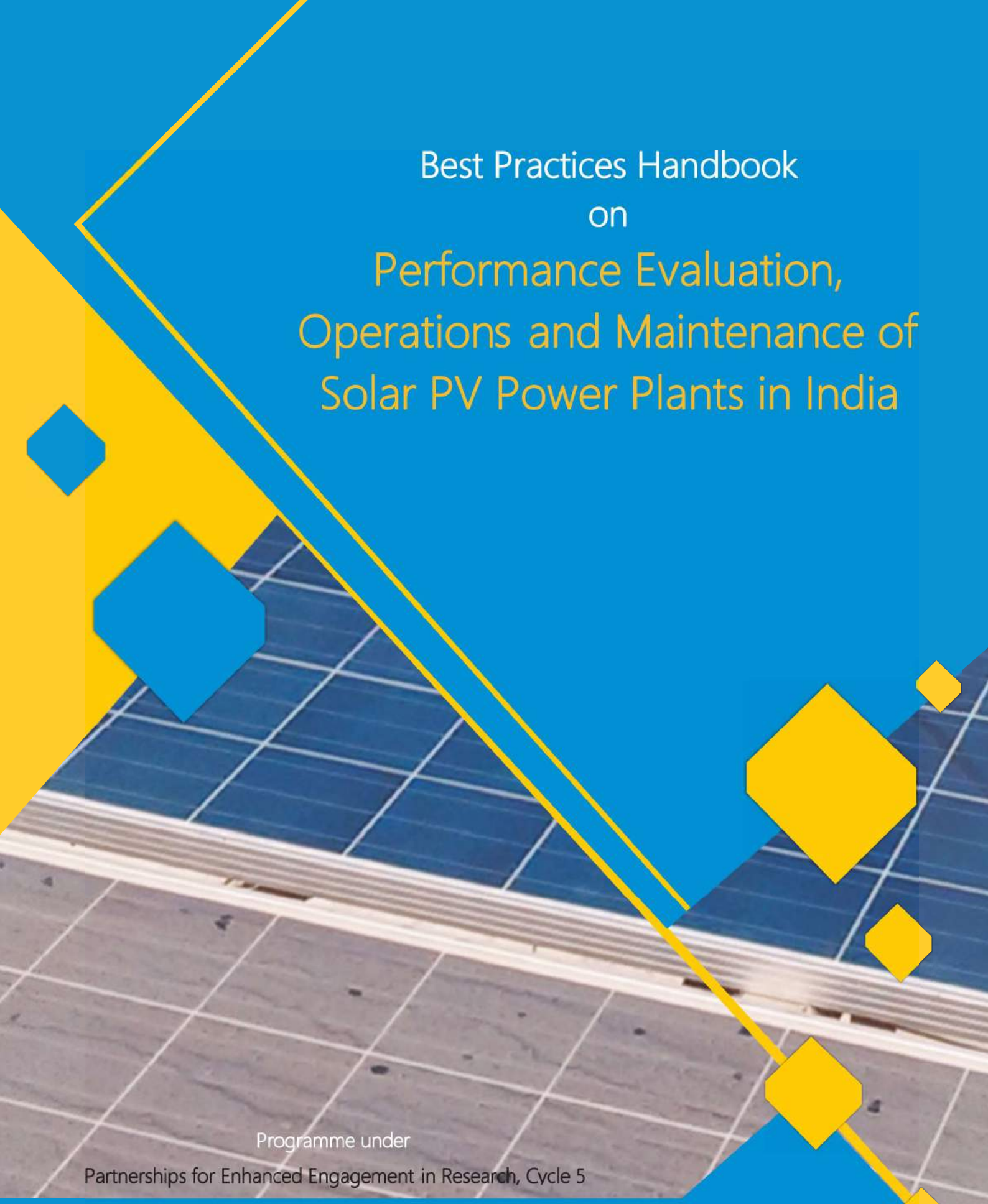
Best Practices Handbook on Performance Evaluation, Operations and Maintenance of Solar PV Power Plants in India



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Prepared by

WISE
WORLD INSTITUTE OF SUSTAINABLE ENERGY

Program under

Partnerships for Enhanced Engagement in Research, Cycle 5

Best Practices Handbook

on

Performance Evaluation, Operations and Maintenance of Solar PV Power Plants in India

Supported by

United States Agency for International Development

Prepared by

World Institute of Sustainable Energy

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Disclaimer

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And finally, WISE would like to express its deep gratitude to G M Pillai, Founder Director General, WISE, for his guidance and mentorship during the course of the project period; and the project team members for their significant contribution in implementing the project.

PREFACE

On behalf of the World Institute of Sustainable Energy (WISE), I am pleased to present the *Best Practices Handbook* on *Performance Evaluation, Operation and Maintenance of Solar PV Plants*. This is an important outcome of the two-year project supported by the United States Agency for International Development (USAID), under its "Partnerships for Enhanced Engagement in Research (PEER), Cycle 5" program. Besides USAID, the project also received the able and critical support of the National Academy of Sciences (NAS), USA; and GE Global Research, Bangalore.

The project team from WISE's *Centre for Solar Energy* visited numerous solar plants spread across the country to study the operation and maintenance practices carried out. It was observed that a huge information and knowledge gap is present among the O&M staff, for both rooftop solar as well as utility scale power plants, resulting in reduced or poor energy generation over the plant's lifetime. This was found to not only result in huge revenue losses, but also lead to increased thermal power demand, thereby contributing to increased emissions. Hence, timely bridging of the knowledge deficit gap and development of an efficient network of independent O&M service providers are of critical essence and need of the hour.

The *Best Practices Handbook* aims to fulfil these very objectives. Efforts have been made to explain the technical aspects of the O&M in simple and succinct language. Sample formats included as annexures can be referred to and used as per individual solar plant's requirements. Apart from the Handbook, WISE has also developed a knowledge portal **www.maintainsolar.in** that elaborates on some of the topics briefly discussed in the Handbook. We hope that both the Handbook and knowledge portal are widely used by the concerned stakeholders and they benefit from these resources in the long term.

G M Pillai
Founder Director General
WISE

सत्यमेव जयते
आनन्द कुमार
ANAND KUMAR

सचिव
भारत सरकार
नवीन और नवीकरणीय ऊर्जा मंत्रालय
SECRETARY
GOVERNMENT OF INDIA
MINISTRY OF NEW AND RENEWABLE ENERGY

FOREWORD

The contribution of renewable energy in India's total energy mix has significantly increased over the last two decades, contributing around 22% of total installed capacity today. Of various renewable energy sources, contribution of grid-connected solar power is 34%. The total installed cumulative capacity of solar power in India is over 27 GW now, accelerating the momentum towards meeting the 100 GW national target by 2022. This exponential growth in solar capacity addition is a result of conducive policies, increased investor confidence, and favourable environment for collective and effective participation of stakeholders.

Currently, MNRE is making all efforts to standardize the technical specifications of solar plants so as to ensure quality of solar projects. However, it is also essential to follow appropriate operation and maintenance (O&M) practices, as these have a huge bearing on the long-term performance of the solar plants. Besides, effective O&M tracks projects generation over its lifetime, resulting in optimizing performance. Currently, challenges such as distributed installation of solar projects, lack of technical know-how, etc. are hindering the long-term performance of solar power plants. The Best Practices Handbook on 'Performance Evaluation, Operation and Maintenance of Solar PV Plants in India', prepared by WISE, with financial support from USAID, aims to address these challenges and to provide hands-on solutions and customized information to maximize overall performance of the solar systems. We welcome this valuable initiative taken by WISE.

The Handbook includes scientific explanations on design considerations for effective O&M of solar power plants over their plant life, methods of analyzing performances of solar power plants, common failure reasons, etc. in simple and easy-to-understand language. We hope this Handbook will be useful to all the stakeholders from the Indian solar industry and provide the required impetus for further boosting solar energy development and deployment in India.

[Anand Kumar]

अक्षय ऊर्जा से देश विकास
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FOREWORD

Upendra Tripathy
Director General
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I am glad to note that the World Institute of Sustainable Energy (WISE), Pune, with the support from United States Agency for International Development (USAID), is executing a two-year project "*Developing Performance Evaluation and O&M Strategy for the Indian Solar Sector*". It is a privilege for me to release a Best Practices Handbook developed by WISE on '*Performance Evaluation, Operations and Maintenance of Solar PV Plants*.'I have also been informed that WISE proposes to develop a portal on this subject. Since India ranks third in the world in terms of annual capacity addition of solar power and aims to achieve a target of 100 GW solar power by 2022, this publication is bound to propel India's global ranking and confirm its position as a front runner in solar power, while jointly meeting the global commitment (NDCs) of moving towards a low-carbon and zero-emissions economy.

The best practices handbook developed by WISE would cover the related and requisite technical aspects of performance evaluation, operation and maintenance in a holistic and comprehensive manner. Though this handbook caters to the Indian Solar sector, it can also be referred to by the ISA Member countries.

I wish WISE all success in the venture.

(Upendra Tripathy)

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Abbreviations

AC	Alternating Current
ACDB	AC Distribution Board
AJB	Array Junction Box
AM	Air mass
ARC	Anti-reflective coating
BD	Bypass diode
BoS	Balance of System
BOOT	Build, own, operate, transfer
CEA	Central Electricity Authority of India
cm	Centimeter
CM	Corrective maintenance
CO	Carbon monoxide
CO_2	Carbon dioxide
CT/PT	Current transformer/power transformer
CUF	Capacity utilization factor
DC	Direct current
DHI	Direct horizontal irradiance
DPR	Detailed project report
DISCOM	Distribution company
DNI	Direct normal irradiance
EHS	Environmental health and safety
EL	Electroluminescence
EPC	Engineering, Procurement and Construction
EPDM	Ethylene propylene diene methylene
EPI	Energy performance index
EVA	Ethylene vinyl acetate
FF	Fill factor
FTP	File Transfer Protocol
GFDI	Ground fault detector interrupter
GHI	Global horizontal irradiance
HALS	Hindered Amine Light Stabilizers
HT	High tension
IEC	International Electrotechnical Commission
IGBT	Insulated-gate bipolar transistor
IR	Infrared
I-V curve	Current voltage curve
KPI	Key performance indicators
kVA	Apparent power
kVAR	Reactive power
kW	Active power, killowatt
LA	Lightning arrester
LeTID	Light elevated-temperature-induced degradation
LID	Light induced degradation
LOTO	Lock-out, tag-out
LT	Low tension
m	meter
mA	Milliamps
Mbps	Megabit per second
MC	Multicontact
MCCB	Molded Case Circuit Breaker

MJB	Main Junction Box
mm	Millimeter
MMS	Module mounting structures
MPPT	Maximum Power Point Tracking
MW	Megawatt
Na+	Sodium ions
NREL	National Renewable Energy Laboratory
O&M	Operations and Maintenance
OC	Open circuit
OEM	Original equipment manufacturer
OSHA	Occupational Safety and Health Administration
Pa	Pascal
PE	Performance evaluation
PERC	Passivated emitter and rear cells
PID	Potential Induced Degradation
PM	Preventive maintenance
PoA	Plane of array
PPA	Power purchase agreement
PPE	Personal protective equipment
PPI	Power performance index
PR	Performance ratio
PV	Photovoltaic
PV curve	Power Voltage curve
PVO	PV offset box
QAP	Quality Assurance Plan
RE	Renewable Energy
RESCO	RE service company
RFQ	Request for quotation
RH	Relative humidity
SC	Short circuit
SCADA	Supervisory control and data acquisition
SLD	Single line diagram
SLDC	State load dispatch center
SM	Scheduled Maintenance
SPD	Surge Protection Devices
SPV	Solar Photovoltaic
SR	Soiling ratio
STAAD	Structural analysis and design
STC	Standard Test Condition
ToD	Time of day
TRANSCO	Transmission company
UPS	Uninterruptible power supply
UV	Ultraviolet
UVAbs	UV absorber
V	Voltage
W	Watts
WLAN	Wireless Local Area Networking
ZCC	Zig-zag chopper circuit

Chapter 1

Introduction

Introduction

India is endowed with abundant solar energy, capable of producing 5,000 trillion kilowatts of clean power. The country is blessed with around 300 sunny days a year and with solar insolation of 4-7kWh/m^2/day. If this energy is harnessed efficiently, it will reduce demand from conventional power and will ensure reduction in carbon emissions. Since the rate of electricity demand is increasing exponentially, electricity generation using solar PV energy will play a huge role in meeting India's energy demand. When considering other electricity generation technologies, solar PV technology is simple and modular. This makes solar PV power plants easy to install anywhere, and of any capacity.

In the Indian context, if we consider the expected solar PV capacity addition in the near future, a huge quantum of power will be generated which will reduce the demand for conventional thermal sources. However, gradually over a solar PV plant's life, the power output from it will reduce due to degradation of solar PV modules. Further, the output will also reduce if the plants are not operated at optimum efficiency levels. Hence, along with aggressive capacity addition, adequate efforts are required to ensure the effective operations of these power plants. As such, SPV power plants are distributed in nature and involve large numbers of stakeholders spread across the country. This makes bridging the stakeholders' knowledge gap in ensuring resource optimization a difficult task. To this end, a scientific approach to performance evaluation and effective O&M of SPV power plants is required. Otherwise, the power deficit due to improper O&M of solar power plants will lead to increased electricity demand from thermal sources and reduction in the active installed capacity of SPV power plants.

From the continuous analysis and research on SPV power plants, it was found that 'performance evaluation (PE) and O&M' are critical elements that decide the long term operations of solar power in India. However, we found that the distributed nature of the SPV power plant installations, and social-environmental and geographical factors, decide the quality of PE and O&M.

Along with these difficulties, the knowledge gap of the O&M team is also an issue. Even though SPV power plants need less operational activities compared to other technologies, a strategic approach to operational activities will reduce the chances of failure and help the asset owner to achieve the expected power generation from his/her SPV power plant. Solar PV power plants are expected to have an operational life of 25 years, if one takes into consideration that the life of a PV module is 25 years. However, there are other plant components which may fail to operate for 25 years in the absence of proper O&M.

If we align the annual installation plan under NSM, 100 GW will be commissioned by 2022. As the OEM's are providing warranty support up to 5 years, the plants will effectively work up to 5 years from the date of commissioning. However, after 5 years of project life, major O&M issues will emerge due to the ageing of electronic components. Further, due to non-availability of an OEM's warranty support, plant downtime may increase followed by generation loss.

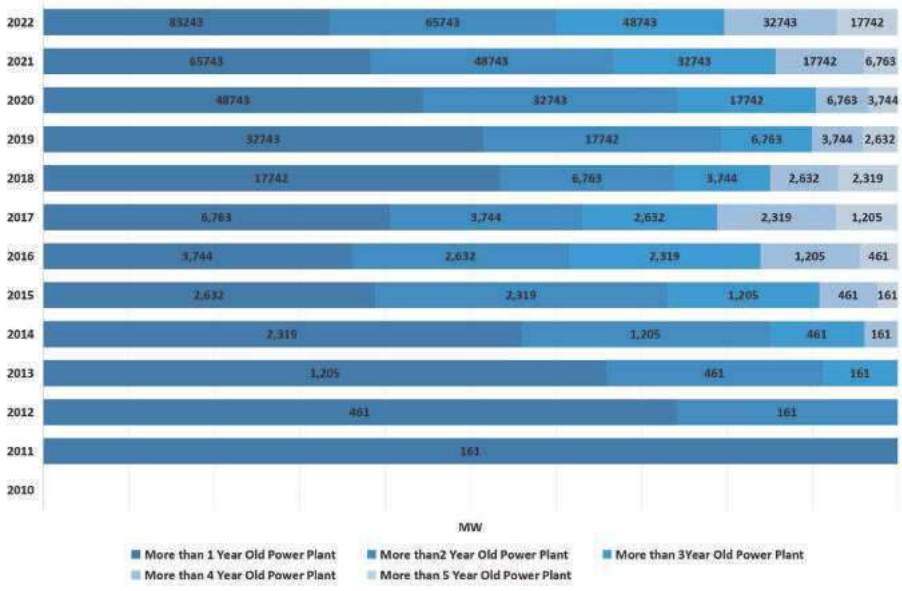

Figure 1.1: Expected O&M solar market, taking into account increase in plant O&M requirements as it ages (considering India's NSM of 100 GW solar)

From the Figure 1.1, it can be observed that by 2022 more than 17.7 GW of SPV power plants will cross 5 years of operational life along with increased O&M requirements. After the bifurcation of NSM's target into 60 GW for utility

scale and 40 GW for rooftop SPV power plants, a large quantum will be commissioned in the rooftop segment. These rooftop SPV power plants are of capacities varying from a few kW to MW and may not have dedicated full time O&M teams to manage them. Such power plants may face huge operational issues compared to utility scale SPV power plants. Hence, their O&M is crucial for ensuring optimum performance. Due to distributed installation of the projects, their O&M is undertaken by local maintenance teams who may not be knowledgeable about solar power plant PE and its effective O&M. Hence, this handbook will be a good guide in helping bridge the knowledge gap of an O&M team.

1.1 About project

World Institute of Sustainable Energy (WISE), Pune, was awarded a project under "**PEER - Partnerships for Enhanced Engagement in Research, Cycle 5**" programme with the support of the **United States Agency for International Development (USAID)**, for "Developing Performance Evaluation and O&M strategy for the Indian Solar Sector", which is intended to provide the best PE and O&M procedures in a strategic manner, as opposed to conventional maintenance practices, as well as developing an implementation strategy. Taking into consideration the importance of this project's topic in the current energy market scenario, the project has been framed to meet the following objectives:

- Development of performance evaluation strategy.
- Development of standards of O&M methods.
- Capacity building of stakeholders for the long term implementation of strategies.
- Support Government of India to achieve the 2022 solar target.

This two year project was divided into two sections. During the first year of the project, a team visited existing solar power plants all across India to understand the O&M requirements of SPV plant stakeholders and the site conditions in various climatic zones in the country.
The second year focused on preparing the PE and O&M handbook after holding multiple seminars on content and information dissemination. For the larger dissemination of information, the project team developed a dedicated knowledge portal www.maintainsolar.in where PE and O&M related information for all SPV power plants has been published, along with a platform for sharing experiences of the solar O&M industry. This handbook will be made available in PDF form on this web portal.

1.2 How to use this document

This document intends to give an in-depth understanding of best practices for performance evaluation and O&M of SPV power plants which can be followed right from the design stage to regular O&M activities. It is expected that by using this document, users will be able to follow best practices for undertaking performance evaluation and operations and maintenance of a SPV power plant. Due to limitations of space, some of the information is briefly presented in this handbook and some content, like sample formats, procedures, etc., are given in the annexures. The sample formats are for ready reference and the reader needs to customise them taking into consideration his/her plant's site conditions and configuration. Additional information is presented on the knowledge portal: www.maintainsolar.in for reference.

A brief summary of the contents in each chapter is presented below as an introduction to this handbook.

Chapter 2: Brief overview of a solar plant

Chapter 2 intends to give a brief introduction to the SPV power plant and functional information of its components. The chapter briefly gives information on how to include O&M requirements of an SPV power plant during the conceptual stage.

Chapter 3: Environmental health and safety in the solar industry

This chapter introduces environmental health and safety aspects of a solar power plant. It describes the hazards and risk mitigation measures including personal protective equipment to be used in solar power plants.

