules installed must be kept as spares. PPA contracts are for 20 years but the module warranty is for 25 years.

6. Cracked glass, snail tracks and hot spots were the most common module faults. Here the quality of the panel and care during shipping is vital. Batch electroluminescence testing is recommended to test the quality of panels after production. This test shows faults in the panels such as micro surface cracks, cell damage and sub-standard welds that are not visible to the naked eye.

7. It is recommended that at least two complete central inverters be kept as spares, because manufacturers could change their design or go out of business. Furthermore, the extended warranty of the inverters should be exercised beyond the standard 5 years. In the design of the inverter room/cabin one must ensure that the hot air from the inverter is extracted outside of the room/cabin.

8. Frequency of module washing and vegetation control is site specific. Weather affects module soiling and vegetation growth. Module cleaning should be performed with a tractor equipped with attachments for washing modules. In SA reverse osmosis plants are recommended to purify water for washing panels.

9. Pyranometers should be cleaned weekly. Early morning dew on pyranometers can influence readings.

10. The plant must be remotely monitored 7 days a week during normal working hours. Site staff should work 5 days a week, 8 hours per day. A team of two persons should be on standby every week, including the weekend. Mobile phone text messages must be sent to staff to notify them of trips and alarms.

11. Infrared thermography must be performed on the solar modules.

12. The annual performance ratio of a solar plant should be above 79%, at least for the first 5 years. Annual availability of a plant should be 98% or above.

13. The O&M Manager must ensure that staff maintain the document management system. Documents such as proof of maintenance, commissioning report and invoices are required for warranty claims. The cost of shipping faulty modules to the manufacturer and the cost of shipping the replacement modules is not paid by the module manufacturer in most cases. Therefore sourcing PV modules from the closest Tier 1 manufacturer is important.

This research has provided valuable insights into the world of solar PV plant O&M in SA. The use of solar panels to generate electricity will continue to grow as the world becomes more concerned about climate change. Solar panel efficiencies will increase over time and together with advancement in battery storage technology will cause people to go off grid and utilities to lean more towards renewable energy sources. Solar PV O&M cost is the lowest amongst all renewable energy technologies (Patel, 2016)

4.2 Achievement of the objectives of the study

The objective of this study was to unlock the maintenance activities and knowledge required to operate and maintain a utility scale solar PV plant. The O&M of utility scale solar PV plants is a relatively new activity in SA. Common strategies for solar O&M were presented and discussed as obtained from the questionnaires returned by solar PV O&M managers. The most common inverter faults, module faults and skills required to operate and maintain a utility scale PV plant were determined and presented. This research has detailed the activities and knowledge required to operate and maintain a utility scale solar PV plant.

4.3 Recommendations of future research

When at least 10 years of operation of solar IPPs in South Africa has been achieved, this research should be conducted again to determine which faults PV plants are experiencing. What will be the failure and degradation rate of modules? Only time will tell if modules will actually degrade according to manufacturer's specifications. Currently it seems that the annual power degradation of the modules is low, but this could change.

Will the O&M cost per MW increase or decrease? Will the inverter manufacturers still be in business? Most inverter manufacturers state that it is more cost effective to replace the inverter completely after 15 years (Briones & Blasé, 2011). The question to be asked after 15 years of operation is whether inverters were replaced or what components have been replaced. String inverters fail more often than central inverters (Patel, 2016), but will this still be the case in the future.

Will the PV module manufacturer still be in business to honour warranties? These are questions that can only be answered after the industry has gained more experience in maintaining inverters and solar modules. Solar PV IPPs who are currently waiting for a PPA from Eskom will be given a contract not exceeding 77 cents/kWh (Creamer, 2017). Therefore, O&M costs will be under pressure and an O&M strategy will be key to keep operating costs as low as possible. The O&M strategy must consider the number of staff employed, skill levels of staff, warranties of equipment, spares kept on site, vegetation control, module washing frequency etc.

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APPENDIX 1 - Detail Maintenance Plan per Component

Sub Group	Equipment	Sub unit	Task	Frequency	Importance
Documentation	as -built	AC-System	Complete and correct of documentation AC-System	initial/ ongoing	necessary
Documentation	as -built	Auxiliary Systems	Complete and correct documentation of all auxiliary systems (security, monitoring, ICT, energy supply, civil works, etc.)	initial/ ongoing	necessary
Documentation	as -built	DC-System	Complete and correct of documentation DC-System	initial/ ongoing	necessary
Documentation	as -built	System Documentation (IEC 62443)	System Data, Wiring diagram, mechanical design, O&M information (e.g. Operation and maintenance information shall be provided and shall include, at a minimum, the following items: a) Procedures for verifying correct system operation. b) A checklist of what to do in case of a system failure. c) Emergency shutdown and isolation procedures. d) Maintenance and cleaning recommendations (if any), Test results and commissioning data,	initial/ ongoing	necessary
Documentation	as -built	System Verification	Inspection, Testing 1)Test continuity of equipment grounding conductors and system grounding conductors (if applicable). 2) Test polarity of all dc cables and check for correct cable identification and connection. 3) Test open-circuit voltage [Voc] for each PV source circuit. 4) Test short-circuit current [Sic] for each PV source circuit. 5) Test functionality of major system components (switchgear, controls, inverters), including inverter anti-islanding. 6) Test the insulation resistance of the dc circuit conductors	initial/ ongoing	necessary
Documentation	O&M-Duration	Plant Audit	Audit of a power plant at take-over by O&M contractor, checking O&M reports, faults, repairs, design conformity and changes, monitoring, performance, etc.	initial + 3-5 yrs.	necessary

Documentation	O&M-Duration	Log Book	Checking and keeping records for tickets, faults, inspection results, or other events into one log book, as well as feedback and ensuing work plan for internal purpose, client, insurance, etc.	daily	necessary
Documentation	O&M-Duration	Maintenance	Creation of a maintenance protocol (about maintenance done according to manufacturer requirements or at least to mandatory national regulatory regulations)		necessary
Documentation	O&M-Duration	Inspection	Creation of an inspection protocol		necessary
Documentation	O&M-Duration	Work Plan	Action Plan following Audit, Maintenance Protocoled, and Inspection Protocoled, in order to monitor or fix issue and inform client	ongoing	necessary
Documentation	O&M-Duration	Report	Ongoing reporting as specified in O&M Contract to inform client about issues, diagnosis, and repairs, as well as plant performance (Summary of failures, losses, KPIs, human activity on site)	monthly/ quarterly/ annually	necessary
Documentation	O&M-Duration		Variance analysis	ongoing	necessary
Power Generation	Modules		Integrity inspection	Annual	necessary
Power Generation	Modules		Cables visual inspection	Annual	necessary
Power Generation	Modules		Thermography inspection	Monthly	necessary
Power Generation	Modules		Measurements inspection	Annual	necessary
Power Generation	Modules		Retightening	Monthly	necessary
Power Generation	Modules		Modules cleaning	Annual	necessary
Power Generation	Modules		On-Site degradation measurement (with most accurate and available technology) with pre-defined reference modules and strings. NB: accurate module and string selection necessary + stable+high irradiation	Annual	optional/according to client
Power Generation	LV Switchboard	Array/String Junction Box	Integrity inspection	Semi-annual	necessary
Power Generation	LV Switchboard	Array/String Junction Box	Documents inspection	Semi-annual	necessary
Power Generation	LV Switchboard	Array/String Junction Box	Cables visual inspection	Semi-annual	necessary
Power Generation	LV Switchboard	Array/String Junction Box	Labelling and identification	Semi-annual	necessary
Power Generation	LV Switchboard	Array/String Junction Box	Electrical protections visual inspection	Semi-annual	necessary
Power Generation	LV Switchboard	Array/String Junction Box	Thermography inspection	Semi-annual	necessary
Power Generation	LV Switchboard	Array/String Junction Box	Sensors functional verification	Annual	necessary