Chapter 4: Data monitoring and reporting

The basic manner in which to assess the performance of a power plant and its components is to monitor the plant's functional parameters. Chapter 4 gives an introduction to the different monitoring methodologies and components, as per international standards. A brief background on monitoring systems will enable the reader to select an appropriate system based on his plant's capacity and requirement. This chapter discusses various data sources and their acquisition for future reference and analysis.

Chapter 5: Operation of solar PV power plants

Chapter 5 introduces various operational requirements of a SPV power plant for enabling smooth operation and strategic planning of the power plant.

Chapter 6: Performance evaluation and key performance indicators

This chapter is divided into two sections. The first section gives an introduction to different key performance indicators (KPIs) that can be introduced in SPV power plants for performance evaluation. The second section gives basic performance evaluation activities, test procedures, different faults and failures identification procedures, failure modes and their effects on the plant's performance.

Chapter 7: Effective maintenance of solar power plant

Chapter 7 intends to give an introduction of various maintenance activities and troubleshooting methodology. After reading this chapter, users will get a brief insight into O&M activities to be performed at a SPV power plant and they will be able to optimize these activities based on the plant's capacity.

1.3 About PEER

The Partnerships for Enhanced Engagement in Research (PEER) programme is a competitive awards programme that invites scientists in developing countries to apply for funds to support research and capacity-building activities on topics of importance to USAID and conducted in partnership with US Government (USG)-funded and selected private sector partners. A key element of this strategy is to support scientific and technological research through the Partnerships for Enhanced Engagement in Research (PEER) programme.

1.4 About WISE

The World Institute of Sustainable Energy (WISE) is a not-for-profit institution established in 2004 in Pune, India, committed to the cause of promoting sustainable energy and sustainable development, with specific emphasis on issues related to renewable energy, energy security, energy efficiency, and climate change. Influencing public policy through research, advocacy, development of action plans/roadmaps, capacity building, training and outreach activities, are the prime objectives of WISE. This 2 year project has been executed through WISE's Center for Solar Energy (CSE). The main activities of CSE are as follows:

- Consultancy services and project management consultancy (PMC) for solar project owners/ individuals/government organizations and agencies.
- Research enabled technical, policy, and financial advisory support to government or private organizations and agencies.
- Research studies on feasibility analysis.
- Performance evaluation of existing power plants and O&M strategy preparation.
- Research study on integration of hybrid renewable energy technologies.
- Industrial and academic oriented training programs in solar.
- Planning, and implementation of corporate CSR activities.

1.5 About project supporting partner

The awarded PEER funded projects have USG-supported partnership to help the project during various stages of its execution. Through these partnerships, PEER applicants benefit from the skills, laboratory access, and other resources of their USG-supported partner. Both the PEER applicant and the USG-supported researcher benefit from one another's expertise and team up on truly collaborative research.

GE Global Research, Bangalore, is the USG partner organization for PEER cycle 5 projects in India. GE's first and largest global lab outside the United States is located in Bangalore, India. The John F. Welch Technology Centre (JFWTC) houses close to 5,300+ GE technologists from Global Research and other GE businesses.

Chapter 2

A Brief Overview of Solar PV Power Plant

A Brief Overview of Solar PV Power Plant

The simplicity of energy generation from solar PV (SPV) power plants makes it the most customizable technology for new and renewable electricity production. Solar PV plants can be customized to any size, and can be installed anywhere feasible, even in isolated areas. For any SPV power plant, the basic initial step is the site feasibility study, usually performed via two steps: on-site visit and analysis of collected site information.

On-site visits must be thorough to provide accurate information, which is needed to complete the initial design/analysis and planning. Any insufficiency in information from the site visit will raise costs for travel and manpower to fetch the additional required information or will lead to improper design and material selection, unexpected installation hurdles, etc. A perfect site visit should elicit answers to the following points:

- Requirement of the customer.
- Budget of the customer.
- Location details (address, latitude,longitude, direction).
- Ownership of proposed site.
- Energy consumption pattern of the customer (in case of captive plant).
- Total connected load and contract demand, applicable policy and regulations, etc.
- Available area, type, measurement, roof orientation, site photographs, etc.
- Proposed site accessibility, obstruction to installing power plant.
- Component installation and termination of output power.
- Availability of nearest grid interconnection point, its distance from the proposed plant location, nearby substation details and distance from the site.
- O&M provisions (e.g. water availability at site).

A sample checklist for collecting the information during site visit is given in Annexure I.

2.1 Categorization of solar PV power plants and their working

Based on the site conditions and requirements, the SPV power plant can be broadly categorized as follows:

Table 2.1: Categorization of Solar PV Power Plants

Type of Installation	Rooftop SPV power plants	Typical application: For captive use of solar power or sale to utility/third party. Size: As per roof area available and captive power requirement.
	Ground-mounted SPV plants	Typical application: Power generation for captive use or sale to utility/third party. Size: Captive power plant (as per area availability and power requirement), utility-scale power plant (1 MW and above).
Type of use	On-grid SPV plants	Plant will be connected to the grid.
	Off-grid SPV plants	Plants with battery storage and no direct connection to the grid.
	SPV plants with hybrid inverters	Plants with battery storage and direct connection to the grid.

2.1.1 Based on location of installation

SPV power plants are divided into two categories based on the location of the intended installation, i.e. rooftop or ground-mounted.

A) Rooftop SPV power plants

The installation of SPV power plants on the rooftops of the buildings and industrial shades is primarily for captive use, to reduce consumption of costly power from the utility, improve power reliability, etc. However, the chances of installing utility scale rooftop SPV plants are less because of space constraints. The capacity of a rooftop SPV plant primarily depends on the electricity demand and connected load followed by external factors like roof space, type of roofing material, orientation of the roof, strength of roof, etc. Further, excess capacity of rooftop SPV plants is also not desired if captive requirement is low compared to the optimum capacity of the SPV plant. Hence, a feasibility study is very critical for optimising resources and returns from the plant. Following are the general components in rooftop SPV power plants (this document concentrates on on-grid SPV plants, so battery is not considered):

PV module	Inverter	Protection systems
DC cable	AC cable	Monitoring system
DC connectors	AC Distribution Board (ACDB)	Safety systems
Array Junction Box (AJB)	Energy Meters	PV module cleaning system

B) Ground-mounted SPV power plants

Large capacity, utility scale, SPV power plants are opting for ground-mounted installations mainly because a larger area requirement. Further, small capacity ground-mounted SPV power plants are used for captive purposes if sufficient roof area is not available. The working principle and components of ground-mounted SPV power plants are similar to that of rooftop SPV power plants. However, due to its larger capacity, there are more components such as auxiliary transformer, plant substation, switchyard, etc. Broadly, the components of a utility scale SPV power plant are as follows:

PV module	Inverter	Protection systems
DC cable	AC cable	Monitoring system
DC connectors	AC Distribution Board (ACDB)	Safety systems
Array Junction Box (AJB)	Energy meters	PV module cleaning system
Control room	Power transformer	Auxiliary transformer

2.1.2 Based on grid connection

Solar PV power plants can further be categorized based on their connection to the utility grid:

A) On-grid SPV power plants

These are the most common type of SPV power plants. They are also known as grid-tied, grid-connected, or grid-direct systems. Based on the type of power usage, they are generally divided into two categories: captive (Figure 2.1) and utility scale (Figure 2.2) power plants. Basic schematic diagrams of on-grid systems are as follows:

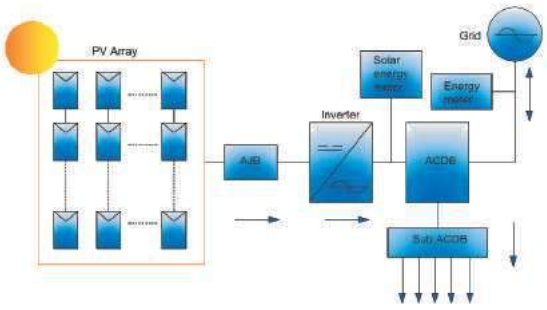

Figure 2.1: Schematic of on-grid SPV plant for captive use

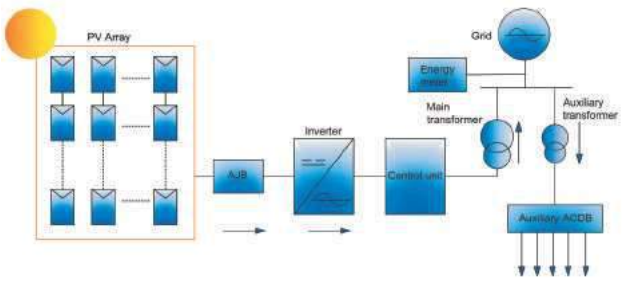

Figure 2.2: Schematic of Utility Scale on-grid SPV plant

In the case of captive on-grid SPV power plant, the generated power will be used primarily to meet the captive load and any surplus power will be fed to the utility grid through net/gross metering system. In case of non-availability of solar power, the captive power requirement will be met through import from utility supply. Exported solar power is virtually banked with the utility and is adjusted against captive consumption from the utility.

In the case of utility scale SPV power plants, generated power is directly fed into the utility's grid through a step-up transformer. For auxiliary power requirements, the auxiliary power transformer is either connected to the solar plant's internal grid or gets its supply through a different utility supply meter. In case of large utility scale power plants inverter duty transformers are widely used.

Grid-tied SPV plants can operate only when utility supply is available along with sun radiation. Such plants are equipped with an anti-islanding safety feature, so the inverter will work only if it is connected to the live utility grid. This feature shifts the inverter into sleep mode in case of power outages and thus protects the utility grid.

B) Off-grid SPV power plants

Off-grid SPV plants have no direct connection to the utility grid but have the facility to store electricity in a storage system when radiations are available. However, solar generated power can be directly used by the load or from stored electricity at any point of the time. Such plants can also be used with the utility supply, in isolated mode, for supply to partial captive load (Figure 2.3). A basic schematic diagram of an off-grid SPV plant is given below:

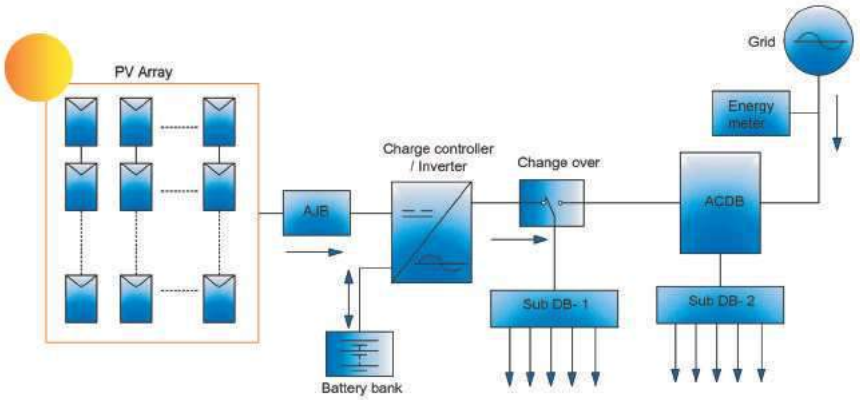

Figure 2.3: Schematic diagram of off-grid SPV plant

Such plants require batteries or other storage systems to store electricity. The capacity of solar PV modules is decided on the load requirement and battery autonomy. Such plants have limitations with regard to the connected load due to the capacity of the inverter and require battery maintenance and replacement after every five to six years.

C) SPV power plants with hybrid inverter

SPV plants with hybrid inverter can operate as off-grid plants and also in grid-tied mode (Figure 2.4). When solar radiations are available, the plant will generate power and feed it to the load. If the load is not available, it will charge the batteries and after the batteries are fully charged, it will feed any surplus power into the utility grid. This way it provides reliable power with battery backup and also uses surplus generation for feeding to the utility. The size of battery required is small for meeting the power requirement of essential loads during short periods of power failure.

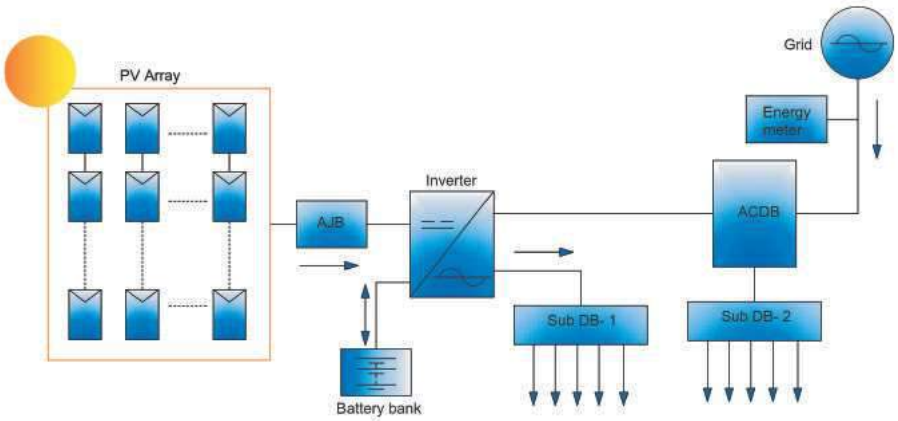

Figure 2.4: Schematic diagram of hybrid SPV plant

2.2 Components of a SPV power plant

2.2.1 Solar PV modules

A solar PV module consists of a series and parallel combination of solar cells made from Photovoltaic (PV) materials. The PV materials convert light energy into electrical energy which is called the "Photoelectric Effect". Solar cells or Photovoltaic cells produce electricity and are made up of semiconductor materials like silicon. These modules are further connected in series to have the desired output voltage, and such series strings are connected in parallel to have the desired current or power from the combination. A typical solar cell, module and array formation are as shown in Figure 2.5 below:

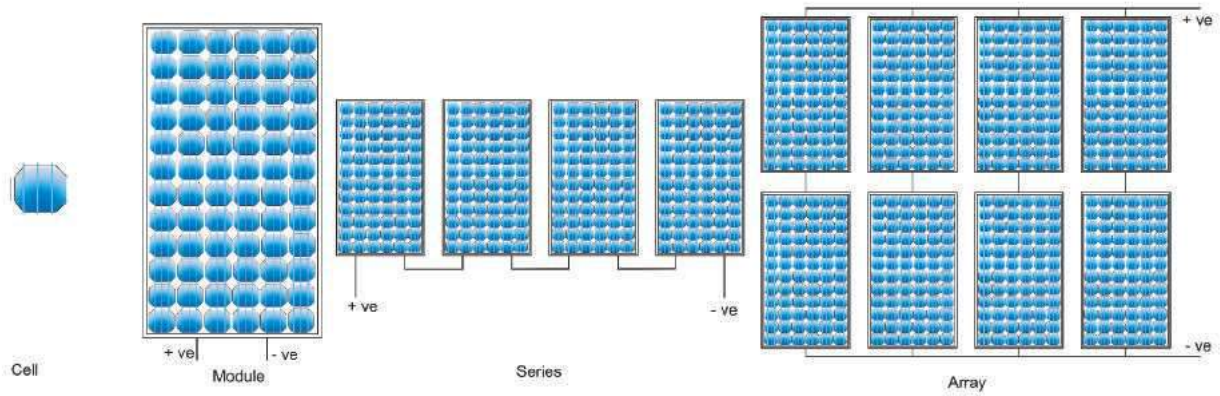

Figure 2.5: Typical solar cell, module and array arrangement

There are currently three commercial solar PV cell manufacturing technologies available, which are described as follows:

Single/Mono crystalline

- Uses single silicon crystal.
- Silicon is formed into bars and cut into wafers for manufacturing solar cells.
- This is the oldest and more expensive production technique.
- Most efficient sunlight conversion technology available.
- The record lab cell efficiency of a mono crystalline cell is 26.7%.[1]

Polycrystalline or Multi-crystalline

- Many fragments of silicon are melted together to form the wafer for the PV module.
- Uses multi crystals.
- This has a slightly lower conversion efficiency compared to single crystalline.
- Manufacturing costs are lower compared to mono crystalline PV module.
- The record lab cell efficiency of polycrystalline is 22.3% .[1]

Thin film

- PV modules are manufactured by depositing photovoltaic substances on a solid surface like glass.
- A combination of substances is used to form a cell, e.g.
  - ✓ Amorphous Si
  - ✓ Dyesensitized solar cell
  - ✓ Copper indium gallium selenide (CIGS) solar cell.
  - ✓ Cadmium telluride (CdTe) etc.
- Manufacturing cost is lower than other methods.
- The record lab cell efficiency of CIGS thin film is 22.9% and CdTe thin film is 21.0%. [1]

Solar PV module manufacturers use the standard test conditions (STC) output parameters for display on their name plates. During the STC, PV modules are exposed to artificial sunlight with an intensity of 1000 W/m^2, at 25°C and air mass 1.5 (AM1.5) to measure the output. The performance of a solar PV module in site conditions differs from those of the STC. Selection of array configuration is based on location specific irradiation, in a software based simulation. In India, typically a 1000VDC string configuration is used for forming a string. However, 1500VDC string configuration is also being used to reduce the BoS components and costs. Accordingly, appropriate selection of solar PV modules is required based on the string configuration for maximum system voltage of 1000VDC and 1500VDC, respectively. Further, solar PV modules are bound to degrade over the plant's operational life and will gradually reduce the output power. Manufacturers are specifying the deration factor for their PV modules, which needs to be considered when assessing the estimated generation over the SPV power plant's life cycle.

2.2.2 Solar inverters

A solar inverter is an important electronic device that converts DC electrical power generated by a solar PV array into clean AC power supply. While a single inverter will be sufficient for a small domestic installation, multiple inverters are required when there is an increase in the scale of an SPV plant. Over the years, inverter technologies have advanced significantly, and apart from converting DC to AC, they also have the following additional features:

- Extracting the maximum possible power from solar PV modules for a given radiation (MPPT feature).
- Synchronisation of output power with the utility grid.
- Providing real time operation data and signaling.
- Providing advanced utility controls.
- Active and reactive power control.
- Electrical protection and safety, etc.

Solar inverters are classified as per their use, as follows:

According to power plant type

- **Off-grid solar inverter:** Such inverters are used to provide electrical supply in areas where the utility grid is not available or its availability is poor. Off-grid inverters operate in isolated mode and have a charge controller to control the battery charging from solar PV modules. The inverter supplies electricity, as and when required, from the charged battery to the connected load in off-grid mode.

- **On-grid solar inverter:** Such inverters are used in areas where the grid is available. All utility scale solar power plants and grid-tied rooftop solar power plants use grid-interactive solar inverters. Grid-interactive inverters are of four subtypes, depending on the purpose and scale of use.

According to inverter topology

- **Central inverters**: PV strings are combined together using array junction boxes (AJB) and main junction box (MJB) before connecting them to the inverter. A larger number of PV strings can be accommodated in central inverters and so they are commonly used in ground-mounted large scale power plants. Commercially available capacities of central inverters can be from 1 kW to several MW.

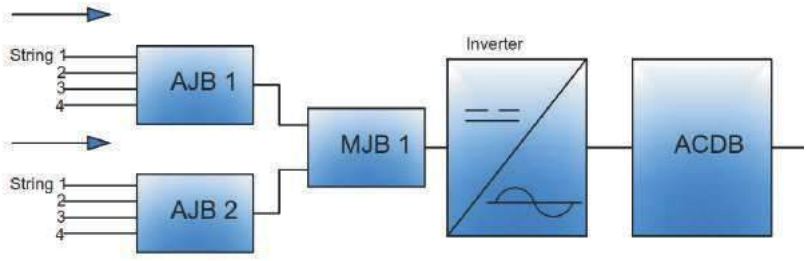

Figure 2.6: Central inverter connection

- **String inverters:** String inverters have the facility to connect multiple PV string separately to the inverter. Transformerless string inverter technology makes the inverter design simpler, modular and efficient. These inverters are widely used in small scale applications. Large utility scale SPV power plants also use string inverters to improve uptime and reliability. The commercially available capacity of string inverters can be from 1 kW to 100 kW. Since the maximum available capacity of the inverter is small, the plant will need to use multiple inverters. Thus multiple MPPT will improve plant's performance.

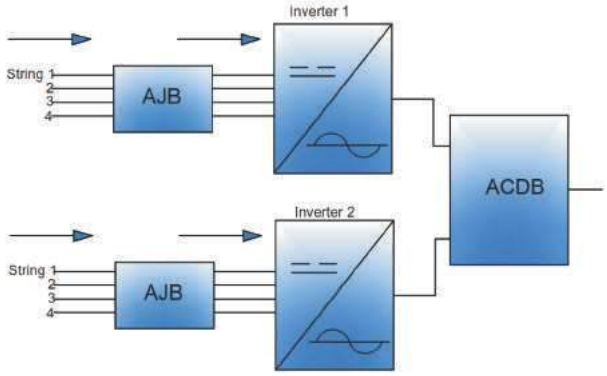

Figure 2.7: String inverter connection

- **Micro-inverters**: These come in the size of a small box which can be mounted beneath PV module. PV modules coupled with micro-inverters will enable delivery of AC power to small applications. Use of micro-inverters will increase the number of MPPT and hence improve the overall power output of the plant by avoiding mismatch effects. The cost of micro-inverters is high (followed by string and central inverters), therefore micro-inverters are preferred in small scale power plants or where mismatch losses are anticipated (due to shadow or multiple PV module capacities and rating).

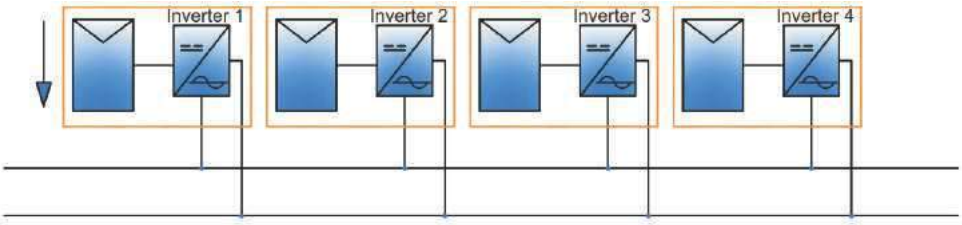

Figure 2.8: Micro inverter connection

- **Hybrid Inverters:** Hybrid inverters operate in on-grid as well as off-grid mode. There could be different configurations and uses of solar power. In the simplest system, the batteries will continue to charge from a solar PV module when there is excess solar power available after supply to captive load. When the batteries are fully charged and there is no requirement from the load, the excess solar energy will be supplied to the grid. Also, in case of grid failure, the inverter will continue to supply load requirement from the charged batteries.

2.2.3 Balance of system

All the components of an SPV power plant, other than solar PV modules and inverter, are encompassed in the balance of system (BoS). Brief information of all the components used in the BoS is presented below. However, based on the scale of the plant, its type and purpose, some of the components may not be required or used.

A. Cable

Cabling in SPV power plants are of two types: DC and AC. Irrespective of the type and capacity of the system, DC cabling is considered one of the most complex undertakings. Cables are subjected to thermal, mechanical and external loads. Like all other components in a SPV power plant, cables need to last the planned 25 years. Compared to AC cables used in SPV power plants, DC cables are more exposed to harsh environmental conditions like temperature fluctuations and direct ultraviolet (UV) rays, etc.

DC cables: DC cables are used for carrying DC current from the PV module/strings to the AJB and to the inverter. The size of the cable depends on the current capacity of the string and the voltage drop up to the inverter terminals. Solar DC cables are generally single core, flexible, tinned multi-stranded copper conductor cables of diameter 4 or 6 mm^2 rated for maximum voltage between 1.5 to 1.8 kVDC. Black DC cable is used for connecting the negative terminal of the string and for connecting the positive terminal a black DC cable with red strip is used, as shown in the Figure 2.9.

DC Solar PV cable construction | -ve DC Supply Solar Cable | +ve DC Supply Solar Cable

Figure 2.9: DC Solar PV Cable

DC cables can be used for indoor and outdoor applications and should be able to withstand extreme weather conditions of -40°C to +85°C, and should have IP-67 and UV rating. For extended life and for mechanical protection, DC cables should be used with cable conduits/trays.

Installation of DC cables

DC cabling for SPV power plants can be divided into three parts: PV module inter-connection, PV string cables and main DC cables. While laying the cables, they must be routed in such a way that large conductor loops are avoided. The power (DC and AC) cables and data lines (e.g. radiation sensor, yield monitoring) must be routed separately or else equipotential bonding conductors will need to be routed along the entire route.

- **PV module interconnection**: PV modules come with junction boxes connected with positive and negative inter-connection cables. Generally, for PV modules of rating >250Wp, copper solar DC cables of 4mm^2 are placed along with MC4 inter-connectors. DC cables are used to interconnect PV modules to form a string. These factory fixed cables are UV protected.

Figure 2.10: Solar PV module Interconnection

- **PV string cables**: Interconnected PV modules forming a string are connected to an AJB using string cables. In case of SPV power plants using a string inverter with internal string protection, the strings are directly connected to the inverter. Even if the solar DC cables are designed to sustain harsh environmental conditions, it is recommended to route the cables through a proper cable conduit or tray. Cable sizing can be determined depending on the short circuit current and length of the string. It is always recommended to use string identification ferrules at the beginning and the end of the strings.

Figure 2.11: PV string cables with identification ferrules

- **Main DC cables**: The DC cables connecting the AJB and inverter are called main DC cables. The main DC cable size will vary according to the number of strings connected to AJB, type of cable, its routing and length, etc.

AC Cables: AC cables are used for connecting the output of an inverter to ACDB, and ACDB to main Incomer. Based on the cumulative capacity of the solar plant, the size of the AC cable is decided. Further, cable cross section also depends on the length of cable required so as to limit cable losses in permitted limits. Generally, armoured XLPE Aluminium AC cable is used in a solar plant.

B. DC connectors

DC connectors are used for interconnecting PV modules, junction boxes and/or the inverter. The provision of DC connectors with a DC cable connected to junction boxes has made installations easy and saved installation time. Failure of a DC connector will lead to loss of generation in one string and eventually in the entire MPPT. Hence, adequate care needs to be taken while selecting the proper size of DC connector in order to avoid overheating and risk of fire. Improper DC connections can lead to increased contact resistance, DC arcing and fire, power loss, downtime, electrocution of working personnel, etc. Nowadays, the MC4 connector is mainly used in solar plants. The letters 'MC' stand for Multicontact, and digits 1 to 4 stand for the contact pin cross section in sq.mm. Parts of a MC4 connector are shown in Figure 2.12.

Figure 2.12: Parts of MC4 connector

Improper size and quality of DC connector will lead to following issues:

- **Mismatch loss**: DC connectors using different materials or brands for a single PV string may lead to mismatch of connections, resulting in poor connections.
- **Fire hazards**: Low quality material may cause rise in connector temperature, which could result in overheating of the system and lead to fire, or could allow water to enter and possibly cause electrocution.
- **Chances of electrocution**: Touching a connector with poor connections, or poor insulation which allows water and dust to enter thereby reducing the insulating properties of the connector, may cause electrocution. It is suggested always to use proper size cables for interconnection and to provide proper sealing at the end cap of the MC4 connector to prevent moisture ingress.
- **Financial loss**: For the identification of faulty connectors and their repair/replacement, extra manpower costs will be incurred. Also, faulty DC connectors will lead to loss of power generation and hence loss of revenue for the SPV power plant.
- **Reliability**: MC4 connectors are subject to work for 25 years in extreme weather conditions and so low quality materials will not be able to withstand these stresses.

C. Array junction box (AJB):

Combiner boxes usually called array junction boxes (AJBs) are an integral part of PV installations. They serve as a "meeting place" where the output of solar strings is combined to generate a single set of output. The main functional features of an AJB are:

- To obstruct sudden surges due to lightening strikes during cloudy and rainy conditions and to ground the surges immediately.
- Efficient string monitoring (Optional).
- Disconnect DC at the source.
- Fuses for overcurrent protection on each string.
- Blocking Diodes for reverse current flow protection.
- DC-termination.
- String cable management.
- To enable step by step trouble shooting methodology.
- Reliable electrical safety to avoid hazard.

The term combiner box/array junction box (AJB) is applicable only to central inverters, where several strings are combining together and a single positive and negative cable is routed to the inverter. In case of string inverters there is no junction box required between string and inverter; each string can be routed separately to the inverter. However, in O&M and from a safety perspective, it is always recommended to use an AJB even in case of a power plant using a string inverter. Figures 2.13 and 2.14 show the difference between AJBs used in a central inverter and in a string inverter.

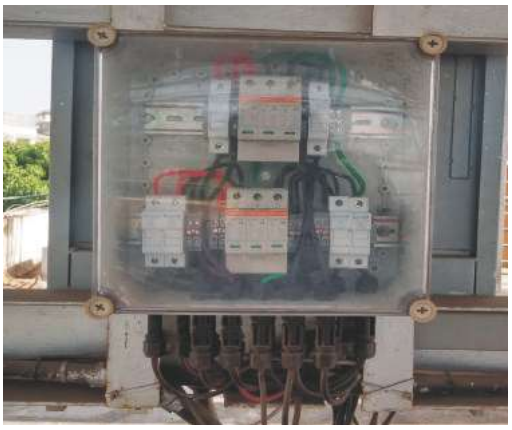

Figure 2.13: 3 in 3 out AJB for string inverter

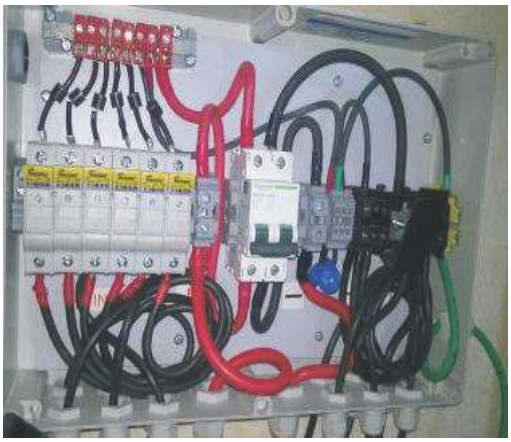

Figure 2.14: 6 in 1 out AJB for central inverter

Normally, utility scale power plants with central inverters are equipped with string monitoring facility as shown in Figure 2.15. In such cases the AJB may have two sections — a string junction and next to it, string monitoring.

Figure 2.15: AJB with string monitoring

The combiner box should consist of the following key features [2]:

- IP65 Enclosure: The AJB enclosures are typically made out of thermoset (GRP or polyester), or thermoplastic (polycarbonate) material, and come with IP65 protection. Enclosures come in different sizes, depending on the number of input strings and protection features implemented in the AJB.
- Fuse protection for strings: DIN rail mounted fuse holder with DC fuses rated from 2A to 25A should be used in the AJB to provide overcurrent protection.
- Surge protection device: Surge protection devices (SPDs) are placed in an AJB to protect electrical and electronic equipment from power surges and voltage spikes. SPDs, divert the excess voltage and current from transient or surge into grounding wires. Usually, type 2 SPDs are used.
- DC disconnect/isolator: An isolator switch is recommended for placement before the inverter to disconnect the DC side of the system when maintenance is being carried out on the inverter.
- Cable glands/connectors: Cable glands are provided in the AJB for entering and supporting the cables. MC4 connectors are used at the input and output sides of the box to terminate the array strings, and are provided with proper identification ferrules.
- String monitoring: In some AJBs, a string monitoring facility is provided to check the output for proper functioning.
- PV fuses: AJBs should have PV fuses or other overcurrent protection. It is recommended to use PV fuses rather than normal DC fuses. This is because PV current will fluctuate due to weather conditions, especially dynamic shadow caused by clouds, and an arc can develop in standard DC fuses which is not sufficient to melt the insulation granulate and thus the fuse is not triggered. This will increase the temperature inside the AJB which may then catch fire. PV fuses are designed to overcome this issue. Figure 2.16 shows a typical solar PV DC fuse used in a AJB.

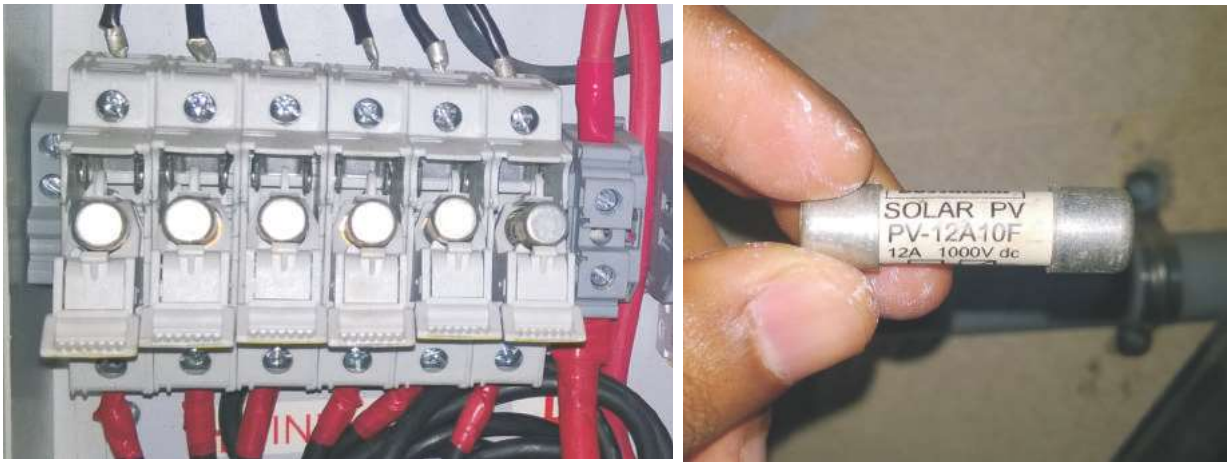

Figure 2.16: Cylindrical PV fuse used in AJB

D. AC distribution board (ACDB)

Power generated from the inverter/s is connected to AC distribution board, where the utility reference supply is connected from main distribution board (in case of captive power plants) or from the grid directly (in case of utility scale power plants). ACDB are equipped with isolation, protection and measurement devices.

E. Solar module mounting structures (MMS)

Solar module mounting structures (MMS) are one of the key components of SPV power plants and should comply with all applicable standards. They must also withstand on-site loading, wind and other climatic conditions, for a period of 25 years. GI material with galvanization of 80 to 120 microns is used in solar MMS. In case of rooftop power plants, aluminium MMS are commonly used to reduce weight on a rooftop. Solar structures can be broadly classified into two types as per the application, such as: ground-mounted MMS and rooftop MMS

Ground-mounted MMS: This is the most commonly found installation in large scale utility power plants. In this type, the structure is erected on a concrete foundation. The MMS can be further divided into:

- **Fixed MMS**: The module mounting structures support the PV modules at a fixed tilted angle facing south (Figure 2.17). These are simple in construction, in operations and maintenance, and hence are widely used.
- **MMS with seasonal tilt**: In this type of MMS, PV modules are tilted seasonally, two to three times depending on the provisions made for the tilt so as to optimize generation from the SPV power plant (Figure 2.18). This kind of system requires additional manpower for seasonal tilting and is subject to slightly more maintenance than fixed MMS. Fixed MMS and MMS with seasonal tilt are shown in the following Figures 2.17 and 2.18 :

Figure 2.17: Fixed MMS

Figure 2.18: MMS with seasonal tilt

- **Solar tracker system**: A solar tracker MMS is designed to follow the sun path everyday, i.e. east to west. This requires a special type of MMS and control system. Solar tracker systems are further divided into two categories, namely, single axis and dual axis trackers.
  Single Axis Trackers: Single axis trackers move on only one axis, commonly east - west (Figure 2.19).
  Dual Axis Trackers: Dual axis trackers follow the sun path and can track on two axis to ensure that the modules face the sun all the time (Figure 2.20). Such MMS have more moving parts and control systems and hence require more maintenance. SPV power plants with dual axis tracking yield more generation than any other MMS systems (Figure 2.20).

Figure 2.19: MMS with single axis trackers

Figure 2.20: MMS with dual axis trackers

Rooftop MMS: Rooftop MMS selection depends on the type of roof and its strength. Different types of rooftop MMS installations are:

- **Flat roof normal MMS**: This simple roof installation is much like a ground-mounted MMS (Figure 2.21). However, depending on site conditions elevated MMS are also used (Figure 2.22). The MMS is anchored into the roof or concrete blocks. In case of roof penetration proper sealing is recommend.

Figure 2.21: Flat roof normal MMS

Figure 2.22: Flat roof elevated MMS

- **Flat roof MMS with ballast**: These are used where penetration of the roof is not allowed. In this, concrete ballast is used as counter weight (Figure 2.23). Maintenance is very easy and the structure can be shifted to another location, if required.

Figure 2.23: MMS with ballast

- **Tilted roof penetration MMS**: In this type of mounting structure, solar PV module are mounted on channels/rails by penetrating the metal roof sheet (Figure 2.24). Proper sealing needs to be provided to avoid water seepage.

Figure 2.24: Tilted roof penetration MMS

- **Tilted roof non-penetration MMS**: This type of mounting structure has the solar PV module mounted on channels/rails on the metal roof sheet using a clip lock arrangement (Figure 2.25). This mounting is possible only if the roof sheet has the clip lock profile.

Figure 2.25: Tilted roof non-penetration MMS

F. Earthing

A SPV power plant is defined as a grounded system when one of the DC conductors (either positive or negative) is connected to the grounding system, which in turn is connected to the earth. In general, it is recommended to earth the mounting system and other conductive parts of the power plant for potential equalization. All PV modules are grounded through MMS by way of using serrated washer based nut bolt system of separate earthing wire. Proper earthing of the generating systems is mandatory because of the following reasons:

- Provides safety to persons and animals.
- Protects the installation and equipment.
- Enhances quality of signal (reduced electromagnetic distortion).
- Provides a fixed reference voltage for equipotentialization.

Figure 2.26 shows the points to be grounded of an on-grid power plant.