Power Generation	LV Switchboard	Array/String Junction Box	Measurements inspection	Semi-annual	necessary
Power Generation	LV Switchboard	Array/String Junction Box	Check correct operation	Semi-annual	necessary
Power Generation	LV Switchboard	Array/String Junction Box	Electrical protection correct operation	Semi-annual	necessary
Power Generation	LV Switchboard	Array/String Junction Box	Check fuse status	Semi-annual	necessary
Power Generation	LV Switchboard	Array/String Junction Box	Monitoring operation test	Annual	necessary
Power Generation	LV Switchboard	Array/String Junction Box	Check cables terminals	Semi-annual	necessary
Power Generation	LV Switchboard	Array/String Junction Box	General cleaning	Semi-annual	necessary
Power Generation	LV Switchboard	Generator Junction Box	Integrity inspection	Annual	necessary
Power Generation	LV Switchboard	Generator Junction Box	Documents inspection	Annual	necessary
Power Generation	LV Switchboard	Generator Junction Box	Cables visual inspection	Annual	necessary
Power Generation	LV Switchboard	Generator Junction Box	Labelling and identification	Annual	necessary
Power Generation	LV Switchboard	Generator Junction Box	Electrical protections visual inspection	Annual	necessary
Power Generation	LV Switchboard	Generator Junction Box	Thermography inspection	Semi-annual	necessary
Power Generation	LV Switchboard	Generator Junction Box	Sensors functional verification	Semi-annual	necessary
Power Generation	LV Switchboard	Generator Junction Box	Measurements inspection	Annual	necessary
Power Generation	LV Switchboard	Generator Junction Box	Electrical protection correct operation	Monthly	necessary
Power Generation	LV Switchboard	Generator Junction Box	Check fuse status	Annual	necessary
Power Generation	LV Switchboard	Generator Junction Box	Monitoring operation test	Semi-annual	necessary
Power Generation	LV Switchboard	Generator Junction Box	Check cables terminals	Annual	necessary
Power Generation	LV Switchboard	Generator Junction Box	General cleaning	Annual	necessary
Power Generation	LV Switchboard	AC Combiner Switchboard	Integrity inspection	Semi-annual	necessary
Power Generation	LV Switchboard	AC Combiner Switchboard	Documents inspection	Semi-annual	necessary
Power Generation	LV Switchboard	AC Combiner Switchboard	Cables visual inspection	Annual	necessary
Power Generation	LV Switchboard	AC Combiner Switchboard	Labelling and identification	Annual	necessary
Power Generation	LV Switchboard	AC Combiner Switchboard	Electrical protections visual inspection	Semi-annual	necessary
Power Generation	LV Switchboard	AC Combiner Switchboard	Thermography inspection	Semi-annual	necessary
Power Generation	LV Switchboard	AC Combiner Switchboard	Sensors functional verification	Annual	necessary
Power Generation	LV Switchboard	AC Combiner Switchboard	Measurements inspection	Semi-annual	necessary
Power Generation	LV Switchboard	AC Combiner Switchboard	Check correct operation	Annual	necessary
Power Generation	LV Switchboard	AC Combiner Switchboard	Electrical protection correct operation	Annual	necessary
Power Generation	LV Switchboard	AC Combiner Switchboard	Check fuse status	Annual	necessary
Power Generation	LV Switchboard	AC Combiner Switchboard	Check cables terminals	Monthly	necessary
Power Generation	LV Switchboard	AC Combiner Switchboard	General cleaning	Annual	necessary
Power Generation	LV Switchboard	AUX Switchboard	Integrity inspection	Semi-annual	necessary
Power Generation	LV Switchboard	AUX Switchboard	Documents inspection	Semi-annual	necessary
Power Generation	LV Switchboard	AUX Switchboard	Cables visual inspection	Semi-annual	necessary
Power Generation	LV Switchboard	AUX Switchboard	Labelling and identification	Semi-annual	necessary

Power Generation	LV Switchboard	AUX Switchboard	Electrical protections visual inspection	Semi-annual	necessary
Power Generation	LV Switchboard	AUX Switchboard	Thermography inspection	Semi-annual	necessary
Power Generation	LV Switchboard	AUX Switchboard	Measurements inspection	Semi-annual	necessary
Power Generation	LV Switchboard	AUX Switchboard	Electrical protection correct operation	Semi-annual	necessary
Power Generation	LV Switchboard	AUX Switchboard	Check fuse status	Semi-annual	necessary
Power Generation	LV Switchboard	AUX Switchboard	Check cables terminals	Semi-annual	necessary
Power Generation	LV Switchboard	AUX Switchboard	General cleaning	Semi-annual	necessary
Power Generation	Cables	DC Cables	Integrity inspection	Semi-annual	necessary
Power Generation	Cables	DC Cables	Cables visual inspection	Annual	necessary
Power Generation	Cables	DC Cables	Labelling and identification	Annual	necessary
Power Generation	Cables	AC Cables	Cables visual inspection	Semi-annual	necessary
Power Generation	Cables	AC Cables	Labelling and identification	Annual	necessary
Power Generation	Cables	AC Cables	Measurements inspection	Semi-annual	necessary
Power Generation	Inverters	Central Inverters	Safety equipment inspection	Annual	necessary
Power Generation	Inverters	Central Inverters	Integrity inspection	Semi-annual	necessary
Power Generation	Inverters	Central Inverters	Documents inspection	Semi-annual	necessary
Power Generation	Inverters	Central Inverters	Cables visual inspection	Annual	necessary
Power Generation	Inverters	Central Inverters	Labelling and identification	Annual	necessary
Power Generation	Inverters	Central Inverters	Electrical protections visual inspection	Semi-annual	necessary
Power Generation	Inverters	Central Inverters	Thermography inspection	Annual	necessary
Power Generation	Inverters	Central Inverters	Sensors functional verification	Annual	necessary
Power Generation	Inverters	Central Inverters	Measurements inspection	Annual	necessary
Power Generation	Inverters	Central Inverters	Parameters check	Semi-annual	necessary
Power Generation	Inverters	Central Inverters	Electrical protection correct operation	Semi-annual	necessary
Power Generation	Inverters	Central Inverters	Check ventilation system operation	Annual	necessary
Power Generation	Inverters	Central Inverters	Check fuse status	Annual	necessary
Power Generation	Inverters	Central Inverters	Check cables terminals	Semi-annual	necessary
Power Generation	Inverters	Central Inverters	Battery replacement	Every five years	According to manufacturer's recommendation s
Power Generation	Inverters	Central Inverters	Fans replacement	Every five years	According to manufacturer's recommendation s
Power Generation	Inverters	Central Inverters	General cleaning	Semi-annual	necessary
Power Generation	Inverters	Central Inverters	Ventilation cleaning	Annual	necessary
Power Generation	Inverters	String Inverters	Safety equipment inspection	Semi-annual	necessary
Power Generation	Inverters	String Inverters	Integrity inspection	Semi-annual	necessary
Power	Inverters	String Inverters	Cables visual	Annual	necessary