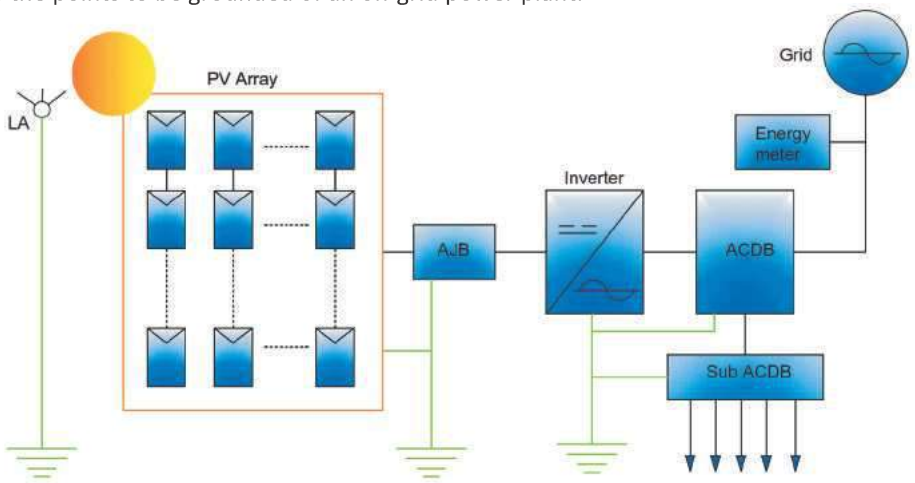

Figure 2.26: Earthing points of on-grid power plant

Table 2.2: Earthing points in SPV power plant

DC Earthing	PV module, MMS, AJB, battery bank (if any).
AC Earthing	Inverter, transformer, HT panels, LT distribution system, auxiliary ACDB, power evacuation system, the HT part of the power plant.
Special Earthing	SCADA, CCTV, and any other communication systems.
LA	Lightning arrestor.

Factors like soil resistance, system fault level as per local regulations and rules, etc., need to be considered when designing the earthing system. In the case of small rooftop power plants it is possible to connect AC earthing to the existing earthing of the customer; proper evaluation and up-gradation of the existing building's earthing needs to be done before connecting the solar PV system's earthing.

In case of DC earthing, the industrial practice is to loop a set of MMS (Figure 2.27) and connect them to earth pits; the number of earth pits required will depend on the fault level and earth resistance, as mentioned earlier. In rooftop power plants, all MMS rails should be made equipotential by connecting a copper cable. All earth connections should be made from corrosion resistant materials. It is recommended to protect the earth pits with a proper earthing chamber (Figure 2.28) wherever applicable, and earth pit information sign-boards should be displayed, as shown below.

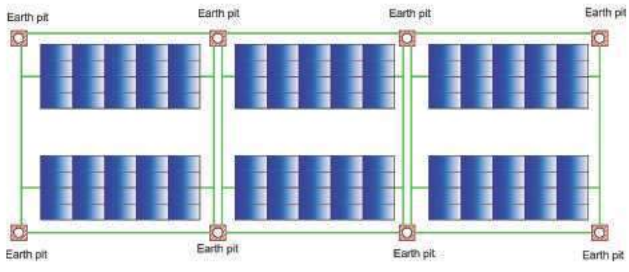

Figure 2.27: MMS earth looping

Figure 2.28: Earth Pit with information label

G. Lightning arrestor

Lightning arrestors are particularly aimed at providing personal protection when there are direct lightning strikes. SPV plants can get damaged by direct lightning strikes to MMS or power lines, or from indirect strikes caused by cloud to ground or cloud to cloud strikes which cause induction and surge.

Direct lightning strikes to the plant are protected by lightning rods, and indirect strikes which cause surge are shielded by surge arrestors. A lightning rod is placed above a building and near PV modules to discharge static charges and prevent a strike. It also provides a path to the ground if a strike occurs. Surge protection devices (SPDs) which must be installed upstream of the device to be protected on the A.C., D.C. and data sides have proven to be very effective in protecting electrical systems from such destructive voltage surges. For utility scale power plants, early streamer emission (ESE) lightning protection is used to safeguard against direct lightning. It offers wise range of radius of protection up to 107m.

The probability of a direct lightning strike can be calculated using buildings dimensions, information on the environment and the average number of lightning strikes for the region. Lightning rods are typically used at sites that experience extreme electrical storms. As per IEC 62305: Part 3 - Supplement 5: 2014 - lightning and overvoltage protection for photovoltaic power supply systems, a minimum lightning protection level III is specified for all PV systems greater than 10 kW. The selection of lightning arrestors should be undertaken after the risk assessment of the site has been gauged. lightning arrestors should be selected as per IEC 62305:2014. The lightning conductor should be earthed through flat strip conductors, as per applicable Indian/International standards, with earth pits. Each lightning conductor should be connected to an individual earth pit as per the required standards, including accessories.

H. Surge arrestors

Surge protection devices (SPD) help to protect the SPV power plant's components from transient power surges that may occur if the PV system or nearby power lines or structures are struck by lightning, switching actions and electrostatic discharges. A power surge is an increase in voltage significantly above the designed voltage over a short duration of time which can damage the PV modules and other electronic equipment.

Figure 2.29: Surge protection devices (SPD)

An SPD is connected in parallel between the energized conductor and the ground. It changes its state from a high-impedance device to a low-impedance device when overvoltage occurs and discharges the associated transient current, thereby minimizing the overvoltage present at the equipment terminals.

There are three types of SPDs [3]:

Type 1 SPD: This type of SPD is recommended for the service-sector and industrial buildings and is protected by a lightning protection system or a meshed cage. It protects electrical installations against direct lightning strikes. It can discharge the back-current from lightning spreading from the earth conductor to the network conductors.

Type 2 SPD: These are installed where there are indirect impacts of lightning strikes on the solar energy system, but they cannot handle direct lightning strikes and are used in low voltage electrical installations. The device is used in distribution panels or in incoming power supply panels in areas with low exposure to lightning strikes and where buildings are not fitted with external LAs.

Type 3 SPD: These SPDs have a low discharge capacity. They must, therefore, mandatorily be installed as a supplement to type 2 SPDs and in the vicinity of sensitive end-devices that need to be protected. These are installed when there is an indirect surge simulated by the current and voltage that can reach the long-distance circuits, and for individual equipment that needs to be protected. It is often useful to combine the protection of the power supply to the protection of other interfaces in the end-device, such as data or communication lines.

In solar PV power plants, surge protection devices are positioned inside the AJB on the DC side, and for inverters and ACDB on the AC side. They are also installed in communication or monitoring systems.

The maximum voltage level in SPV power plants varies according to the its capacity. At present, the industry is moving towards 1500V DC systems. While selecting SPDs, the voltage protection level of the SPD must be lower than the

dielectric strength of the PV system it is supposed to protect (20% lower). Nowadays inverters are equipped with SPDs. Hence, while selecting SPDs for AJB, co-ordination between the type 2 SPD and the input circuit of terminal equipment should be ensured.

I. Transformers in solar power plant

All utility scale grid-tied solar PV plants include a power transformer and an auxiliary transformer. The function of a power transformer is to provide galvanic isolation, step up the voltage and transfer energy to the utility's grid. While choosing a transformer for solar PV power plants, it is important to select the correct power rating and voltage rating on both the primary side and the secondary side of the transformer. Transformers are typically rated in kVA. The kVA rating of a transformer is selected in such a way that, it is allowed to overload (as per manufacturer's recommendation) for daily peak generation. Power transformers are generally installed on plinth and are associated with switchyard containing isolator, circuit breaker and related protection and metering systems. Compact substations are also used on some sites to reduce space requirements. Apart from the power transformer which feeds the generated power, the auxiliary transformer is also used in some plants to feed the plant auxiliaries through a separate transformer. Photographs of a compact substation (Figure 2.30) plinth mounted power transformer (Figure 2.31) and auxiliary transformer (Figure 2.32) are given below:

Figure 2.30: Compact substation

Figure 2.31: Plinth mounted power transformer connection

Figure 2.32: Auxiliary transformer

J. Weather monitoring system

Performance of a SPV power plant depends directly on dynamic weather parameters. As the weather varies, the output of the PV plant changes. The key driving factor of a SPV power plant is irradiance. However, along with solar radiation data, weather parameters like ambient temperature, relative humidity, wind speed, wind direction, atmospheric pressure and rain are the other important factors that affect the performance of the plant.

Photovoltaic cells in PV modules have a direct relationship with the cell temperature and have negative temperature coefficient. If the surface temperature of a PV module rises beyond a specified limit, the efficiency of the module will reduce. Further, the module temperature will depend on the ambient temperature, wind speed, direction, humidity, rain, etc. Hence, while assessing the performance of a PV plant, it is necessary to monitor and compare the plant's performance vis a vis actual weather parameters.

Since the SPV power plant's performance depends on weather parameters it is recommended to monitor those parameters while analysing the SPV plant performance. Along with performance analysis, weather details are also used for optimizing the O&M of the plant. As per IEC 61724-1 (Photovoltaic system performance – Part 1: Monitoring) the following sensors need to be placed according to accuracy class [4]:

Table 2.3: Monitoring parameters and accuracy class

Parameters	Unit	Monitoring purpose	Class A	Class B	Class C
Irradiance	W/m^2	Solar resource input to PV module			
PV module temperature	^0C	Determining temperature related losses			
Ambient air temperature	^0C	Connection to historical data, plus estimation of PV temperatures			
Wind speed	m/s	Estimation of PV temperatures			
Wind direction	degree				

Rainfall	cm	Estimation of soiling losses			
Snow		Estimation of snow-related losses			

	Indicates a required parameter to be measured on site.
	Indicates a parameter that may be measured at site or estimated based on local or regional meteorological data or satellite data.
	Indicates a parameter not necessarily be measured at site.
Class A or Class B – Are most appropriate for large PV systems, such as utility-scale and large commercial installations. Class B or Class C – Are most appropriate for small systems, such as small commercial and residential installations.	

The measurement of weather parameters and sensors used for the same are as follows:

- Irradiance (W/m2) measurement
- PV module temperature measurement
- Ambient temperature measurement
- Wind speed and direction sensor
- Humidity measurement sensor

K. Data monitoring system

A solar PV monitoring system is installed for continuous monitoring and performance evaluation of power plants. All data monitoring systems have the facility to record generation details, measured weather parameters and event logs. Except in small residential systems, it is always recommended to install data monitoring systems which will enable continuous monitoring of plant performance for optimization of generation and O&M.

Currently, two types of monitoring methods are widely used in the industry, namely: (a) web based remote monitoring system, (b) SCADA system.

Web based remote monitoring system: It has more footprints in case of small and medium scale SPV power plants. It can also be termed as inverter based monitoring due to acquisition of data from the inverter. Most inverter manufacturers provide their own solution for web-monitoring, or their inverters have the facility to integrate with web-monitoring systems of different service providers. Advantages of web-monitoring systems are as follows:

- Low installation and maintenance cost.
- Multiple inverters can be connected to a single monitoring system (integration of more than 15 inverters).
- No separate control room is required as this is adopted with string inverters.
- Cloud based data storage allows data security, usability and accessibility to the recorded data from any location.
- Monitoring and analysis of a solar plant can be accessed by multiple persons.

SCADA (supervisory control and data acquisition) based data monitoring: SCADA is being used in the power industry for the last few decades. Functions and methodology of SCADA systems is the same in the solar industry as well. Large capacity solar PV plants having installed Class A weather monitoring systems are recommended to use SCADA based monitoring. Some of the features and advantages of SCADA based monitoring are as follows:

- String level monitoring: By installing monitoring circuitry and junction boxes, string level monitoring is possible.
- ACDB and grid monitoring: It is possible to measure details beyond inverter level.
- Controlling: If required, control of any system is possible.
- Customization: Monitoring, evaluation and reporting tools can be customized as per site requirements.

L. Energy meter

Purpose of energy meters in a solar power plant is to measure (a) electricity generation from solar PV plant and (b) to measure net energy imported/exported by the captive consumer for utilities' billing purposes. As per the type and capacity of a solar PV power plant, location of the energy meter varies. Bi-directional meters as proposed by CEA (Installation and Operation of Meters) Regulations 2006 and its amendments, are used for measurement of generated electricity from solar power plants.

Large power plants export power during day time and consume minimum electricity for auxiliaries during night time. Such meters are bi-directional, TOD meters and connected to HT side of a power transformer. Small residential, commercial and industrial consumers, installing solar power plants to meet their partial captive electricity needs require bi-directional energy meters. For such consumers, electricity generation metering and settlement is done on the basis of net-metering or gross metering regulations under which the solar plant was implemented. The electricity billing and settlement mechanism available under these regulations are described as below.

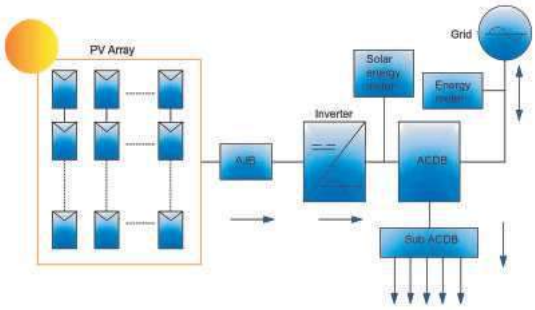

Figure 2.32: Net metering arrangement

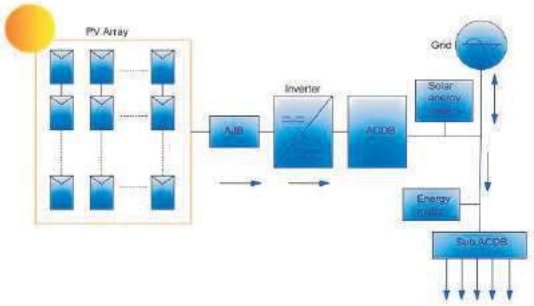

Figure 2.33: Gross metering arrangement

Net metering : Under net meter arrangement, energy produced by the solar power plant will be utilized by the consumer first, and if there is any surplus generation then the same will be injected into the grid; in case of solar energy generation shortfall, electricity will be imported from grid (Figure 2.32). Total energy consumed by the consumer will be adjusted against exported surplus energy and the consumer will pay for net electricity consumption. If the electricity injected into grid is more than consumption from grid then the surplus injection will be carried forward till the closure of the settlement period.

Gross metering: Under gross metering, all the electricity generated by the solar power plant will be exported to the utility's grid and the utility will pay for the gross electricity generated by the SPV power plant at a tariff determined by the state regulator (Figure 2.33). Further, the electricity consumed by the consumer will be imported from the grid as he/she was doing before the installation of the solar plant and there is no change in energy meter and billing mechanism for said consumption.

Solar generation meter under gross metering or net metering regulations will be installed near the inverters/ACDB of the solar plant (Figure 2.34). The net meter installed under the net metering regulation shall be at the start of main incoming supply to the consumer.

Figure 2.34: Solar energy meter installed near ACDB

An energy meter practically requires no maintenance. However, periodic calibration is needed to comply with the regulatory requirements.

M. Control rooms

Control rooms (Figures 2.35 to 2.37) are present mostly in large utility scale power plants. The control room consists of indoor central inverters, HT/LT control panels, auxiliary LT distribution board, monitoring and communication systems, security monitoring, UPS, battery, toilets, etc. Ultra large utility scale power plants will have multiple inverters and control rooms, but centralised monitoring and control will be done through a single main control room.

Control rooms should have the following minimum requirements:

- Display of safety instructions, plant layout, SLDs, list of contact numbers of personnel to be contacted in case of emergencies.
- Space to store personal protective equipment (PPE), measuring instruments, tools, spares, rubber mats (used in front of control panels and inverters), etc.
- Control rooms should have fire extinguishers, sand buckets (Figure 2.37) and fire detection system, etc.
- Plant monitoring equipment, display of real-time plant outputs, working/fault status, security system and its monitoring, etc., should also be provided in the control room.
- Space for engineers, technicians, meeting room and rest room, etc., should be included.
- Telephone, batteries and UPS, computer, printer, attached toilets, first-aid kit, etc., should be present.

In most cases, the plant's switch yard is located near the control room for easy access and monitoring. It is advised to provide proper ventilation systems with air ducts and lighting. The room should be air-conditioned for proper functioning of electronic components (if necessary).

Figure 2.35: Control room

Figure 2.36: Switch yard near control room

Figure 2.37: Sand buckets near control room

N. Plant accessibility

Better accessibility to each and every solar PV module and inverter for installation and O&M within the SPV power plant will help in easy approach. In case of ground-mounted power plants, the first step in the installation process is land preparation which includes land leveling grading, internal approach roads/access roads to individual plots, etc (Figure 2.38). The plant's internal access road is required for vehicles of the O&M team, water tankers and mini trucks for movement of materials, etc. Restricted access should be provided for the plant's security and to protect animals and unauthorised personnel from electrically live components. The plant should be protected by a boundary wall/barbed wire fence and round the clock security along with CCTV cameras need to be provided.

Figure 2.38: Plant internal road

In the case of rooftop power plants, handrails and ladders should be provided for easy and safe access to all the PV modules (Figure 2.39). It is necessary to initiate the plant's installation by providing accessibility components like walkways and hand rails and safety supports like lifelines/fall arrestors, safety net/mesh on skylights, etc. Proper space for walkways should be provided which are crucial for operations and maintenance of the plant.

Figure 2.39: Walkway

Figure 2.40: Access ladder

It is noticed that in some power plants poor accessibility to O&M leads to loss of power output and increased time for fault rectification.

2.3 Solar PV power plant O&M planning

It is observed in various solar power plants that even if their operating procedures were proper, their performance was seen to be declining only because of inferior material quality or improper installation practices. As solar power plant performance has a direct relation to quality of material, installation and O&M, its planning needs to be done at the design stage itself so as to ensure the plant's operation is in accordance with the expected key performance indicators (KPIs). Hence, O&M requirements of a solar PV plant need to take into consideration at different stages of its development and should be included in the design, installation, testing and commissioning.

O&M considerations of solar PV plant

A. Design stage

The design stage is the first step in a power plant's installation process, where specifications and sizes of all technical components of the power plant will be decided. Since, it is expected that the solar plant will operate for 25 years of its life, it is recommended to list out the expected operational activities, and to design the system to meet such requirements. For example, a rooftop power plant where water is not available for cleaning the PV modules should have provision for water piping at the design stage itself. Following are a few points that need to be considered in solar plant's design stage:

- Walkways, ladder, handrails, lifeline, fall arrestors, etc., for proper and safe approach (Figures 2.41, 2.42, 2.43, and 2.44).
- Adequate inter-row spacing to avoid shadow and to provide approach for PV module cleaning.
- Water piping arrangement on the roof for cleaning purposes.
- Water treatment system, if quality of water does not meet the required criteria.
- Remote power plant monitoring provisions to monitor its operation and performance.
- Display boards containing safety/technical information.
- Quality Assurance Plan (QAP) for ensuring material and installation quality.
- Measures to control vegetation or shadow.
- Designing of technical information and site specific O&M manual.

Figure 2.41: No provision to access tail end structures (wrong practice)

Figure 2.42Proper inter row spacing (best practice)

Figure 2.43: Rooftop SPV plant without safe access (wrong practice)

Figure 2.44: Rooftop power plant with proper walkway and handrail for O&M activities (best practice)

B. Installation

The installation of various components of an SPV plant should be undertaken using proper tools and tackles to avoid possible damage to equipment which may lead to maintenance issues during operation. Material supply needs should be planned in line with installation sequence by taking into account local weather conditions. Installation delays need to be avoided to prevent last minute rush which may lead to poor workmanship and increased maintenance, e.g. if the sealing of a rooftop power plant installation with roof penetration MMS type is not done properly, roof leakage is possible in the future leading to extra expenses and cost of manpower.

Figure 2.45: Improper cable conduit installation and proper installation of conduit in same site.

C. Testing and Commissioning

As per industrial practices, generally, there are 2 sets of testing needed before the final handing-over of a power plant, i.e. pre-commissioning testing and post-commissioning testing.

Pre-commissioning testing: Includes checking of connections and quality of the installation, cross-checking with design parameters, polarity, voltage etc. If any rectification needs to be carried out, it should be done before the commissioning of the SPV power plant.

Post-commissioning testing: Check the performance parameters of the power plant. For example, general performance KPIs can be checked during the post-commissioning testing stage and changes undertaken if required.

D. Post-commissioning O&M considerations

The post-commissioning stage includes proper implementation of all O&M activities, as planned in the pre-commissioning stage. While planning O&M activities of solar PV power plants some factors need to be considered, such as capacity of the power plant, local climatic conditions, desired accuracy class, type of installation, etc.

As per power plant performance analysis, it was observed that more residential small rooftop SPV power plants are under-performing due to lack of proper maintenance compared to utility scale SPV power plants. Also O&M activity and effectiveness of SPV plants varied according to installed capacity. There for if an asset owner of a small rooftop SPV power plant is responsible for the O&M of his/her plant, then they should receive at least the minimum O&M training.

An effective quality assurance plan at the time of solar plant's procurement, installation and commissioning will help ensure that the best quality of material is used in its installation thereby optimizing plant's performance. Further, pre-commissioning and post-commissioning followed by proper corrective action will help ensure proper operations of a solar PV plant.

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[4] IEC 61724-1 (Photovoltaic system performance – Part 1: Monitoring

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Chapter 3

Environmental Health and Safety in the Solar Industry

Environmental Health and Safety in the Solar Industry

Environmental Health and Safety (EHS) is a collection of processes, rules, standards, laws, and regulations that provides a systematic approach to the protection of the environment, company, employees, and the public from harm. The EHS policy of a company ensures that its work practices do not cause any environmental damage, protects worker's health and safety is in compliance with legislation and provides a risk free work place.

Environmental aspects involve creating a systematic framework for complying with environmental regulations, such as managing waste or emissions and helping sites reduce their workplace carbon footprint. Health and safety aspects are very important in any organization for protecting the well-being of its employees, customers and visitors.

Health refers to the general well-being of a person where there is a sense of mental, physical and social wellness. Safety is a feeling of security in which a person can work without fear of danger or injury. Every workplace is not an ideal space and people may suffer injuries and accidents. Proper health, use of safety equipment and procedures can help in eliminating problems to a great extent. In the Indian solar industry, a majority of the workforce falls in the un-skilled and semi-skilled categories and hence it is essential to sensitize personnel about the hazards, risks and the proper use of personal protective equipment (PPE), including work procedures, to ensure a safe work environment. The hazards and risks involved in solar power plants are discussed in this chapter along with personal protective equipment and safe work procedures/practices. Based on the installation and site conditions, appropriate selection of PPE and proper work procedures/practices should be followed.

3.1 Hazards in solar power plants

As per OSHA (Occupational Safety and Health Administration), a hazard is a condition or a set of circumstances that present a potential for harm. This can be divided into health (occupational illness) and safety hazards (physical harm). The hazards mainly involve tripping or falling from heights, electrical and weather related hazards and other common risks. All hazards can be avoided or their intensity reduced or transferred, by adopting suitable mitigation techniques and procedures. Some hazards in solar power plants are discussed along with mitigation techniques listed below.

A. Fall from heights

Solar rooftop power plants are installed at the top of highrise buildings, elevated structures or sloping roofs and are generally difficult to access for day-to-day work. Workers who perform routine operations and maintenance activities, including cleaning of PV modules, are prone to fall hazards. Common fall hazard causes are slanted/wet roof, hole openings, slips, broken skylight, snow accumulation, dangerously hot temperatures, heavy winds, etc. Falling from heights can lead to serious injuries including death.

As per OSHA, those working at a height of 6 feet (1.82m) or more, should employ fall protection methods. In India, the floor to ceiling height is more than 3 meters in the case of residential, schools and commercial buildings and may be more than 3 meters in industrial shades. Hence, fall protection systems need to be employed.

Mitigation: Use of fall protection systems like (a) Guard rails; (b) Safety net systems; (c) Personal fall arrest systems; (d) warning lines, etc.

- It is better to be prepared for all weather conditions by making roofs safe and able to withstand the challenges of climate.
- Make sure there are clear, safe paths for workers to use when accessing the roof, and eliminate non-essential roof access during hazardous conditions.
- Do not perform any activities on roofs during thunderstorms.

B. Slippage on roofs

Slips occur when a person loses balance and falls due to limited friction between the roof's surface and the soles of footwear. This may be caused by wet or oily surfaces, vegetation growth on the roof (mosses), etc.

Mitigation: Slips can be prevented by:

- Undertaking proper housekeeping which includes cleaning of all water or oil spills immediately.
- Providing safety signs for wet areas.
- Removing any vegetation growth on the roof.
- Re-coating or replacing floors, installing rubber mats, etc.
- Use of PPE, e.g. safety shoes, safety helmets, etc.

C. Electric shock

Electric shock is the sudden passage of electric current through the body. Electric shock can directly lead to burns or death in severe cases, and indirect effects like a startle reaction to shock or an involuntary body reaction could lead to a fall or slip.

As per the National Fire Protection Agency's (NFPA 70E) standard on electrical safety in the workplace, less than 50 V is considered safe from the standpoint of an electric shock hazard. But for wet surfaces, if the DC voltage exceeds 30 V it is considered a shock hazard. When the voltage exceeds 50 V AC or DC and is in the shock hazard zone, the operator should wear rubber insulating gloves and leather protectors. In solar power plants, electric shock can occur even on contact with wires in damaged insulation, broken energized PV modules with poor earthing, etc.

Mitigation:

- Electric shock protection involves making hazardous live parts inaccessible to direct contact and by placing proper danger/safety signs to bring attention to the risks. Limited access should be provided to the live parts of the power plant.
- Proper insulation of wires or enclosures should be maintained and inspected routinely.
- Regular inspection, testing and maintenance of earthing should be done
- Use of rubber hand gloves, as per IS 4770, while working at different voltage levels should be practiced. Leather gloves should be worn over rubber gloves to protect them from cuts and tears.
- Use of safety shoes of conductive, anti-static or insulating type, as per the site conditions.
- Implementation of safety systems which include electric work permits, LOTO systems and electric insulating mats, etc.
- Training to staff and display of procedures to be followed, for recovering from an electric shock

LOTO System

Electrical Insulating Mat

Safety Signs

D. Electric arc

An electric arc fault results in an arc flash or a spark occurring between connections, which may lead to fire. In solar power plants, the risk of serious arc flash is negligible from a single PV module, but high in series connection of PV modules in the form of a string. An arc flash might be accompanied by an arc blast in which energy is released explosively by intense sound pressure and vapourized metal. An electric arc can lead to fire, flying objects (often molten metal), sound blast and extreme heat which can cause burns. The incident might result in a worker receiving burns, falling or slipping, which can cause severe injury. Electric arc can be caused by a loose connection, falling of metal tools causing short circuits, failure or malfunctioning of overcurrent protection devices, etc.

Mitigation: Risk of electric arc hazard can be mitigated by use of proper PPE, like safety shoes, safety goggles, helmets with face shield, rubber gloves, etc., and such incidents can be avoided by regular inspection of the plant and its components.

Fire hazard due to electric arc

E. Failure of module mounting structure (MMS)

Poor design and material, manufacturing and installation issues, corrosion, etc., can lead to failure of MMS. Common hazards include sharp edges or corrosion which can cause damage and weakening of the structure, and fall of PV modules from the roof due to loosened nuts and bolts.

MMS Failure

Mitigation: Rusted galvanized structures should be replaced during the period of warranty, or rusted parts of the structure should be protected by applying zinc spray coating. Periodic inspection to maintain tightness of nuts and bolts and galvanization of the solar structure should be undertaken. Any structure with sharp edges will pose a danger and should be smoothened.

F. Flora and fauna menace

- Animals, birds, insects may be present in the area of the solar power plant and nearby areas which can cause damage to the PV modules, wires, inverter, etc. This will lead to hazardous situations like earth fault, short circuit, DC arc or electrocution.
- Vegetation growth on rooftops may lead to slippery surfaces and can enhance the risk of fall from a height.
- Birds, like pigeons, usually build their nests underneath PV modules which can retain water and damage the roof or create a potential hazard.
- Rodents like rats and squirrels can damage the insulation of wires and junction boxes which may lead to leakage of current.
- Monkeys can cause damage as they jump over PV modules, leading to cracks.
- Snakes, bees or other poisonous reptiles may be present in the area which can pose a danger to house owners or plant staff.
- Termites can damage cables, leading to short circuit.

Rats damaged MC4 connectors

Vegetation

Bird nest

Conduit opening

Mitigation:

- Remove vegetation growth before the start of the rainy season.
- Provide proper fencing to the solar power plant area or roof and control access.
- Regularly monitor any nesting of birds or presence of bees and remove the same.
- Do not leave any machinery or objects unattended.
- Cables should be tied and protected with cable trays of suitable sizes. Use cables with anti-termite and anti-rodent properties.
- Snakes can be prevented by planting snake repellent plants like Indian lemon grass, or using snake catcher, or use of gumboots, etc.
- Dried grass can catch fire and hence the area surrounding the plant needs to be cleared immediately after the monsoon.
- MMS/conduit opening should be properly sealed to avoid ingress of insects.

G. Thermal burns and sun burn

During peak generation, the surface of the PV modules becomes extremely hot and can reach surface temperatures of over 90^0C. Touching the PV modules without proper protection can lead to burns. Prolonged working in the sun can lead to UV radiation exposure effects which include skin burn, sun stroke in the short term, and skin cancer, cataract, etc., over a long period.

Mitigation:

- Use of leather gloves to protect from thermal burn risk.
- While working in the field it is better to use sun protection clothing, sunscreen lotion, UV protection glasses, etc.
- Check the UV index for the day and use proper PPE.
- When working on sunny days, rotate tasks and cover the head, neck and arms as these areas are more prone to skin cancer.

H. Hazards due to environmental effects

It is not possible to avoid environmental hazards. However, their impact can be reduced and losses can be insured.

Wind

As per IEC 61215, a PV module can withstand wind load of 2,400 Pa, equivalent to wind pressure of 141.5km/hour. Above this limit, the PV modules can get damaged. High wind can lead to risk of injury by falling PV modules or shattering of PV module glass which can cause cuts.

Mitigation:

- During high wind speeds, PV module replacement/maintenance activity should not be carried out.
- Monitoring and tightening of module supports should be done prior to the monsoon or windy season.
- The plant needs to be thoroughly inspected for any possible hazards and breakage after a major storm.
- Plant and equipment need to be insured against damage caused by such extreme events. It is recommended to record wind speed to support insurance claims.

Hailstones

Hail is irregular shaped balls formed by super cooled water and whose formation takes place in the clouds. The size of hail balls tend to range between 5 and 150 mm in diameter. Hail can result in cracking of glass, damage to PV modules and expose live wiring, which is a serious hazard. As per IEC 61215, PV modules should be able to withstand hailstones of 25 mm diameter, 7.53 grams weight, falling at a velocity of 23 meters per second.

Mitigation: Use PV modules with better hail protection or insure the plant from such risk.

Lightning

Lightning is a major hazard for solar power plants as it can lead to damage of PV modules, fire or even loss of life. Since the impact of lightning is site specific, it is recommended to consider the lightning zone where the plant is located and provide adequate protection while designing the power plant.

Mitigation:

- Lightening arrestors and surge protectors guard the PV modules and electronic components from lightning hazards.
- Effective grounding and periodic checks for continuity should be carried out.

Natural Calamities

Solar power plants are also subjected to environmental risks, such as sandstorms, floods, earthquakes, landslides and storms. Continuous immersion in water has the potential to damage the power plant's components, and can lead to insulation failures. Landslides or soil erosion also pose a major danger if the soil beneath the foundation is washed away. This can lead to damage of PV modules, loss of generation, dangers leading to risk in O&M.

Mitigation:

- Construction of a proper storm water management system/drainage system.
- Planting and maintaining the grass and other vegetation at the site which will prevent soil erosion.
- Construction of elevated structures in flood prone areas and areas where there is water logging.
- Cables should have resistance to water absorption.
- Insurance against the hazard.

Damaged PV module due to hailstone

Land sliding due to flood

Land sliding due to flood

I. Material handling hazards

Material handling is an activity involving transporting, shifting and movement of PV modules, inverter, structures, cables, cable trays, etc., to the solar power plant. Material handling can be categorized as manual handling and machine handling:

Manual handling: Load is handled by one or more workers.

Hazards: Mishandling of solar equipment leads to back injury, cuts, etc., including equipment damage. Common accidents are due to dropped or falling objects, loss of balance, trips, slips and falls, incorrect or over lifting, etc.

Machine handling: Load handling involves the use of specialized machinery for this purpose.

Hazards: Overturning, collisions, overhead obstructions or contact with transmission lines, falling objects, structural/mechanical failure etc., may lead to hazards. Reasons for this could be poor maintenance, poor vision, pedestrians movements, dangerous stacking, overloading, lack of driver training, etc.

Mitigation:

- Use proper personal protective equipment (PPE): Gloves to protect hands when working with sharp objects, eye protection, steel-toed safety shoes and helmets.
- Proper training of workers for handling materials and operating lifting equipment.
- Job rotation and breaks should be provided to reduce the frequency of manual handling activity.
- Lifting/hoisting equipment should be periodically inspected.
- Do not overload the equipment beyond its safe load bearing capacity.
- Use safety signs and safeguard the area surrounding the crane/lifts, etc.

J. Fire hazards

Fire in a solar power plant can be caused by insulation failure, short circuit, voltage flashover, lightning strikes, burning from the surrounding vegetation, improper storage of inflammable materials like transformer oil, diesel etc. Day time fire due to any external reasons can lead to insulation failure of PV modules followed by destruction of the supporting mounting structure, or the surrounding surface getting energized that can create further electrical shocks or arc flashes. This increases the fire fighter's risk while working on rooftops and other elevated structures. Common hazards due to fire are as follows:

- **Electrical shock**: Electric shock can occur from direct contact or spray of water on live damaged PV module or wires.
- **Slips and falls:** Limitations of space can reduce access and may cause slips or falls.
- **Arc or ground fault**: A fire can start from arcs emanating from exposed conductors in energized PV power plants.
- **Toxic Gases**: Toxic gases released from burning of PV modules or building materials.
- **Collapse of roof solar structure**: This can be a major issue in case of a rooftop power plant and can lead to a major hazards including damage to property and loss of life.

Mitigation:

In case of fire in a solar power plant, the following minimum steps need to be practiced [3]:

- Once it is confirmed that the power plant is affected by fire, immediately disconnect the power plant from the ACDB and open the DC isolator, if it is easily accessible.
- Flammable toxic gases (CO, CO_2) may be released from a fire involving PV modules. Wear protective masks regardless of the ventilation conditions in the building. Turn off the ventilation systems in the building[4]
- In case of rooftop power plants, the roof may collapse inwards and so fire-fighters need be aware of the danger.
- In case of large scale distributed power plants, fire fighters must refer to an updated plant layout blueprint to identify the plant's exits, before going into action.
- Handling of defective switches and isolation of PV modules should be carried out only by qualified technicians and that to while using proper PPE.
- Arcing and resistive heating may cause fires. Protect the areas against arcing, and let technical staff shut down the power plant.

- Keep a distance of at least 1 meter from electric systems and components (that should be disconnected) at the time of spraying water. All local fire fighting rules and steps need to be followed.

Type of fire extinguishers suitable for the different classes of fire are given in Table 3.1:

Table 3.1: fire extinguisher classes

Fire class	Description of fire	Type of extinguishers
Class A	Solid combustible materials. eg: wood, paper, rubber, plastics, etc.	Water, foam, ABC dry power and halocarbons.
Class B	Flammable liquids or liquefiable solids or the like where a blanketing effect is essential.	Foam, dry powder, clean agent or carbon dioxide extinguishers.
Class C	Flammable gases under pressure including liquefied gases.	Dry powder, clean agent or carbon dioxide extinguishers.
Class D	Combustible metals, such as magnesium, aluminium, zinc, sodium, potassium, etc., when burning are reactive to water and water containing agents, and in certain cases to carbon dioxide, and dry powders.	Extinguishers with special dry powder for metal fires.
Electrical Fire	Fire involving energized electrical equipment, where non-conductivity of the extinguishing media is of utmost importance.	Dry powder, carbon dioxide (without metal horn) or clean agent.

For electric fires, once the electrical equipment is de-energized, extinguishers suitable for that class of the fire should be used as given in Table 3.2[5]. Detailed review of fire hazard causes and usage of fire extinguishers is given in Annexure II.

Table 3.2: fire extinguishing agents and its usage

Extinguishing Agent	Usage on Electric Fire	Fire Class
Carbon dioxide	Used where contamination and cleanliness of sensitive electrical equipment like control instruments, electronic equipments are of prime importance. Can be used for high and low voltages. Most commonly used in solar applications.	B,C, Electric
Clean agent	Used in control panels, distribution box where contamination and cleanliness of sensitive electrical equipment is of prime importance. Clean agents are costlier than carbon dioxide and dry powder.	A,B,C, Electric
Dry powder	Not preferred in confined spaces as using this reduces visibility for a few minutes and temporarily jeopardizes escape, rescue or other emergency actions. Also it can damage electrical and electronic components.	A,B,C, Electric
Water	Should be avoided as it is conductive and solar PV power plants are live as long as there is light. Do not use salt water (near coastal areas) as the conductivity of the salt water is 50 times more than that of fresh water and could be very dangerous.	A
Foam	Not preferred, as PV modules are mounted on a tilt and the foam could simply slide off the slope. Not suitable for domestic use.	A,B

3.2 Safety procedures and practices

3.2.1 Use of personal protective equipment (PPE)

It is recommended to wear proper personal protective equipment (PPE) to avoid injury. PPE are specialized equipment or clothing worn by employees for protection against health and safety hazards. These are designed to protect different parts of the body, i.e. eyes, head, face, hands, feet, ears, as well as the complete body.

PPE is classified as follows:

- Head Protection: Helmets
- Body Protection : Full sleeves shirts, long pants
- Hearing Protection: Ear plugs
- Eye and Face Protection: Spectacles/safety glasses/goggles visor
- Foot and Leg Protection: Safety shoes, gumboots
- Hand and Arm Protection: Leather and rubber gloves

In the Table 3.3, different hazards have been listed along with the common control methods and use of personal protective equipment against these hazards. PPE becomes effective when other control methods fail to protect workers. Detailed list of PPEs and their specifications are given in Annexure III.