Generation			inspection		
Power Generation	Inverters	String Inverters	Labelling and identification	Semi-annual	necessary
Power Generation	Inverters	String Inverters	Electrical protections visual inspection	Semi-annual	necessary
Power Generation	Inverters	String Inverters	Thermography inspection	Annual	necessary
Power Generation	Inverters	String Inverters	Measurements inspection	Semi-annual	necessary
Power Generation	Inverters	String Inverters	Parameters check	Annual	necessary
Power Generation	Inverters	String Inverters	Electrical protection correct operation	Annual	necessary
Power Generation	Inverters	String Inverters	Check ventilation system operation	Semi-annual	necessary
Power Generation	Inverters	String Inverters	Check cables terminals	Annual	necessary
Power Generation	Inverters	String Inverters	Battery replacement	Every five years	According to manufacturer's recommendations
Power Generation	Inverters	String Inverters	Fans replacement	Every five years	According to manufacturer's recommendations
Power Generation	Inverters	String Inverters	General cleaning	Annual	necessary
Power Generation	Inverters	String Inverters	Ventilation cleaning	Semi-annual	necessary
HV Systems	Cables	HV Cables	Cables visual inspection	Semi-annual	necessary
HV Systems	Cables	HV Cables	Labelling and identification	Semi-annual	necessary
HV Systems	Power Transformer		Integrity inspection	Semi-annual	necessary
HV Systems	Power Transformer		Cables visual inspection	Annual	necessary
HV Systems	Power Transformer		Mechanical visual inspection	Annual	necessary
HV Systems	Power Transformer		Labelling and identification	Annual	necessary
HV Systems	Power Transformer		Thermography inspection	Semi-annual	necessary
HV Systems	Power Transformer		Sensors functional verification	Semi-annual	necessary
HV Systems	Power Transformer		Measurements inspection	Semi-annual	necessary
HV Systems	Power Transformer		Parameters check	Annual	necessary
HV Systems	Power Transformer		Check correct operation	Semi-annual	necessary
HV Systems	Power Transformer		Check cables terminals	Semi-annual	necessary
HV Systems	Power Transformer		Power transformer cleaning	Semi-annual	necessary
HV Systems	HV Switchgear		Integrity inspection	Annual	necessary
HV Systems	HV Switchgear		Cables visual inspection	Annual	necessary
HV Systems	HV Switchgear		Mechanical visual inspection	Semi-annual	necessary
HV Systems	HV Switchgear		Labelling and identification	Annual	necessary
HV Systems	HV Switchgear		Electrical protections visual inspection	Semi-annual	necessary
HV Systems	HV Switchgear		Thermography inspection	Semi-annual	necessary
HV Systems	HV Switchgear		Sensors functional verification	Annual	necessary
HV Systems	HV Switchgear		Measurements inspection	Annual	necessary
HV Systems	HV Switchgear		Check correct operation	Annual	necessary

HV Systems	HV Switchgear		Check fuse status	Annual	necessary
HV Systems	HV Switchgear		Check cables terminals	Semi-annual	necessary
HV Systems	HV Switchgear		General cleaning	Annual	necessary
HV Systems	HV Switchgear		Mechanical lubrication	Semi-annual	necessary
HV Systems	Main Switchboard	Main AUX Switchboard	Integrity inspection	Annual	necessary
HV Systems	Main Switchboard	Main AUX Switchboard	Documents inspection	Annual	necessary
HV Systems	Main Switchboard	Main AUX Switchboard	Cables visual inspection	Annual	necessary
HV Systems	Main Switchboard	Main AUX Switchboard	Labelling and identification	Annual	necessary
HV Systems	Main Switchboard	Main AUX Switchboard	Electrical protections visual inspection	Annual	necessary
HV Systems	Main Switchboard	Main AUX Switchboard	Thermography inspection	Annual	necessary
HV Systems	Main Switchboard	Main AUX Switchboard	Sensors functional verification	Semi-annual	necessary
HV Systems	Main Switchboard	Main AUX Switchboard	Measurements inspection	Semi-annual	necessary
HV Systems	Main Switchboard	Main AUX Switchboard	Parameters check	Annual	necessary
HV Systems	Main Switchboard	Main AUX Switchboard	Check correct operation	Semi-annual	necessary
HV Systems	Main Switchboard	Main AUX Switchboard	Electrical protection correct operation	Annual	necessary
HV Systems	Main Switchboard	Main AUX Switchboard	Check fuse status	Annual	necessary
HV Systems	Main Switchboard	Main AUX Switchboard	Software maintenance	Annual	necessary
HV Systems	Main Switchboard	Main AUX Switchboard	Monitoring operation test	Annual	necessary
HV Systems	Main Switchboard	Main AUX Switchboard	Check cables terminals	Annual	necessary
HV Systems	Main Switchboard	Main AUX Switchboard	Battery replacement	Every five years	According to manufacturer's recommendations
HV Systems	Main Switchboard	Main AUX Switchboard	General cleaning	Annual	necessary
HV Systems	Main Switchboard	Main AC Switchboard	Integrity inspection	Annual	necessary
HV Systems	Main Switchboard	Main AC Switchboard	Documents inspection	Semi-annual	necessary
HV Systems	Main Switchboard	Main AC Switchboard	Cables visual inspection	Annual	necessary
HV Systems	Main Switchboard	Main AC Switchboard	Labelling and identification	Annual	necessary
HV Systems	Main Switchboard	Main AC Switchboard	Electrical protections visual inspection	Annual	necessary
HV Systems	Main Switchboard	Main AC Switchboard	Thermography inspection	Semi-annual	necessary
HV Systems	Main Switchboard	Main AC Switchboard	Sensors functional verification	Annual	necessary
HV Systems	Main Switchboard	Main AC Switchboard	Measurements inspection	Annual	necessary
HV Systems	Main Switchboard	Main AC Switchboard	Check correct operation	Annual	necessary
HV Systems	Main Switchboard	Main AC Switchboard	Electrical protection correct operation	Annual	necessary
HV Systems	Main Switchboard	Main AC Switchboard	Check fuse status	Annual	necessary
HV Systems	Main Switchboard	Main AC Switchboard	Check cables terminals	Semi-annual	necessary
HV Systems	Main Switchboard	Main AC Switchboard	General cleaning	Annual	necessary
HV Systems	Power Monitoring	Power Analyser	Battery replacement	Every five years	According to manufacturer's recommendations
HV Systems	Power Monitoring	Power Analyser	Cables visual inspection	Annual	necessary
HV Systems	Power Monitoring	Power Analyser	Labelling and identification	Annual	necessary
HV Systems	Power Monitoring	Power Analyser	Measurements inspection	Annual	necessary