Table 3.3: Classification of hazards and PPE required

Hazards	Body Zone to be Protected	Controls	PPE to be Used
Falls from Heights: Fall from a high rise building, pit fall, etc.	Whole Body	Guard rails Safety net system, Fall arrest systems	• Body: Fall harness, lifeline, reflective jacket. • Head: Helmets . • Feet: Safety shoes/boots.
Slip: Oily surface, cleaning activities, etc.	Head, Feet	Removal of oil or wet spill: Safety warning signs, non -slippery mats.	• Head: Helmet. • Feet: Non-skid safety shoes.
Trips: Obstructed view, poor light, uneven surface.	Head, Feet	Proper lighting Removal of obstacles Safety warning signs	• Head: Helmet. • Feet: Safety shoes.
Falling objects: Heavy objects like hammer, spanner, etc.	Head, Feet, Eyes	Safety net to catch falling objects.	• Head: Helmets. • Feet: Safety shoes/boots. • Eyes: Spectacles/safety glasses/goggles visor.
Electric Shock: Electrocution, burns, fatality, falls.	Hands, Body	Rubber mats, proper insulation and earthing, LOTO, electrical work permit.	• Head: Safety Helmet. • Eyes: Safety glasses. • Hands: Insulated rubber gloves. • Body: Coveralls. • Feet: Safety shoes.
Electric Arc: Burns, death.	Hands, Eyes, Body	Proper insulation and earthing.	• Eyes: Safety goggles. • Hands: Rubber gloves. • Body: Full sleeves shirts, long pants. • Feet: Safety shoes. • Face: Face shield as splash or splatter may occur.
Flying objects: Due to blast from electric arc, etc.	Head, Eyes	Safety signs.	• Head: Helmets with face shield. • Eyes: Spectacles/safety glasses/goggles visor. • Body: Full sleeve shirts, long pants. • Feet: Safety shoes.
Fire: short circuit, arc, lightning, surroundings, etc.	Whole Body	Fire extinguishers, Fire alarms and detectors.	• Hand: Gloves. • Head: Helmet. • Body: Fire approach suits/close proximity suits.

			• Feet: Safety shoes.
Cuts/Abrasions: Corroded structure, etc.).	Hands		• Hand: Leather gloves. • Feet: Safety shoes/boots.
Poisonous Reptiles: Snakes, Bees.	Hands, Feet, Body	Vegetation control, Snake repellent plants like Indian lemon grass.	• Hands: Leather gloves. • Body: Full sleeves shirts, long pants, safety footwear. • Feet: Safety hoes, gumboots.
Hot Surface Burns: Hot PV modules.	Hands, Eyes, Body		• Eyes: Safety goggles. • Hands: Leather gloves. • Body: Full sleeves shirts, long pants. • Feet: Safety footwear.
Sun Radiation(UV Radiation): Burns, Skin Cancer.	Whole Body	Check UV Index and take precautions.	• Head & Neck: Hard hat covering neck or neck protection clothing. • Eyes: Safety goggles. • Hands: Rubber gloves. • Body: Full sleeves shirts, long pants, reflective jacket. • Feet: Safety shoes. • Face: Sun-screen lotion.
Dust: Sand, surrounding activities.	Eyes, Face		• Dust goggles, respirators.
Noise	Ears		• Hearing protection devices.
Material Handling hazards: Bruises, fractures, musculoskeletal disorders(MSD).	Whole Body	Use mechanical equipment like trolleys, pallet jacks or forklifts.	• Head: Helmet. • Hands: Leather gloves. • Feet: Safety shoes.

3.2.2 Display of safety signs, symbols and labels at prominent locations

Safety is of utmost importance while working with any electrical systems. Compared to other power generating systems, solar power plants need more attention in terms of safety. This is because of the following factors:

- It deals with high voltage DC (1,000 VDC to 1,500 VDC).
- Any non-technical person can access live parts (e.g. building rooftop is accessible).
- Wide-spread utility scale power plant, with a larger area makes it very difficult to control access by others.

It is recommended that safety signals or signs are provided announcing appropriate hazard warnings at the site which will also be a guide for emergency response teams, in case of an incident, for isolating the system. Safety signs or marks at a solar plant can be:

- General information about power plant's accessibility.
- About electrically charged parts.
- About type of power, e.g. AC/DC and voltage levels, etc.
- Evacuation plan in case of emergency caused by hazards.
- Caution and instructions regarding the risks of hazard.
- Location of fire fighting equipment and fire alarm activation points.
- First-aid and procedure for shock treatment, etc.

A) Different types of safety signs [6]

1. **Prohibition signs**: A sign prohibiting behaviour that is likely to increase or cause danger. In the workplace, they should be used to reinforce instructions prohibiting dangerous activities.
   e.g.: *No access to unauthorised persons; No Smoking; Do Not Drink, etc.*

2. **Mandatory action signs:** A sign prescribing specific behaviour or action. These signs should be used to indicate actions that must be carried out in order to comply with statutory requirements.
   e.g.: *Wear protective equipment, eye protection, etc.*
3. **Warning signs:** A sign giving warning of a hazard or danger. These signs should be used to make people aware of a nearby danger.
   e.g.: *Danger: Electricity, High Voltage, Hot Surface, etc.*
4. **Safe conditions:** These signs should be used to indicate escape routes, emergency exits, first aid equipment, emergency showers, etc. Safe condition signs shall comply with the layout requirements.
   e.g.: *First aid box, Fire exit, Fire assembly point.*
5. **Fire safety signs:** These signs are used to mark the location of fire fighting equipment and fire alarm activation points.
6. **Supplementary and complimentary signs:** These are signs used to describe, supplement, or clarify the meaning of a safety sign. The supplementary safety information should be placed on a separate supplementary sign or could be included as part of a combination sign or a multiple sign.

B) Using safety signs and labels [6],[7]

The following points have to be noted for the proper use of signboards:

- Inverters generate heat and should be provided with sufficient ventilation to avoid loss in generation. They can be placed with a label – "DO NOT BLOCK VENTILATION" – placed next to the inverter. It is also recommended that inverters carry the sign 'INVERTER - ISOLATE AC AND DC BEFORE CARRYING OUT WORK'.
- Marking is required also for DC circuits, both on interior and exterior DC conduits, raceways, enclosures, cable assemblies and junction boxes to alert the fire service against cutting them, or to be suitably informed in case they need to cut them to extinguish a fire. If deemed necessary, such marking signs should be placed every 10 feet, at turns, and above and/or below penetrations, including at all DC combiner and junction boxes.
- A sign should be mounted on or next to the PV power plant's service disconnecting means, stating: "PV POWER PLANT - DISCONNECT".
- Ground-mounted power plants should have a warning label on the inverter or near the ground fault indicator at a visible location, stating: "WARNING - ELECTRIC SHOCK HAZARD".
- The warning sign must be placed at least every 10 meters of the electrical duct from the arrays to the inverter's cabin and before all entrances and along the way out of the PV plant.
- **Placement and size**: Signboards should be sufficiently large to be easily seen and understood. They should be placed at locations that give people enough time to avoid the hazard and where there is no obstruction to viewing them. The safety sign should clearly indicate the location of the equipment when describing it. There should be adequate illumination of the signboard and the size of the lettering should be appropriate for the intended viewing distance.
- Permanent signboards are necessary, except in cases when the workplace hazard is temporary. In case of temporary hazards, a portable warning sign should be placed. For example, use of a portable warning sign during routine cable check which is undertaken for a short period.
- Avoid use of too many signboards in close proximity so as to prevent confusion or important information being overlooked.
- If a hazard no longer exists, ensure the removal of that particular signboard to avoid the display of misleading information.
- Use of safety sign with text to aid understanding, especially when using a new or unfamiliar sign, or when using a general danger or warning sign.
- Any supplementary sign or text used with a particular safety sign must be chosen to reflect the same safety sign category. So, if a mandatory sign is used, ensure that the accompanying text (if any) describes the mandatory nature (using the word 'must' rather than 'should' or 'may') of the action to be taken, e.g.'Face protection must be worn'.

3.3 Planning of EHS activities for solar PV power plant

Even after following all EHS measures as per the site conditions, there are certain procedures to be followed for its successful implementation. These include strict implementation and adoption of policies, procedures and work rules. The designated EHS department personnel should perform the following activities:

- Conduct periodic workplace audits and inspections.
- Report accidents, near miss events and other incidents, on time.
- Proper accident investigation, corrective action to be taken and record keeping.

- Coordination of special environmental services such as vegetation assessment.
- Initial site induction and periodic safety training.
- Emergency response and site evacuation plan.
- Environmental compliance, construction and occupational safety.

The main hurdles in implementing EHS measures in solar power plants are:

- Every solar power plant site has site specific material handling procedures and implementation procedures.
- Distributed nature of the power plant.
- Lack of awareness among semi-skilled and unskilled contractual workforce.
- Safety signs and symbols placed at the time of power plant commissioning are exposed to sun radiation and are likely to fade/likely to be misplaced after one or two years of operation.
- Lack of safety training during operations and maintenance of the plant.
- Lack of safety audit and risk assessment at the start of the plant installation phases.

In solar power plants the EHS activities are planned as per the progress of the power plant right from site preparation to installation, commissioning and O&M. Every stage has a different set of activities and associated risks which need to be addressed. Proper work planning and implementation of safe work practices can reduce the chances of accidents at the site. Some of the safe work practices/activities to be followed at a solar power plant site are listed in the following sections.

3.3.1 Job hazard analysis

A job hazard analysis is a technique that focuses on job tasks as a way to identify hazards before they occur. It focuses on the relationship between the worker, the task, the tools, and the work environment. After identification of the hazard, necessary steps have to be taken to eliminate or reduce it to an acceptable level. The hazards are usually reduced using PPE, safe working practices like work permits, LOTO systems, etc. Analysis of each work activity can be performed before starting it in order to identify possible hazards and explore or set the work procedure to minimise the risks. This activity ensures proper procedures for work permits, monitoring protocol, PPE requirement and availability during execution, training need assessment, measures to be taken at the time of emergencies, etc.

3.3.2 Tailgate/Toolbox meeting

Toolbox meeting is an informal safety meeting which is usually conducted at the power plant site prior to job commencement or at the start of a work shift. Toolbox talk (Figure 3.1) mainly focuses on safety topics related to specific jobs such as workplace hazards and safe work practices to be followed for ongoing/planned activities for the day. Benefits of toolbox meeting are as follows:

- The Safety Incharge can discuss the planned activities for the day and their related hazards. He can refresh the workers' knowledge and make them alert to possible risks well before the start of activities.
- Tool box meeting can enhance safety discussions among workers and encourage workers to clarify their doubts while improving understanding of risks and safety work procedures, etc.
- The Safety Incharge can discuss the accident incidences from his experience to sensitise workers to the intended purpose.
- The Safety Incharge can arrange for extra PPE if required.
- Being able to understand the work flow and difficulties faced by workers will help him to modify the set procedures, if required, for future activities.
- The Site Incharge can explain the planned task for the day and can delegate the work to workers, which increases awareness of activities by co-workers.
- The Site Incharge can discuss the last day's work progress and prepare the snag-list.

In addition to this, a weekly site safety meeting should be organized which would evaluate the work scheduled and safety practices to be followed. It is recommended to conduct the toolbox meeting regularly during the installation phase. During O&M, toolbox meetings are necessary for large scale power plants only.

Figure 3.1: Site toolbox talk

3.3.3 Site orientation/ induction training

All site and management personnel should undergo site orientation training before work at the site begins. The site orientation training should elaborate on the solar plant overview, organizational structure, dress code, decision-making processes, office protocol, site safety requirements, reporting of emergencies, medical assistance, etc. All personnel should be aware of the hazards at the site and mitigation methods, fire extinguishers, other safety equipment location and operation, muster points, evacuation plan, etc. Induction training records should be maintained at the site.

3.3.4 Pre-job briefings

A pre-job briefing is the process of thinking through a job, in advance, with briefing on the job and hazards, and mitigation measures to be taken. This can prevent serious injuries and accidents. Pre-job briefing should contain the following points:

- Work to be performed.
- Individual responsibilities.
- Hazards involved and mitigation measures.
- PPE to be used and their inspection frequency.
- Clarification of any doubts regarding the job that the employees may have, etc.

3.3.5 Post job review

After the job is completed, the work has to be reviewed in order to identify any improvements that need to be made in the future from the point of execution sequence, risk assessment, adequacy of equipment and instruments, etc.

3.3.6 Safety meetings

Safety meetings are important in order to heighten safety awareness among employees and also for updating employees about recent accidents, inspections required and to discuss new EHS topics. The safety meetings should be done weekly and monthly. And attendance roster should be kept and minutes of the meeting should be recorded. Medical fitness of workers should be evaluated at the start of work and if required the same should be checked based on the observations of the Site Incharge.

3.3.7 Accidents and near miss incidents reporting

A near miss incident is an event that didn't result in injury or any damage but had the potential to do so. A near miss incident that is not reported can result in an accident in the future. All accidents and near miss incidents have to be reported to the Site Incharge or O&M manager as soon as possible after the incident occurs. An accident investigation reporting has to be done after the incident. The accident investigation has to be carried out by an experienced person for identifying and analyzing the cause and for ensuring proper precautions so that such incidents are not repeated. The report should also be shared with other relevant personnel of the company so that such incidents can be avoided at other solar plants of the company.

3.3.8 Safety audit/inspection

Site staff responsible for safety of the power plant and its personnel should undertake periodic safety inspections of all power plant activities so as to promote and implement safe working practices. Job hazard analysis report should be kept on record and should be available to site employees upon request.

Periodic safety audits of the site should be carried out to prevent deviation from the safety standards of the power plant. The safety audit should cover the following aspects of a solar power plant:

Accident control	Hygiene facilities	Electrical systems
Fire prevention	Demarcated areas	Mechanical equipment
Safe work practices	Storage areas	Material stacking
Housekeeping	Safety statistics	Display of emergency numbers
MSDS sheets	Safety training	Personal Protective Equipment
Safety meetings	First-aid facilities	Traffic control, Signage, etc.

The safety audit should be undertaken in utility scale power plants by a qualified professional who is aware of all solar safety hazards. It is also recommended to conduct the safety audit before a new O&M team is appointed.

3.3.9 Safety mock drills & training

Safety mock drills and training have to be conducted at the site, as per site requirements so that all employees are familiar with what to do and not do in case of an emergency.

3.3.10 Solar power plant visitor's log and safety

All visitors' entry and exit shall be through the security gates located at the plant. A visitor's log book should be maintained at the gate where all visitors should sign in and sign out. Visitors should be provided with the basic necessary PPE, like safety helmet, safety shoes and other equipment like rubber gloves, if required, as per the hazard they may encounter. They should also be given basic safety orientation and should be accompanied by a site worker who has undergone site orientation training.

3.3.11 Safety work permits

A safety work permit is a document which describes the activities to be performed, hazards involved, safety precautions to be taken, which include written authorization of work and use of personal protective equipment. Sample copies of different safety work permits being used in solar power plants is enclosed in Annexure IV and the list is presented as follows:

- **Permit for work at heights**: Taken before working at any elevated spaces and for floor opening, open edges, fragile surfaces where there are chances of falls.
- **Hot work permit**: Should be taken before commencement of welding/ cutting work, etc.
- **Excavation permit**: Required before carrying out excavation or trenching activities at site.
- **Night work permit**: Working during night hours involves additional hazards. This requires special permission, appropriate lighting arrangement and assistance by a worker and requires to make aware of such activity to the site in charge/safety in charge.
- **Disposal permit**: This keeps a track of all the waste which is disposed off including the method of disposal.
- **Permit for working in restricted areas**: For working on junction box, control panel, inverters, server, battery rooms, etc.

3.3.12 Non-compliance reporting and disciplinary action

Non-compliance of safety and health provisions should be recorded and intimated in writing to the responsible person. Strict monitoring of non-compliance and disciplinary action inculcates behavior to abide by the set rules and procedures, which in turn helps to ensure a safe working environment. The disciplinary action is subjective; it depends on the severity of non-compliance and the penalty mechanism can be decided by the management. Tentative disciplinary action against non compliance can be as follows:

- **1st time violation**: Written warning.
- **2nd time violation**: Imposition of penalty as deemed fit by Site Manager.
- **3rd time violation**: Removal from site.

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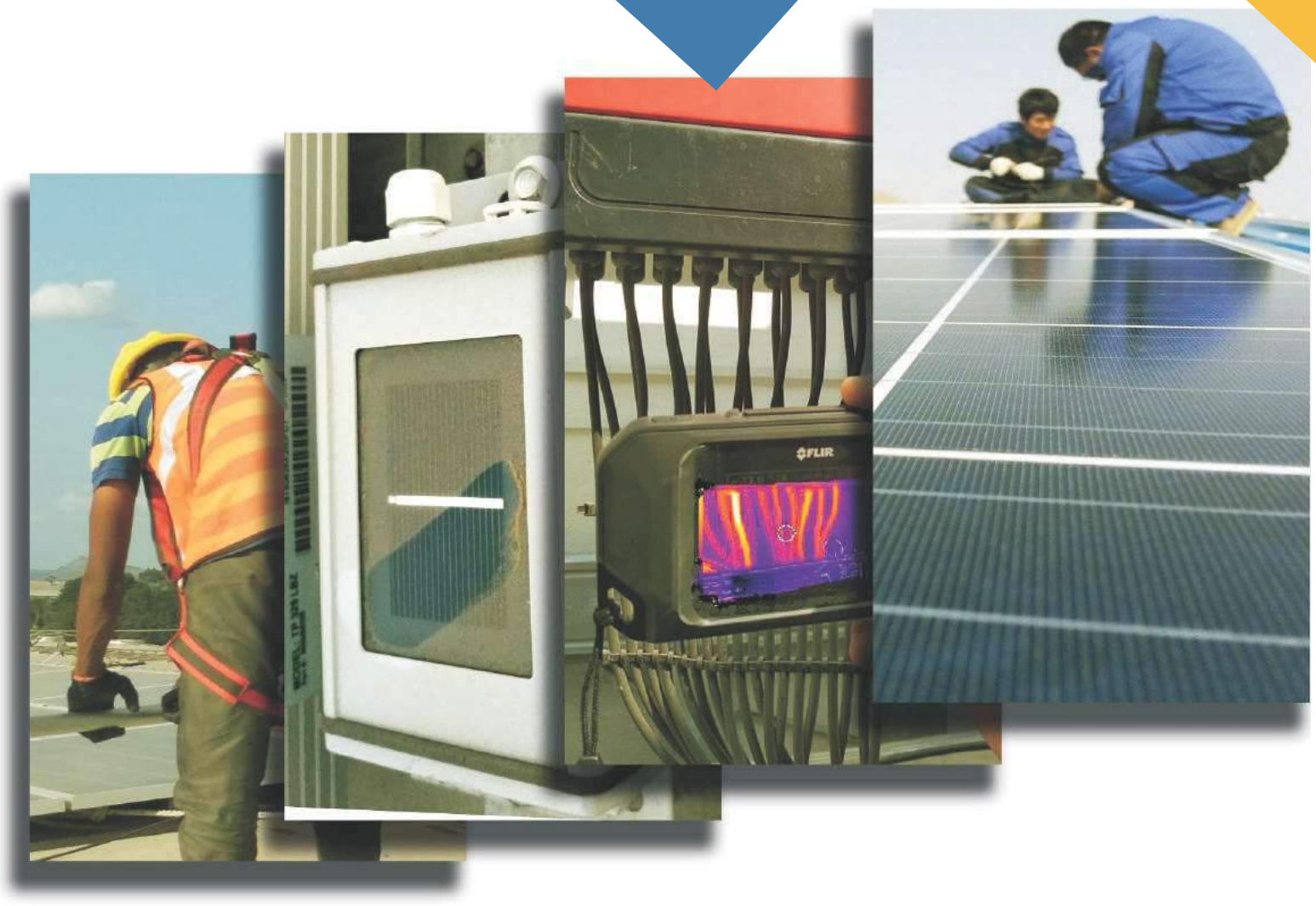
Chapter 4

Monitoring of Solar PV Power Plants



Monitoring of Solar PV Power Plants

The basic intention of having a monitoring system in a solar PV power plant is to acquire data for performance evaluation, maintenance scheduling, recording and reporting, etc. A proper monitoring system will assist the owner to detect faults in the power plant and will help him/her assess the plant's performance through designated KPIs. In the absence of a proper plant monitoring system, the owner will get to know any underperformance or faults in the plant if the issue becomes significant followed by generation loss. A real-time monitoring system will help reduce the fault identification time and will provide real-time plant performance data. A remote monitoring facility assists the owner to keep track of his/her multiple assets and optimize generation and revenue. This chapter briefly discusses the classification of monitoring systems, the different sensors and instruments used for monitoring and the process involved right from data acquisition to customized report preparation.