HV Systems	Power Monitoring	Power Analyser	Integrity inspection	Annual	necessary
HV Systems	Power Monitoring	Power Analyser	Software maintenance	Annual	necessary
HV Systems	Power Monitoring	Power Analyser	Monitoring operation test	Semi-annual	necessary
HV Systems	Power Monitoring	Power Analyser	Parameters check	Semi-annual	necessary
HV Systems	Power Monitoring	Power Analyser	General cleaning	Semi-annual	necessary
HV Systems	Power Monitoring	Energy Meter	General cleaning	Annual	necessary
HV Systems	Power Monitoring	Energy Meter	Cables visual inspection	Annual	necessary
HV Systems	Power Monitoring	Energy Meter	Labelling and identification	Annual	necessary
HV Systems	Power Monitoring	Energy Meter	Measurements inspection	Annual	necessary
HV Systems	Power Monitoring	Energy Meter	Integrity inspection	Annual	necessary
HV Systems	Power Monitoring	Energy Meter	Monitoring operation test	Annual	necessary
HV Systems	Power Monitoring	Energy Meter	Parameters check	Annual	necessary
HV Systems	Power Monitoring	Energy Meter	Check cables terminals	Annual	necessary
HV Systems	Power Monitoring	Multifunctional HV Protection	Battery replacement	Every five years	According to manufacturer's recommendation s
HV Systems	Power Monitoring	Multifunctional HV Protection	Parameters check	Annual	necessary
HV Systems	Power Monitoring	Multifunctional HV Protection	Cables visual inspection	Annual	necessary
HV Systems	Power Monitoring	Multifunctional HV Protection	Labelling and identification	Annual	necessary
HV Systems	Power Monitoring	Multifunctional HV Protection	Integrity inspection	Annual	necessary
HV Systems	Power Monitoring	Multifunctional HV Protection	Software maintenance	Annual	necessary
HV Systems	Power Monitoring	Multifunctional HV Protection	Monitoring operation test	Annual	necessary
HV Systems	Power Monitoring	Multifunctional HV Protection	General cleaning	Annual	necessary
HV Systems	Power Monitoring	Power Control Unit	Battery replacement	Every five years	According to manufacturer's recommendation s
HV Systems	Power Monitoring	Power Control Unit	Electrical protection correct operation	Semi-annual	necessary
HV Systems	Power Monitoring	Power Control Unit	Battery inspection	Annual	necessary
HV Systems	Power Monitoring	Power Control Unit	Cables visual inspection	Semi-annual	necessary
HV Systems	Power Monitoring	Power Control Unit	Labelling and identification	Semi-annual	necessary
HV Systems	Power Monitoring	Power Control Unit	Sensors functional verification	Semi-annual	necessary
HV Systems	Power Monitoring	Power Control Unit	Integrity inspection	Semi-annual	necessary
HV Systems	Power Monitoring	Power Control Unit	Check correct operation	Semi-annual	necessary
HV Systems	Power Monitoring	Power Control Unit	Software maintenance	Semi-annual	necessary
HV Systems	Power Monitoring	Power Control Unit	Electrical protections visual inspection	Semi-annual	necessary
HV Systems	Power Monitoring	Power Control Unit	Monitoring operation test	Semi-annual	necessary
HV Systems	Power Monitoring	Power Control Unit	Check cables terminals	Semi-annual	necessary
HV Systems	Power Monitoring	Power Control Unit	Parameters check	Semi-annual	necessary
HV Systems	Power Monitoring	Power Control Unit	Measurements inspection	Annual	necessary
HV Systems	Power Monitoring	Power Control Unit	General cleaning	Annual	necessary
General Utilities	Backup Power Supply	UPS	Integrity inspection	Annual	necessary
General Utilities	Backup Power Supply	UPS	Cables visual	Annual	necessary

			inspection		
General Utilities	Backup Power Supply	UPS	Thermography inspection	Annual	necessary
General Utilities	Backup Power Supply	UPS	Electrical protection correct operation	Annual	necessary
General Utilities	Backup Power Supply	UPS	Battery inspection	Annual	necessary
General Utilities	Backup Power Supply	UPS	Check ventilation system operation	Annual	necessary
General Utilities	Backup Power Supply	UPS	Check cables terminals	Annual	necessary
General Utilities	Backup Power Supply	UPS	General cleaning	Semi-annual	necessary
General Utilities	Backup Power Supply	Emergency Generator	Integrity inspection	Semi-annual	necessary
General Utilities	Backup Power Supply	Emergency Generator	Mechanical visual inspection	Annual	necessary
General Utilities	Backup Power Supply	Emergency Generator	Measurements inspection	Annual	necessary
General Utilities	Backup Power Supply	Emergency Generator	Parameters check	Annual	necessary
General Utilities	Backup Power Supply	Emergency Generator	Check correct operation	Annual	necessary
General Utilities	Backup Power Supply	Emergency Generator	Electrical protection correct operation	Semi-annual	necessary
General Utilities	Backup Power Supply	Emergency Generator	Battery inspection	Semi-annual	necessary
General Utilities	Backup Power Supply	Emergency Generator	Mechanical verification	Semi-annual	necessary
General Utilities	Backup Power Supply	Emergency Generator	Retightening	Annual	necessary
General Utilities	Backup Power Supply	Emergency Generator	Filters replacement	Every five years	According to manufacturer's recommendations
General Utilities	General Utilities Switchboard		Integrity inspection	Semi-annual	necessary
General Utilities	General Utilities Switchboard		Documents inspection	Semi-annual	necessary
General Utilities	General Utilities Switchboard		Cables visual inspection	Semi-annual	necessary
General Utilities	General Utilities Switchboard		Labelling and identification	Semi-annual	necessary
General Utilities	General Utilities Switchboard		Thermography inspection	Annual	necessary
General Utilities	General Utilities Switchboard		Measurements inspection	Semi-annual	necessary
General Utilities	General Utilities Switchboard		Electrical protection correct operation	Semi-annual	necessary
General Utilities	General Utilities Switchboard		Check cables terminals	Annual	necessary
General Utilities	General Utilities Switchboard		General cleaning	Semi-annual	necessary
General Utilities	Auxiliary System	Lights and Electric Sockets	Integrity inspection	Annual	necessary
General Utilities	Auxiliary System	Lights and Electric Sockets	Cables visual inspection	Annual	necessary
General Utilities	Auxiliary System	Lights and Electric Sockets	Measurements inspection	Semi-annual	necessary
General Utilities	Auxiliary System	Lights and Electric Sockets	Check correct operation	Annual	necessary
General Utilities	Auxiliary System	Lights and Electric Sockets	General cleaning	Semi-annual	necessary
General Utilities	Auxiliary System	HVAC	Air conditioning visual inspection	Semi-annual	necessary
General Utilities	Auxiliary System	HVAC	Heater visual inspection	Semi-annual	necessary
General Utilities	Auxiliary System	HVAC	Ventilation visual inspection	Semi-annual	necessary
General Utilities	Auxiliary System	HVAC	Sensors functional verification	Semi-annual	necessary
General Utilities	Auxiliary System	HVAC	Measurements inspection	Semi-annual	necessary
General Utilities	Auxiliary System	HVAC	Check correct operation	Semi-annual	necessary