Main purposes of the data recording/logging system are as follows:

- Recording system level weather and environmental parameters.
- Recording extreme events (inverter trip, fire alarms, etc.).
- Data backup for future reference and analysis.
- Generation or performance reporting and scheduling.
- Forecasting of events and generation.

The following minimum points should be considered while selecting monitoring systems:

- Data accessibility of at least 99% across the year.
- User friendly monitoring interface.
- Different user access levels - In case of a web monitoring system, multiple stakeholders need access (e.g. O&M Manager, EPC, investor, Asset Manager).
- Graphical representation of measured and calculated parameters.
- Provision to download data in a processable format (.csv, .xls, etc.).
- Event logs.
- Data security.
- User configurable alarms.
- Provision for customized report generation.
- Automatic KPI calculation and indication when the power plant is found to be underperforming.

The solar PV power plant monitoring process can be divided into three basic parts:

1. Data acquisition: Collecting real-time raw data with the help of different sensors.
2. Data processing/analysis: Collected data is processed and analyzed to derive intelligent performance monitoring outputs.
3. Reporting and Data management: Processed data is presented in the desired reporting format and logged for future reference.

The solar plant monitoring system is classified based on the class of accuracy. It varies with the scale of the power plant and the purpose of end use of the solar power generated. Broad classifications of the monitoring system are given in the following section.

4.1 Classification of monitoring system

According to IEC 61724-1, solar plant monitoring systems have been classified into three accuracy classes. Industrial best practices for adopting monitoring systems of different accuracy class are as follows[2]:

Type of user	Capacity of system	Accuracy class	Monitoring system configuration / Level of monitoring
Residential	Small scale (<10kWp)	C	Separate monitoring systems, like SCADA or web-based monitoring, are not mandatory in case of small residential systems. Inverter level data records, monthly generation meter readings, monthly utility electricity bills (with or without weather data) can be used for plant performance analysis. It is not mandatory to measure the meteorological data at the site. The same can be extracted from a nearby meteorological station, for measuring irradiance and temperature. In case of a separate monitoring system, the following points should be ensured: ● Sampling interval of 1 minute and recording interval of 60 minutes. ● One irradiance sensor (any type), sensor alignment accuracy can be 20 tilt angle and 40 azimuth angle. ● Maintenance of the system needs to be done as per the manufacturer's recommendations. ● One ambient temperature sensor (maximum uncertainty ±10C and measurement resolution ≤0.10C). Maintenance of the sensor should be as per the manufacturer's specifications. ● AC power output (kW) and energy generation (kWh) need to be monitored on a daily and monthly basis.
Commercial / Industrial	Medium scale (<100kWp)	C	Web-based monitoring systems or local monitoring systems should be deployed based on a solar PV plant's capacity. Basic analysis of measured parameters will be conducted such as performance ratio (PR), generation data analysis, etc. It is not mandatory to measure the meteorological data at the site. The same can be extracted from a nearby meteorological station, for the purpose of measuring irradiance and temperature. The following minimum points should be observed: ● Sampling interval of 1 minute and recording interval of 60 minutes. ● One irradiance sensor (any type), sensor alignment accuracy can be 20 tilt angle and 40 azimuth angle. Maintenance of the system needs to be done as per the manufacturer's recommendations. ● One ambient sensor (maximum uncertainty ±10C and measurement resolution ≤0.10C). Maintenance of the sensor should be as the per manufacturer's specifications. ● AC power output (kW) and energy generation (kWh) need to be monitored on a daily and monthly basis.

Type of user	Capacity of system	Accuracy class	Monitoring system configuration / Level of monitoring
Commercial/ Industrial/ small utility power plants	Medium scale (<10,000 kWp) Or few hundred kWp	B	Web-based monitoring systems or local monitoring systems should be deployed based on a solar PV plant's capacity. It is not mandatory to measure the details on-site, local meteorological data can also used for measuring irradiance and temperature. The following minimum points should be adhered to: ● Sampling interval of 1 minute and recording interval of 15 minutes. ● Two irradiance sensors to measure in-plane irradiance and GHI can be either thermopile pyranometer (uncertainty ≤8% for hourly total) or PV reference device (uncertainty ≤8% and measurement range from 100 to 1500W/m2). ● Irradiance sensor alignment accuracy can be 1.50 tilt angle and 30 azimuth angle. ● Irradiance sensor recalibration needs to be done within a 2 year span. ● Irradiance sensor cleaning needs to be carried out as per the scheduled maintenance practices or local environmental conditions. ● 2 to 6 numbers of module temperature sensors (uncertainty ≤20C), depending on the size of the system. Recalibration of the sensor should be as per the manufacturer's specifications. ● Ambient temperature sensor (maximum uncertainty ±10C and measurement resolution ≤0.10C), quantity one. Recalibration of the sensor should be done as per the manufacturer's specifications. ● Wind speed sensor - Maintenance of the sensor should be as per the manufacturer's specifications. ● Rainfall Measurement ● Minimum electrical parameters to be monitored - Output voltage AC (Vout) (V), Output current AC (Iout) (A), Output power AC (Pout) (kW, kVA, kVAr), Output Energy (Eout) (kWh), power factor(pf)
Utility scale - commercial	Large scale (>5 MWp)	A	Web-based monitoring system or local monitoring system should be deployed. It is mandatory to measure the local meteorological data. All monitoring data should be real-time and site specific. Minimum monitoring requirements are as follows: ● Sampling interval of max. 3 sec for irradiance, temperature, wind and electrical parameters, etc. ● Sampling interval of 1 minute for other environmental parameters. ● Recording interval can be 1 minute. ● Irradiance sensors to measure in-plane irradiance and GHI can be either thermopile pyranometer (uncertainty ≤3% for hourly total) or PV reference device (uncertainty ≤3% and measurement range from 100 to 1500 W/m2).

Type of user	Capacity of system	Accuracy class	Monitoring system configuration / Level of monitoring
			• The number of irradiance sensors can be 1 for <5MW, 2 for <40 MW, 3 for <100 MW and one extra sensor needs to be added for each 100 MW capacity addition. • Irradiance sensor alignment accuracy can be 10 tilt angle and 20 azimuth angle. • Irradiance sensor recalibration needs to be done each year. • Irradiance sensor cleaning needs to be carried out every week (visual inspection of sensor on alternate days is required to avoid data loss due to special conditions like bird droppings, shadows due to dry leaves, etc.). • Module temperature sensors (uncertainty ≤20C) depend on the size of the system. Recalibration of the sensor needs to be done within a 2 year span. • The number of module temperature sensors can be 6 for <5 MW, 12 for <40 MW, 18 for <100 MW and an extra 6 sensors need to be added for each 100 MW capacity addition. • Ambient sensor (maximum uncertainty ±10C and measurement resolution ≤0.10C), quantity one. Re-calibration of the sensor needs to be done within a 2 year span. • Wind speed and direction sensor - Maintenance of the sensor should be carried out as per the manufacturer's specifications. • Soiling ratio calculation set-up is desired at the site if the expected soil loss is >2%. • Rainfall measurement • Minimum electrical parameters to be monitored are discussed under plant operational data acquisition (Annexure V).

4.2 Data acquisition system

Data acquisition/collection is a vital part of the monitoring process. Selection of monitoring systems needs to be completed during the design stage itself. The accuracy level, interval of data collection, shall be as per IEC 61724-1, discussed in Chapter 4.1 above. Primarily, three categories of data are collected from a solar plant: 1) weather data acquisition: 2) plant's operational data: 3) solar plant maintenance-related data acquisition. Depending on the plant's capacity and its type of use, the data acquisition system and its accuracy and parameters of data to be acquired, varies.

4.2.1 Weather data acquisition

As per IEC 61724-1, the following weather and environmental parameters need to be monitored in a solar power plant:

a) Irradiance

b) Temperature

c) Wind speed and direction

d) Humidity

e) Soiling ratio

a) Irradiance measurement:

Irradiance is the amount of light energy hitting a square meter of surface per second[1]. Irradiance received by a solar plant varies from time to time and so does the output of the plant. The amount of radiation reaching the earth's surface will fluctuate depending upon the location, terrain, climatic and local environmental parameters. In order to optimize the light energy falling on the surface of a PV module, it needs to be kept facing south and tilted at an angle close to the latitude of that location. Hence, irradiance has to be measured at the same tilt angle as that of the plane of array (PoA).

The solar radiation incident on a horizontal surface is called the global horizontal irradiance (GHI). GHI is the sum of direct normal irradiance (DNI), diffuse horizontal irradiance, and ground-reflected radiation, as shown below:

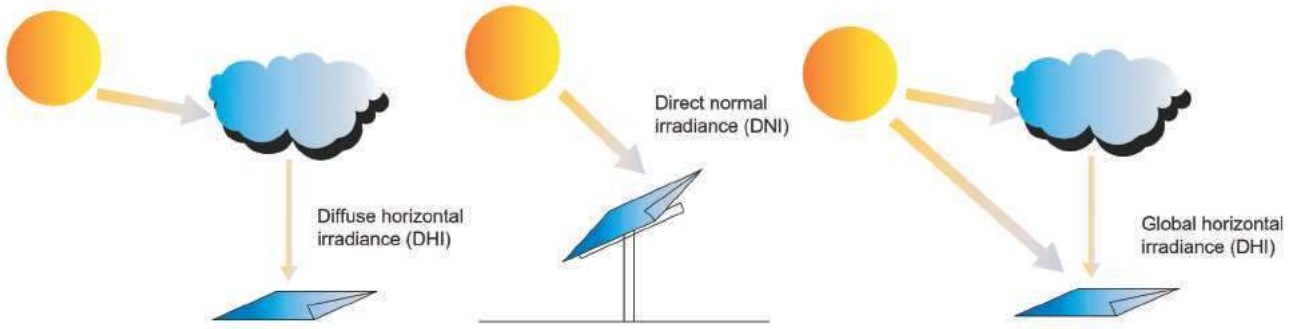


Figure 4.1: Diffuse horizontal, direct normal and global horizontal irradiance

For measurement of irradiance, primarily, a thermopile pyranometer or PV reference cell is used. A pyranometer is used to measure the global solar radiation with a solid angle of 2π on a flat surface. This has high accuracy compared to a PV reference cell.

The PV cell used in the PV reference device for irradiance measurement will have the same characteristics as the PV module as it uses the same type of PV solar cell. Shortcomings in temperature, spectrum and degradation of PV reference cells lead to error and hence are not recommended for high accuracy class monitoring. A PV reference cell should conform to IEC 60904-2, IEC 60904-10 (short circuit current versus irradiance linearity requirements), and IEC 60904-3. PV reference device calibration should be performed with respect to the reference spectrum provided in IEC 60904-3.

It is recommended to install these sensors in a shadow free area, at a tilt angle and orientation similar to that of the PV modules. For multiple tilt and orientation, multiple sensors should be installed to measure irradiance for the representative area acquired by PV modules. Figure 4.2 shows the thermopile pyranometer and PV reference cell used for irradiance measurement.

Thermopile pyranometer

PV reference device

Figure 4.2: Photograph of thermopile pyranometer and PV reference device

b) Temperature measurement

For the same amount of irradiance, the power generated from solar PV module varies with change in temperature. Hence, along with irradiance measurement, temperature measurement is also required. In order to analyse the power output from the PV module, ambient temperature and PV module temperature measurements need to be carried out separately.

For measuring the module temperature, a sensor is affixed to the back of one or more modules. Location of the sensor should be at the centre of the module. It is recommended to conduct thermal imaging of the rear of the solar module to avoid affixing the sensor at a hotspot area. Adhesive material used to affix the sensor, should be able to withstand

outdoor weather conditions and be compatible with the surface material on the rear of the module. As per IEC 61724-1, the total thermal conductance of the adhesive or interface layer should be 500 W/m^2/K or greater.

Figure 4.3: PV module temperature sensor

Figure 4.4: Ambient temperature sensor

For measuring the ambient temperature, the sensor should be installed at a location which represents the array conditions. An ambient temperature sensor should be installed under a solar radiation shield to avoid direct sun radiation and should be ventilated to permit free passage of ambient air. Figures 4.3 and 4.4 shows PV module and ambient temperature sensors.

c) Wind speed and direction measurement

Wind speed and direction do not have any direct relation with the power output from the solar PV module. Wind speed causes soil deposition on the PV modules and also has some impact on ambient air temperature. Though the wind speed and direction measured at the site are not used for solar power output simulation, this information is required for processing insurance claims for damage incurred during extreme event conditions. An anemometer is used to measure wind speed and should have sensor uncertainty of ≤0.5m/s for wind speeds of ≤5m/s, and reading ≤10% for wind speeds greater than 5m/s. The wind vane for recording wind direction and the anemometer for recording wind speed should be installed within the plant's area, at a height, clear of all obstacles. The anemometer and wind vane used in a solar plant are shown in Figure 4.5.

d) Humidity measurement

Relative humidity data along with temperature data is used for calculating hours of wetness due to condensation. Further, relative humidity (RH) can also be used for analysing the effects of humidity and solar radiation on a solar PV power plant's output. A humidity sensor is shown in Figure 4.6.

Figure 4.5: Anemometer and wind vane

Figure 4.6: Humidity Sensor

e) Soiling ratio measurement sensor

The soiling ratio is the ratio of actual power generated by a PV module/array under soiled conditions vis a vis actual power generated by a clean PV module/array. Soiling can be due to dust accumulation, bird droppings, or anything sticking on the PV module surface which prevents irradiance reaching the PV cell. This sensor is used for determining power loss due to soiling and ascertaining the frequency of PV module cleaning. A soiling measurement sensor is shown in Figure 4.7.

Figure 4.7: Soiling ratio monitoring sensor/system (Source: DustIQ Soiling Measurement, Kipp & Zonen B.V)

4.2.2 Plant's operational data acquisition

Real-time plant operation data is collected primarily at three levels: 1) at array junction box level; 2) at inverter level; 3) at AC distribution board level/plant outgoing power measurement level.

The diagram of a solar PV plant's operational data acquisition points is given below in Figure 4.8.

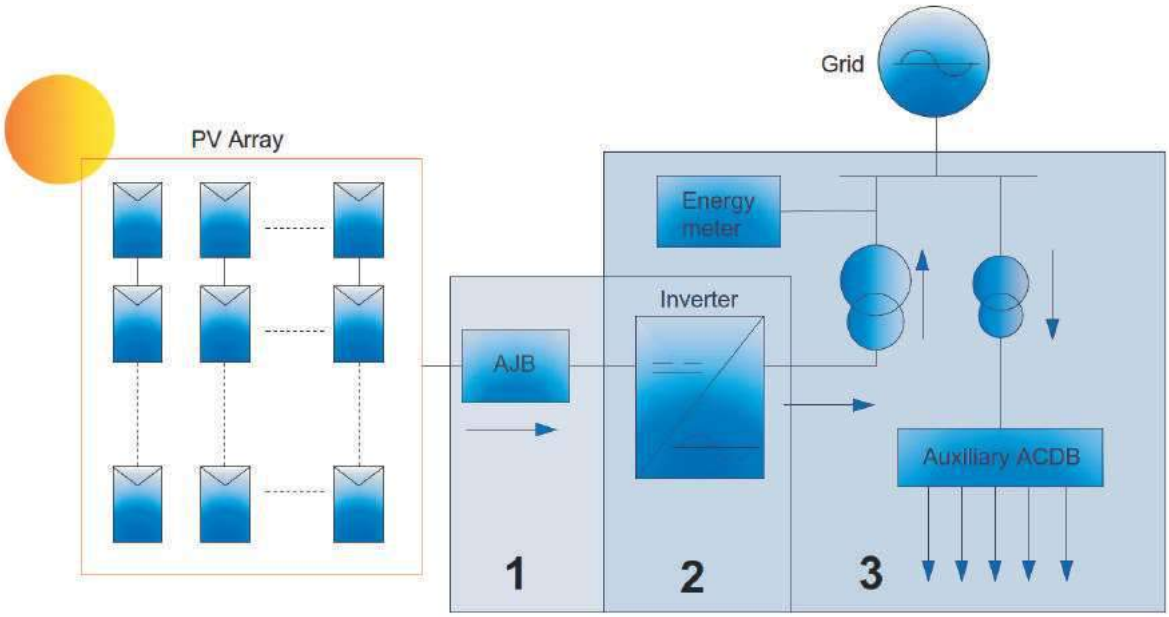


Figure 4.8: Solar PV plant's operational data acquisition points

The solar PV plant's operational parameters are measured at three distinct points and the purpose of these measurements is as follows:

Parameters	Purpose of measurement
1. Array level measurement ● Array voltage DC (V_{array}) (V) ● Array current DC (I_{array}) (A) ● Array power DC (P_{array}) (W)	● String level power monitoring, fault identification. ● Measurement taken using AJBs with string level monitoring. ● Commonly used in utility scale power plants with central inverters. ● Fault identification is easy for wide spread utility scale power plants having string level monitoring.
2. Inverter level measurement ● Inverter MPPT voltage DC (VMPPT) (V) ● Inverter MPPT current DC	● DC measurement is used for calculating DC losses, fault identification. ● AC and DC parameters can be used to calculate the system's performance. ● Power factor, frequency, active/reactive power output,

(IMPPT) (A) ● Inverter MPPT power DC (PMPPT) (W) ● Output voltage AC (Vout) (V) ● Output current AC (Iout) (A) ● Output power AC (Pout) (kW, kVA, kVAr) ● Output Energy (Eout) (kWh) ● Power factor ● Frequency (Hz) ● Temperature	voltage, etc., are measured to monitor power quality related compliance. ● Inverter level monitoring is used to record instantaneous and cumulative generation.
3. ACDB/Grid-level measurement ● Grid voltage (Vgrid) (V) ● Power factor ● Frequency (Hz) ● Energy total (Eout) (kWh, kVAh, kVARh)	● Instantaneous/cumulative power injection for monitoring total plant generation or export to grid. ● To check grid electrical parameters. ● Energy recording for backup measurement of energy meter. ● Events' logs (grid failures, plant start/stop time, overvoltage, extreme/fault events etc.

4.2.3 Solar plant maintenance-related data acquisition

Data related to events of faults and rectification, time consumed for maintenance/fault rectification, power loss, measures undertaken for fault rectification, etc., are acquired manually. Log books should be maintained to record such events. This data is used to calculate O&M-related KPIs. Apart from this, some visual observations are recorded for effective O&M of the plant.