General Utilities	Auxiliary System	HVAC	Check ventilation system operation	Semi-annual	necessary
General Utilities	Auxiliary System	HVAC	Air conditioning cleaning	Semi-annual	necessary
General Utilities	Auxiliary System	HVAC	Ventilation cleaning	Semi-annual	necessary
General Utilities	Auxiliary System	HVAC	Heater cleaning	Semi-annual	necessary
General Utilities	Water Supply System		Integrity inspection	Annual	necessary
General Utilities	Fire Detection Central		Sensors functional verification	Semi-annual	necessary
General Utilities	Fire Detection Central		Check correct operation	Semi-annual	necessary
General Utilities	Fire Detection Central		Electrical protection correct operation	Semi-annual	necessary
General Utilities	Fire Detection Central		Battery inspection	Semi-annual	necessary
General Utilities	Fire Detection Central		General cleaning	Annual	necessary
General Utilities	Fire Detection Central		Cameras & Sensors cleaning	Semi-annual	necessary
General Utilities	Lightning Protection		Integrity inspection	Annual	necessary
General Utilities	Low Voltage Power Transformer		Integrity inspection	Semi-annual	necessary
General Utilities	Low Voltage Power Transformer		Cables visual inspection	Semi-annual	necessary
General Utilities	Low Voltage Power Transformer		Mechanical visual inspection	Semi-annual	necessary
General Utilities	Low Voltage Power Transformer		Labelling and identification	Annual	necessary
General Utilities	Low Voltage Power Transformer		Thermography inspection	Annual	necessary
General Utilities	Low Voltage Power Transformer		Sensors functional verification	Semi-annual	necessary
General Utilities	Low Voltage Power Transformer		Measurements inspection	Semi-annual	necessary
General Utilities	Low Voltage Power Transformer		Parameters check	Semi-annual	necessary
General Utilities	Low Voltage Power Transformer		Check correct operation	Semi-annual	necessary
General Utilities	Low Voltage Power Transformer		Check cables terminals	Semi-annual	necessary
General Utilities	Low Voltage Power Transformer		Power transformer cleaning	Semi-annual	necessary
Infrastructure	Field	Fence	Integrity inspection	Annual	necessary
Infrastructure	Field	Fence	Mechanical lubrication	Annual	necessary
Infrastructure	Field	Vegetation	Vegetation clearing	Semi-annual	necessary
Infrastructure	Field	Paths	Integrity inspection	Semi-annual	necessary
Infrastructure	Field	Paths	Vegetation clearing	Semi-annual	necessary
Infrastructure	Field	Drainage System	General cleaning	Annual	necessary
Infrastructure	Field	Manholes	Integrity inspection	Semi-annual	necessary
Infrastructure	Buildings		Integrity inspection	Annual	necessary
Infrastructure	Buildings		Documents inspection	Annual	necessary
Infrastructure	Buildings		General cleaning	Annual	necessary
Infrastructure	Safety		Safety equipment inspection	Annual	necessary
Infrastructure	Safety		Check correct operation	Semi-annual	necessary
Infrastructure	PV Support Structure	Fixed Structure	Integrity inspection	Semi-annual	necessary
Infrastructure	PV Support Structure	Fixed Structure	Retightening	Semi-annual	necessary
Infrastructure	PV Support Structure	Solar Tracker	Integrity inspection	Annual	necessary
Infrastructure	PV Support Structure	Solar Tracker	Cables visual inspection	Semi-annual	necessary
Infrastructure	PV Support Structure	Solar Tracker	Mechanical visual inspection	Semi-annual	necessary

Infrastructure	PV Support Structure	Solar Tracker	Labelling and identification	Annual	necessary
Infrastructure	PV Support Structure	Solar Tracker	Thermography inspection	Annual	necessary
Infrastructure	PV Support Structure	Solar Tracker	Measurements inspection	Semi-annual	necessary
Infrastructure	PV Support Structure	Solar Tracker	Parameters check	Semi-annual	necessary
Infrastructure	PV Support Structure	Solar Tracker	Check correct operation	Annual	necessary
Infrastructure	PV Support Structure	Solar Tracker	Electrical protection correct operation	Semi-annual	necessary
Infrastructure	PV Support Structure	Solar Tracker	Monitoring operation test	Annual	necessary
Infrastructure	PV Support Structure	Solar Tracker	Check cables terminals	Semi-annual	necessary
Infrastructure	PV Support Structure	Solar Tracker	Retightening	Semi-annual	necessary
Infrastructure	PV Support Structure	Solar Tracker	Battery replacement	Every five years	According to manufacturer's recommendation s
Infrastructure	PV Support Structure	Solar Tracker	General cleaning	Semi-annual	necessary
Infrastructure	PV Support Structure	Solar Tracker	Mechanical lubrication	Annual	necessary
Monitoring System	Weather Station		Integrity inspection	Annual	necessary
Monitoring System	Weather Station		Cables visual inspection	Annual	necessary
Monitoring System	Weather Station		Sensors functional verification	Annual	necessary
Monitoring System	Weather Station		Measurements inspection	Annual	necessary
Monitoring System	Weather Station		Check correct operation	Semi-annual	necessary
Monitoring System	Weather Station		Electrical protection correct operation	Annual	necessary
Monitoring System	Weather Station		Battery inspection	Annual	necessary
Monitoring System	Weather Station		Monitoring operation test	Semi-annual	necessary
Monitoring System	Weather Station		General cleaning	Annual	necessary
Monitoring System	Weather Station		Cameras & Sensors cleaning	Annual	necessary
Monitoring System	Weather Station	Irradiation Sensors	Integrity inspection	Annual	necessary
Monitoring System	Weather Station	Irradiation Sensors	Cables visual inspection	Semi-annual	necessary
Monitoring System	Weather Station	Irradiation Sensors	Sensors functional verification	Semi-annual	necessary
Monitoring System	Weather Station	Irradiation Sensors	Sensors calibration	Annual	necessary
Monitoring System	Weather Station	Irradiation Sensors	Cameras & Sensors cleaning	Annual	necessary
Monitoring System	Monitoring System Cabling		Cables visual inspection	Semi-annual	necessary
Monitoring System	Monitoring System Cabling		Labelling and identification	Semi-annual	necessary
Monitoring System	Monitoring System Cabling		Monitoring operation test	Semi-annual	necessary
Monitoring System	Communication Board		Integrity inspection	Annual	necessary
Monitoring System	Communication Board		Documents inspection	Annual	necessary
Monitoring System	Communication Board		Cables visual inspection	Annual	necessary
Monitoring System	Communication Board		Electrical protection correct operation	Annual	necessary
Monitoring System	Communication Board		Battery inspection	Annual	necessary
Monitoring System	Communication Board		Check ventilation system operation	Annual	necessary

Monitoring System	Communication Board		Monitoring operation test	Annual	necessary
Monitoring System	Communication Board		Check cables terminals	Annual	necessary
Monitoring System	Communication Board		General cleaning	Annual	necessary
Monitoring System	Communication Board		Ventilation cleaning	Annual	necessary
Monitoring System	Monitoring System Software		Measurements inspection	Annual	necessary
Monitoring System	Monitoring System Software		Software maintenance	Monthly	necessary
Monitoring System	Monitoring System Software		Monitoring operation test	Annual	necessary
Monitoring System	Data Logger		Integrity inspection	Semi-annual	necessary
Monitoring System	Data Logger		Check correct operation	Semi-annual	necessary
Monitoring System	Data Logger		Monitoring operation test	Semi-annual	necessary
Security System	Security System Central		Parameters check	Semi-annual	necessary
Security System	Security System Central		Check correct operation	Semi-annual	necessary
Security System	Security System Central		Battery inspection	Annual	necessary
Security System	Security System Central		Check ventilation system operation	Semi-annual	necessary
Security System	Security System Central		General cleaning	Annual	necessary
Security System	System CCTV		Integrity inspection	Annual	necessary
Security System	System CCTV		Sensors functional verification	Annual	necessary
Security System	System CCTV		Cameras & Sensors cleaning	Annual	necessary
Security System	Intrusion Systems		Integrity inspection	Annual	necessary
Security System	Intrusion Systems		Sensors functional verification	Semi-annual	necessary
Security System	Intrusion Systems		Cameras & Sensors cleaning	Annual	necessary
Security System	Security System Cabling		Cables visual inspection	Semi-annual	necessary
Security System	Security System Cabling		Labelling and identification	Semi-annual	necessary
Security System	Security System Board		Integrity inspection	Annual	necessary
Security System	Security System Board		Documents inspection	Semi-annual	necessary
Security System	Security System Board		Cables visual inspection	Semi-annual	necessary
Security System	Security System Board		Electrical protection correct operation	Semi-annual	necessary
Security System	Security System Board		Battery inspection	Semi-annual	necessary
Security System	Security System Board		Monitoring operation test	Annual	necessary
Security System	Security System Board		Check cables terminals	Semi-annual	necessary
Security System	Security System Board		General cleaning	Annual	necessary
Security System	Security System Board		Ventilation cleaning	Annual	necessary
Spare parts			Inventory of stock	Annual	necessary
Spare parts			Visual inspection of stock conditions	Quarterly	necessary
Spare parts			Stock replenishment	Ongoing	necessary
Spare parts			Review failure rates and adjust stock keeping	Annual	necessary

Source: (Solar Power Europe, 2016)

APPENDIX 2 – PV Module Cleaning Methods

AmeriSolar	Rain / Normal water.
Centrosolar	De-ionized water is preferred to prevent spotting and calcium build up
LG Solar	Water, ethanol or a conventional glass cleanser with a micro-fibre cloth can be used for regular washing or rinsing of the front glass to remove dust, dirt or other deposits.
REC Solar	Plenty of water (using a hose).
ReneSolar	Only use soft cloths or sponges to clean the glass surface. Only use clean water as the cleaning solvent.
Renogy Solar	Clean with a wet cloth or glass cleaner if necessary.
Silfab	"Under normal conditions (sufficient rainfall),cleaning of the module is not required. In extreme climatic conditions, the electrical performance of the module may be affected by accumulation of dirt, dust or debris on the glass front cover. In this case, the front cover can be washed using water, commercial glass cleaners, or alcohol/ ethanol/methanol and a soft cloth. "
Trina Solar	Under most weather conditions, normal rainfall is sufficient to keep the PV module glass surface clean. If dust or dirt build-up becomes excessive, clean the glass only with a soft cloth using mild detergent and water. Do not clean the modules with cold water during the warmer hours of the day in order to avoid creating any thermal shock that may damage the module
Sun Edison	"clean the glass only with a soft cloth using mild, non-abrasive detergent and water"
Stion	Cleaning of the modules is not typically necessary (rainfall will have a self-cleaning effect). In dry and other unique climates, and in case of heavy soiling, we recommend cleaning the modules using plenty of water (from a hose) without any cleaning agents and using a gentle cleaning implement (a sponge).

Hyundai	Clean the module surface and remove dirt and contaminants with tap water.
Silevo	Periodically clean the module surface with water and a soft cloth or sponge. Fingerprints may be removed with standard glass cleaner.
China sunenergy	Clean the panel(s) preferably once per annum if possible (dependant on site conditions) using a soft cloth dry or damp, as necessary. Never use abrasive material under any circumstances
Astroenergy	It is not generally necessary to clean the modules (rainfall will have a self-cleaning effect). In case of heavy soiling (which will result in output reductions), we recommend cleaning the modules using plenty of water (from a hose) without cleaning agents and using a gentle cleaning implement (a sponge).
ET solar	Use water and a soft sponge or cloth for cleaning. A mild, non-abrasive cleaning agent can be used if necessary. Do not use dishwasher detergent
Solar World	Given a sufficient tilt (at least 15°), it is generally not necessary to clean the modules (rainfall will have a self-cleaning effect).
Sun Power	Rinse them down with your garden hose.
Suniva	Clean the surface with water and a soft cloth or sponge. Never clean the module in the middles of the day when the glass is hot to avoid injury.
Itek	Typically water and a soft, non-abrasive brush will be adequate to clean the modules.
Kyocera	Normal rainfall is sufficient to keep the module glass surface clean. If dirt build-up becomes excessive, clean the glass surface only with a soft cloth using mild detergent and water
Hanhwa solarone	Hanwha SolarOne modules have a self-cleaning function under rainfall weather condition. Module with a mounted tilt angle more than 15°is more effective than other mounting angle. If heavy soiling build-up is excessive on module glass, use a soft cloth and water for cleaning

APPENDIX 3 - Skills Matrix for O&M Staff

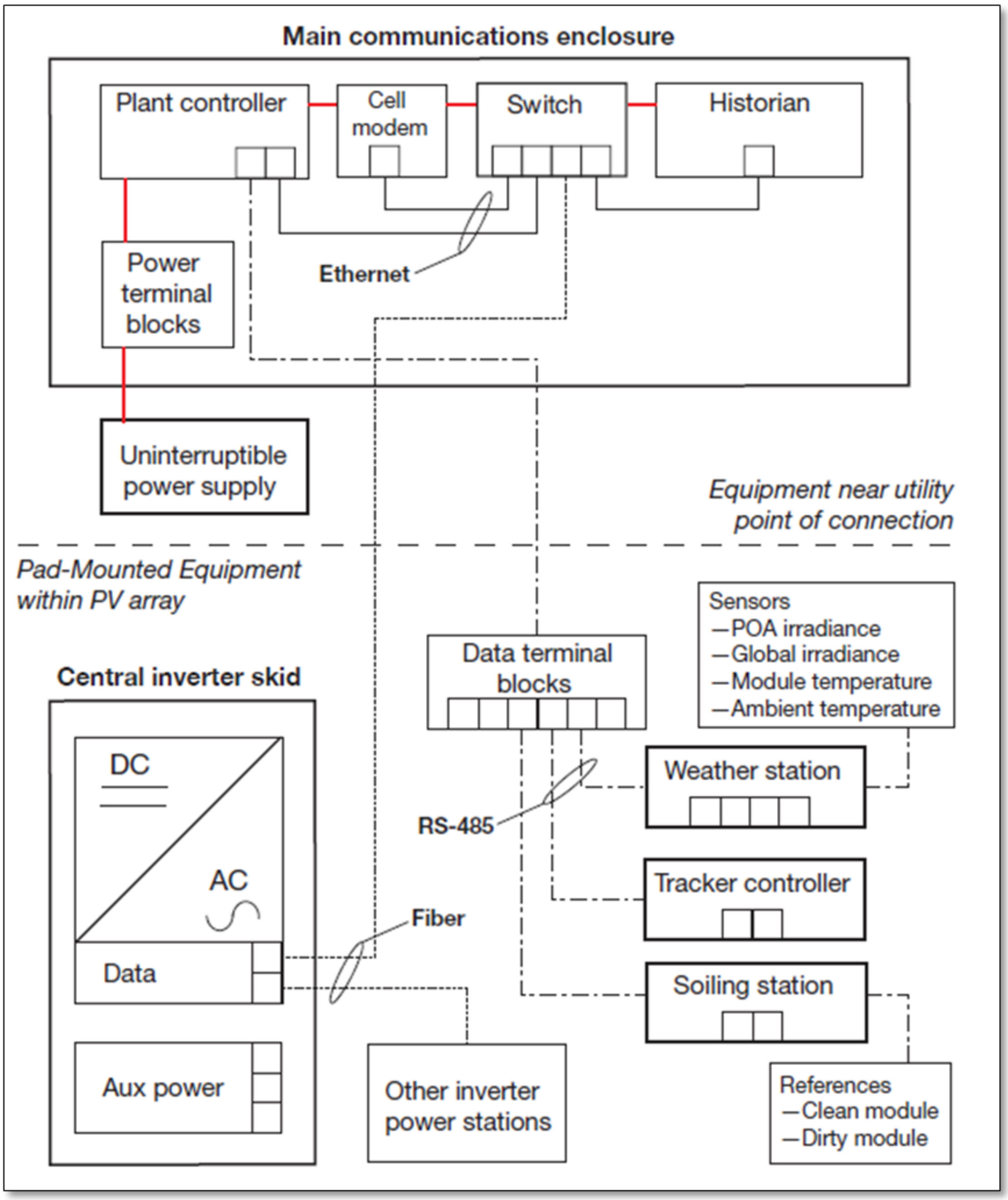
Employee			Health and Safety											
First Name	Surname	Function	Company's Services Induction	Health and Safety assessment test	Manual Handling	Display Screen Equipment	Risk Assessment	Occupational Health and Safety course	Training to handle Health & Safety in a team	Certification of Occupational Health & Safety	First Aid Work	HV Substation access	Managing Contractors	Other tasks, or requirements
		Managerial												
		Administration												
		Technician												
		Controller												
		Trainee												

Source: (Solar Power Europe, 2016)

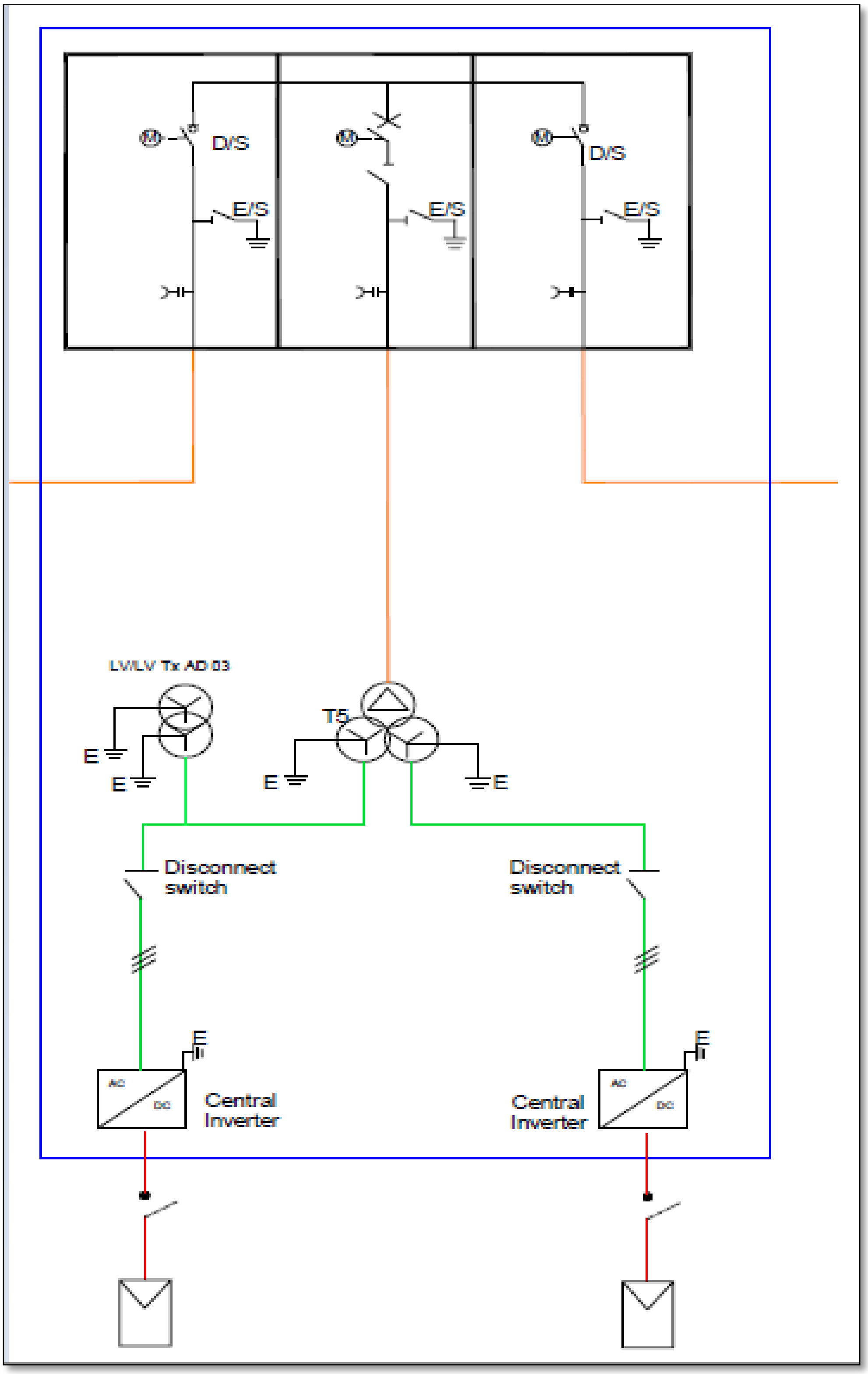
Employee			Environmental		Monitoring & Metering			Inverter			Electrical		Data & Communication				
First Name	Surname	Function	Certification of Environmental Management and Assessment	Other relevant training course or/and certificate of Environmental management	Certain Monitoring tool training	Meter accreditation and calibration	Other relevant skill (e.g. data handling tool etc.)	Power Electronics	Learning Tools Interoperability	Other skills specific to Inverter	Certification of Electrical Qualification	Other relevant skills	Termination and specific communication cabling	Installation of the monitoring system	Installation and connection of meters	Installation of satellite broadband system	Other
		Managerial															
		Administration															
		Technician															
		Controller															
		Trainee															

Source: (Solar Power Europe, 2016)

APPENDIX 4 – SCADA System



APPENDIX 5 – Switchgear room



APPENDIX 6 - Hazards in a PV Plant

Hazard source	**Hazard**	**Effect to**
Electrical current/electricity	Electrocution, short-circuit	P/V system & employees
Fire	Damage of the P/V system, mishaps, burns	P/V system & employees, emergency responders
Contact with sharp surfaces	Mishaps (cuts, bruises etc.)	Employees
Contact with hot surfaces	Burns	Employees
Fall from height	Mishaps, death	Employees
Batteries (oxides)	Burns, respiratory problems, environmental	Employees, environment
Non-ionizing radiation	Health hazard	Employees
PVP system	Communication systems interference	Aviation
Panels	Reflection/glare	Aviation
PVP system	Airspace penetration	Aviation
Debris on airfield's runway	Aircraft engine suck a foreign object (FOD)	Aviation
PVP system	Aircraft's evacuation difficulties	Passengers, emergency responders
PVP system	Aircraft's rescuing difficulties	Passengers, emergency responders
Natural hazards		
Lightning	Lightning Damage of the P/V system, death	P/V system & employees
Strong winds	Damage of the P/V system (snatch), mishaps	P/V system & employees & third parties
Dust	Damage of the P/V system, low energy productivity	P/V system, energy productivity

Heat	Health	Employees
Hail	Damage of the P/V system, mishaps	P/V system, employees
Moisture	Damage of the p/v system (corrosion)	P/V system
Rodents (rats etc.)	Damage of the P/V system, fire	P/V system
Birds nesting	Aircraft engine suck a bird	Aviation
Earthquakes	Damage of the P/V system	P/V system
Flora	Health hazard (allergies)	Employees
Bugs, snakes, scorpions, spiders, wild bees etc.	Mishaps (stings, allergies)	Employees
Vandalism - sabotage-theft	Damage of the P/V system	P/V system

Source: (Kamenopoulos Tsoutsos, 2015))

APPENDIX 7 – SOLAR O&M Questionnaire

Questionnaire

Instructions: Please put a tick ✓ in the box next to your answer of choice or write in the space provided as the case may be.

1. What is the DC Capacity of the plant?

- ☐ 5MW to 10MW
- ☐ 10MW to 20MW
- ☐ 20MW to 30MW
- ☐ 30MW to 40MW
- ☐ 40MW to 50MW
- ☐ 50MW to 60MW
- ☐ 60MW to 70MW
- ☐ 70MW to 80MW

2. Does the plant employ Tracking or Fixed Technology?

- ☐ Fixed
- ☐ Tracking

3. How many employees are permanently employed for O&M? ☐

4. State the number of Electricians employed? ☐

5. State the number of Technicians employed? ☐

6. State the number of Plant Controllers/Operators employed? ☐

7. State the number of General Workers employed? ☐

8. What are the most common faults on the PV plant? (Choose 3 of the most common faults experienced on the plant)

- ☐ Communication from devices to SCADA
- ☐ SCADA
- ☐ Inverter tripping
- ☐ Ground Faults
- ☐ Blown DC fuses
- ☐ Faulty Modules
- ☐ UPS Failure
- ☐ Faulty inclinometers
- ☐ Tracker system
- ☐ Security system
- ☐ AC System
- ☐ DC System
- ☐ Weather Stations
- ☐ Support Structures
- ☐ Inclinometers
- ☐ String Outages/Connectors

9. How often are panels washed in a year?

- ☐ 3 times per year
- ☐ 4 to 6 times per year
- ☐ More than 6 times per year
- ☐ Never
- ☐ Whenever irradiance measurement from an uncleaned reference cell is lower than a cleaned reference cell by a predetermine value.

10. How are panels washed? More than one option can be selected.

- ☐ Manually using hose and squeegee
- ☐ Using a special tractor equipped with attachments for module cleaning
- ☐ Portable firefighting equipment with petro/diesel pump

11. What are the most common panel defects on the PV plant? (Choose 3 of the most common faults experienced on the plant)

- ☐ Cracked glass
- ☐ Blown diodes
- ☐ Hotspots
- ☐ Snail tracks
- ☐ Blown connectors
- ☐ Failed Solar cell
- ☐ Delamination
- ☐ Backing sheet damage
- ☐ Bad connections in Junction box
- ☐ Insulation faults
- ☐ Bad connections within module

12. How often is vegetation control performed / scheduled?

- ☐ Daily
- ☐ Weekly
- ☐ Fortnightly
- ☐ Monthly
- ☐ Quarterly
- ☐ As required

13. How often are the pyranometers cleaned?

- ☐ Daily
- ☐ Weekly
- ☐ Fortnightly
- ☐ Monthly

☐ As required

14. Is the plant manned during weekends?

☐ Yes ☐ No

☐ Staff on standby

15. What are the normal working hours for a day?

☐ < 8 hours ☐ 8 hours

☐ 8 to 10 hours ☐ 10 to 12 hours

16. Are personnel on Standby daily?

☐ Yes ☐ No

17. Is the plant remotely monitored?

☐ Yes ☐ No

18. Are certain alarms/trips sent to mobile phones via sms?

☐ Yes ☐ No

19. Is Infrared Thermography used on the plant to detect defective modules?

☐ Yes ☐ No

20. What is the percentage of total panels kept as spares? ☐

21. How many inverters are kept as spare? ☐

22. Does the plant have an Operation and Maintenance contract?

☐ Yes ☐ No

23. Does the plant have 24 hour security?

☐ Yes ☐ No

25. What is the total cost for O&M per year in percentage of total EPC cost?

☐ < 0.3% ☐ 0.3% to 0.6%

☐ 0.7% to 1% ☐ > than 1%

26. What is the current annual performance ratio of the plant?

☐ < 75% ☐ 75% to 78%

☐ 79% to 82% ☐ > 82%

27. Is the GCC Engineer permanently employed on site?

☐ Yes ☐ No

☐ Shared between sites

29. Has the option for inverter extended warranty been exercised with the manufacturer?

☐ Yes ☐ No

30. Which costs more: the property insurance against damage or the liability insurance to protect workers?

☐ Property insurance ☐ Liability insurance

31. What percentage of annual O&M expenses do insurance premiums account for?

☐ < 10% ☐ 10% to 15%

☐ 15% to 20% ☐ 20% to 25%

32. What are the most frequent inverter component that fails or are problematic? (Choose a maximum of 3 of the most common faults experienced on the plant)

☐ Matrix/IGBT ☐ DC Contactor

☐ Fans ☐ Ground Fault Detection Components

☐ Surge protection ☐ AC Contactor

☐ Power Supply ☐ Boards/Cards

☐ Software ☐ Other

32. Highest level of monitoring employed (highest resolution)?

☐ String level ☐ Array level

☐ Inverter level ☐ Block level

33. Annual availability of the PV plant?

☐ >98% ☐ 95% to 97%

☐ 90% to 94% ☐ <90%

34. What is the source of the water used to wash panels?

☐ Borehole ☐ Borehole & Reverse osmosis plant

☐ Municipal ☐ Municipal & Reverse osmosis plant

APPENDIX 8 – Consent Cover Letter

APPENDIX 9 – Ethical Clearance