4.3 Data communication system

The real-time data collected through different sensors and equipment is transferred via a secured communications network to a central location for processing, monitoring and display. Three kinds of data communication systems are briefly explained here: wired, wireless, and power line communication systems [3],[4]. For a power plant of more than 1 MW capacity, it is advisable to have a local (LAN) monitoring arrangement (accuracy class A, B, or C).

a) **Wired communication:** Coaxial and fiber optics cables are used for wired communication systems. Coaxial cables have low resistance, low error rate and a good data transmission rate of 10 Gbps. The electro-magnetic interference on a coaxial cable is very low. The main limitations of coaxial cables are distance coverage range and deployment [3]. Error rate and delay in communications are found to be high in large power plant monitoring systems using coaxial cables and, hence, fibre optic cables are preferable. These cables can be used for long distances and they offer high data transmission rates from 100 Mbps to 200 Mbps [3]. However, it is an expensive solution and so penetration of fibre optics in the solar industry is low compared to coaxial cables.

b) **Wireless communications:** Satellite-based data communications is one of the wireless communication systems used in the solar industry. Since satellite-based communication is slow and expensive, it is not used extensively [5].
GSM-based data transmission allows high speed and large volumes of data to be transmitted and presents low retransmission and low data loss rates. Most inverter manufacturers provide data hosting and analysis services with a GSM-based data transmission system which is more suitable for small and medium scale solar power plants with accuracy class B and C (web monitoring).

Radio frequency data communications allows the sending and receiving of information at a low cost. It is a good alternative in areas where telecom network is not available. However, it is difficult to implement because of its cost and permissions required for transmission frequency.

Wireless Local Area Networking (WLAN) and File Transfer Protocol (FTP) are widely used in distributed rooftop power plants (which have restrictions of cable laying) and in large utility scale power plants. WLAN covers large areas; is flexible in data transmission and can communicate despite future obstructions that may interfere with communication. Since it has of low bandwidth, inference causes low quality service. Wi-Fi is most commonly

used in this type of monitoring system, however, Zigbee devices are getting more acceptance nowadays because of their low cost and low energy consumption[3], [6],[7], [8].

4.4 Data processing/analysis

The ultimate aim of monitoring of a solar power plant is to analyze the performance of the power plant and take corrective action, if required. Data processing/analysis is a step that carries out the analysis of the data collected (in the data acquisition stage) and uses the results to help decide if preventive/corrective action needs to be taken. All collected data must have a direct or indirect bearing on the power plant's performance and should be categorized as direct and indirect parameters.

4.4.1 Analysis of direct parameters

Depth of analysis will vary according to the capacity and class of accuracy. The analyses of direct parameters for different scales of SPV power plants are as follows:

A. Residential (without monitoring system)	**Small scale (<10 kWp)**
This category of power plant can implement surface level analysis using manually collected data from system level parameters. Small power plants, with no separate data logging facilities, can follow this method. If any deviation from the expected key performance indicators (KPIs) is found during the analysis, corrective action can be taken. Since continuous monitoring is not financially feasible, this type of monitoring is usually charted along with scheduled maintenance activities. **Minimum analysis**: Statistical analysis of present generation data and past data with theoretical estimates. **Involvement and span of monitoring**: Usually a power plant owner will be involved in this activity. Daily/weekly generation data logging is needed for statistical analysis.	
B. Residential (Class C)	**Small scale (<10 kWp)**
If the power plant owner is selecting 'accuracy class C' as per IEC 61724-1, all the parameters mentioned in Chapter 4.1 need to be monitored. As per current industrial practices, cloud-based web monitoring systems are widely used where inverter level data is collected and presented on the inverter/third party service provider's website. Power plant owners can log into the account and monitor the data. Most services providers offer the facility to connect multiple inverters to a single account. By using real-time analysis, power plant owners can analyze the operations and performance of a power plant. **Minimum analysis**: Statistical analysis of present generation data and past data. **Involvement and span of monitoring**: Web-based inverter level monitoring facility will facilitate the plant owner in examining the operations and performance of the plant during its lifetime. The system should generate intelligent outputs/displays, extreme event logs, and should send alerts to the operator/owner.	
C. Commercial/Industrial (Class C)	**Medium scale (<100 kWp)**
Details under Section B above can be followed.	
D. Commercial/Industrial/small utility power plants (Class B)	**Medium scale (<10,000 kWp)**
Usually, local or web-based monitoring systems will be installed under this category of power plants. The monitoring system should have the facility to export detailed, recorded data (sampling as per IEC 61724-1) in '.csv' or any other format which supports the analysis. Both manual and software-based analysis can be performed. Power generation analysis can be done by monitoring the PR and generation data together, and in case of any irregularities after comparison with the previous month's/year's data, a further analysis of operational parameters should be conducted for any fault or maintenance issues. All manually recorded data needs to be entered on a monitoring portal for generation of required KPIs. Graphical display of information/analysis on dashboard will facilitate easy understanding and communication of analyzed results. EPC contractor, consultant, or O&M contractor need to be part of the monitoring system's installation and must know the program's architecture. This is required for any site specific customization in analysis methodology and calculation. A monitoring system's service provider may have default programmes which need to be checked thoroughly and updated by the EPC, project consultant, or O&M contractor (before starting the O&M contract), as and when required.	

Minimum analysis: Performance ratio (PR), instantaneous and cumulative generation/CUF, instantaneous parameters, fault status and alerts, downtime/uptime, KPI's etc. **Involvement and span of monitoring**: The web-based inverter level monitoring facility will enable the plant owner to monitor the operations and performance of the plant over its lifetime. The system should generate intelligent outputs/displays, extreme event logs and should send alerts to the operator/owner.	
E. Utility scale- Commercial (Class A)	**Large scale (>5 MWp)**
Details under Section D above can be followed. It is suggested to divide the power plant into suitable capacity blocks during the initial stage so that fault identification and performance monitoring will be easy.	

4.4.2 Analysis of indirect parameters

Generally, indirect parameters are not considered for data acquisition and analysis. However, for the proper monitoring of a power plant, it is recommended to consider this as well. Parameters to be monitored may vary according to site conditions (plant activities are termed indirect parameters).

It is not necessary to monitor the indirect parameters for all power plants. However, in large scale power plants having monitoring accuracy Class B and above, monitoring of indirect parameters is recommended. These parameters are required for verifying performance irregularities in a power plant's operations. Some examples are give bellow:

- A PV module's performance may be affected by the quality of water used for cleaning. It is desirable to record and verify the quality of water used and the same should be checked against the PV module manufacturer's recommendations. This parameter should be verified for each month/season, as water quality differs in the monsoon and extreme summers. Proper documentation will help to undertake predictive maintenance/actions and allow comparison with past generation data vis a vis water quality.
- For ground-mounted utility scale power plants, vegetation and water-logging may lead to ground faults, shadow issues, etc. By including these parameters in the check list, an O&M team can schedule maintenance activities as per the needs. Also during extreme summer, low soil moisture may lead to increase in soil resistivity.

4.5 Data reporting and management

Apart from the owner and the owner's O&M team, other stakeholders like the O&M contractor and the asset manager should have access to meta data and processed data of the plant in accordance with their role and involvement. Temporary access may be granted to stakeholders during due diligence phases or as per their involvement. The role of different stakeholders, as per the power plant's capacity, can be as follows:

Monitoring by	O&M by	Reporting to	Plant category
EPC Contractor	EPC Contractor	Asset owner	>1 MW utility scale / large scale rooftop plants.
EPC Contractor	O&M Contractor	Asset owner/EPC Contractor	>1 MW utility scale / large scale rooftop plants.
Monitoring Contractor	EPC Contractor	Asset owner	>1 MW utility scale / large scale rooftop plants.
Monitoring Contractor	O&M Contractor	Asset owner/EPC Contractor	>1 MW utility scale / large scale rooftop plants.
O&M Contractor	O&M Contractor	Asset owner/EPC Contractor	>1 MW utility scale / large scale rooftop plants.
O&M Contractor	Asset owner	Asset owner/EPC Contractor	Large scale rooftop or small or medium scale plants.
EPC Contractor	Asset owner	Asset owner/EPC Contractor	Large scale rooftop or small or medium scale plants.
Monitoring Contractor	Asset owner	Asset owner/EPC Contractor	Large scale rooftop or small or medium scale plants.
Asset owner	Asset owner	Asset owner	Small or medium scale plants.

Whoever has direct access to the meta data collected from site, they should have full responsibility to protect and preserve the data along with processed results. In case the power plant monitoring system has a remote plant control facility, the service provider should look after the cyber security of the plant. It is the asset owner's responsibility to ensure that no unauthorised person is permitted remote access to the inverter.

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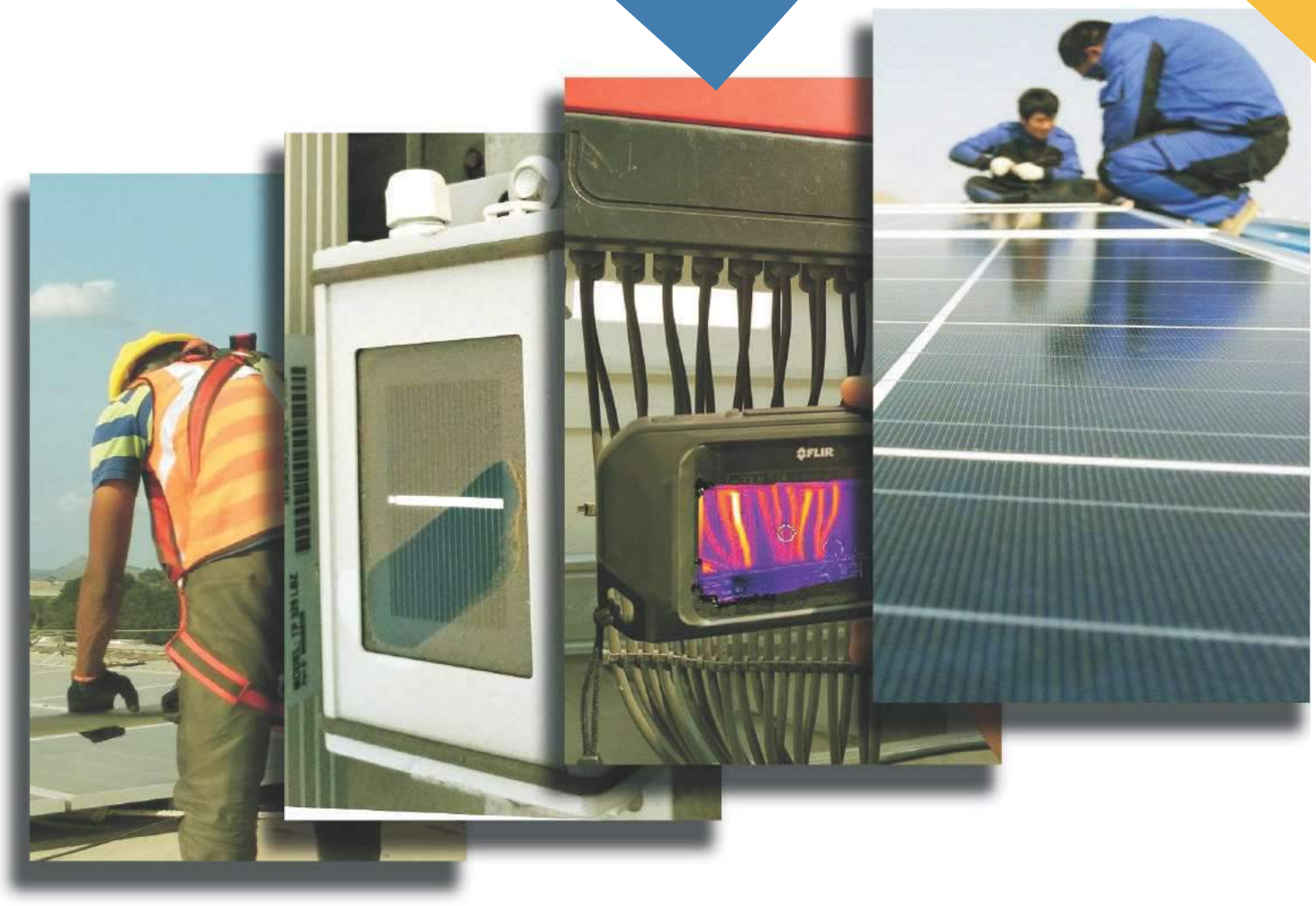
Chapter 5

Operations of Solar PV Power Plants



Operations of Solar PV Power Plants

The operation of a solar PV power plant needs to be strategized well before the start of its operational life, i.e. during its designing, installation and commissioning phases. It is due to the absence of strategic operation planning that some power plants fail to produce the expected results even if they have ensured quality materials and workmanship. This chapter discusses the activities that are required for the effective operations of a solar PV power plant, such as:

- Operational planning during design, installation and commissioning.
- Document management and record keeping.
- Operations and maintenance scheduling.
- Solar PV O&M contract management.
- Regulatory compliance management.
- Insurance management.
- Warranty management.

5.1 Operational planning during design, installation and commissioning

Operational planning should start at the plant design stage. All operational activities including man and material movement for the plant's operation need to be envisaged and the plant's layout, spacing, control room position, location of water supply taps and their control, drainage, storage, etc., need to be planned accordingly. Further, most operational problems can be minimized by ensuring adequate material and workmanship quality which can be done by adopting a Quality Assurance Plan (QAP). Such a plan and its compliance monitoring report should be available with the operations team for their easy reference. It is not possible to have records of all QAP related documents for all plant capacities and hence documents may vary based on a plant's capacity, customer requirements, etc.

A sample QAP document is given in Annexure VI for ready reference and can be used by suitably modifying it as per plant capacity and customer requirements. However, the QAP document should contain the following minimum points relating to quality of material and workmanship for the efficient and effective operations of the solar PV power plant.

- Verification of PV module make, model, rating with respect to design, quality checks for routine test reports, type test reports, interconnecting cable rating and length, manufacturing year, physical inspection (broken glass, frame etc) should be undertaken.
- The orientation, tilt angle, placement of MMS, inter-row spacing, etc., need to be verified with reference to the design.
- Installation of the PV module onto the module mounting structure (MMS) - physical separation between PV modules, connecting clips and its torque, etc., need to follow specifications.
- Specifications regarding DC/AC/data cables, connectors, lugs (size and type), rating, etc., should be verified.
- MMS foundation integrity (flat roof or ground-mounted), galvanizing, etc., need to be verified as per design.
- Proper routing of cables, bending radius, cable conduits/cable trays, demarcation with proper ferule, etc., should be as per specifications.
- Adequate cable protection and cable spacing should be used within the trenches as designed.
- Ensure that the cable conduit is properly installed and glued wherever required and openings are sealed.
- All international test certificates, and factory test certificates of PV module, inverters, cables, ACDB, MMS (as applicable) should be verified.
- Ensure and check the safety measures to be followed during the installation and commissioning process in addition to ensuring the qualifications, expertise and health of the staff deployed for executing the job. Clear description of job responsibilities and supervision by safety and technical supervisors, etc., need to be followed.
- All material movements should be carried out with the help of proper machinery, and the site manager is responsible to ensure that machine operators are qualified for the job.
- Site material storage and record, scrap storage and disposal should be handled efficiently.
- Proper safety signage and labels needed to be used at the site during the installation should be in place.
- Ensure the display of sign boards, labels, instructions, etc., as per safety requirements.
- Inverter numbering, string identification ferules, string labeling should be as per approved SLD.
- Any changes or deviation in installation from the approved SLD and layout should be reflected in the final document, preserved for O&M records.
- Output termination should be as per approved drawings and the equipment manufacturer's guidelines.

Monitoring of the installation process can be carried out by the owner's engineer, third party appointed by asset owner or by an EPC company. Plant owner or EPC service provider can modify the QAP document based on site conditions, plant capacity and requirements.

5.2 Document management and record keeping

Document management and record keeping is an important activity for ensuring the availability of all technical information, specifications, operating procedures, including the plant's O&M history, etc., to the plant O&M team, service providers, vendors, FI's, govt. agencies, etc. Proper documentation will help the plant's operation team to ensure smooth O&M and monitor the performance of the solar power plant. Following are the main objectives of document management and record keeping:

- For ready reference regarding technical details of the power plant during its operation.
- To track any changes or component replacement made in the power plant.
- To track the warranty of system components.
- To track calibration requirements of meters and sensors.
- To track availability of spares, consumables, PPEs, instruments, tools and tackles, etc.
- Documentation of O&M activities will enable comparison of performance changes in terms of O&M.
- Documentation on performance and KPI evaluation will allow analysis of the power plant's operation.
- For enabling the smooth transition from one O&M contractor to another.

The following four categories of records need to be maintained in a solar PV power plant:

A. PV power plant installation records

The PV power plant's installation records should give an overview of all systems and components integrated into the power plant. These records include as-built drawings, datasheets, design considerations, plant planning, procurement, installation stage details, pre-commissioning and post-commissioning test records, QAP compliance, etc. It is also recommended to include all design changes carried out during the installation process, updated documents to be recorded for future reference by the O&M team, as well as the changes made in the drawing and design documents before preparation of as-built documents. The EPC team should hand over the solar PV plant installation records along with the following plant O&M related documents and records to the solar PV plant O&M team/asset owner. These are:

- Site specific O&M manual: The installation team/EPC company involved in installation of the solar PV power plant need to prepare a site specific O&M manual and hand over the same to the O&M team.
- Reporting formats: All O&M related checklists, operating procedures, periodic inspections and maintenance activities, reporting formats (Annexure VII) etc., should be handed over.
- O&M activity charts and performance monitoring plans should also be given to the O&M team.

B. Performance analysis and O&M records

These documents need to be updated during the O&M of the solar PV power plant. The following O&M related documents need to be updated and recorded by the O&M team for future reference and monitoring of the plant by the asset owner, FI, govt. agencies, etc.

- Power generation and monitoring details.
- O&M activity records which include preventive maintenance, corrective maintenance, etc.
- Details and inventory of spare parts, consumables, O&M tools, components, instruments, etc.
- KPI evaluation records and corrective action taken.
- Component replacements and their procurement details.
- Scrap management details.
- Updated as-built drawings.

C. Plant components warranty and calibration records

Warranty terms and conditions, insurances, their validity, etc., need proper documentation as it will help the O&M team keep track of the same and avoid any significant losses. The documents include:

- Main components' warranty certificates.
- Calibration details of all meters and sensors.
- EHS tools and PPEs warranty.
- Insurance papers.

D. Plant's general management records

The plant's general management records include the following documents:

- Management documents related to the O&M team, HR documents.
- O&M contract records.
- Utility bills and payments.
- Statutory fees/charges/duties/tax payments and compliance fees.
- Govt. inspection records/permission records.
- Relevant commercial bills, invoices of materials/consumables, etc.
- Visitor's register, inward/outward records, time sheet, muster, etc.

All documents can be recorded either by electronic copy or physically, as per site conditions and suitability. Only authorized persons should have access to documents/records. Some of the points to be considered while planning documentation are given in Annexure VIII.

5.3 Operations and maintenance scheduling

Scheduling of a solar PV plant's O&M is dependent on the plant's performance analysis, information generated from the monitoring system, etc. Solar O&M activities can be divided under two headings: preventive and corrective maintenance activities.

Preventive maintenance (PM): Preventive maintenance involves activities which protect the power plant from significant power losses/breakdowns. This type of maintenance involves analysis of observations from scheduled maintenance activities. It is basically the performance analysis of the power plant as per the O&M contractual terms and conditions (if any).

Corrective maintenance (CM): Corrective maintenance involves activities that need to be performed after power plant or component failure, or significant power loss, for restoration of power plant. Observations made during the monitoring and scheduled maintenance (SM) activity pertaining to failure of the power plant or plant component(s) which result in significant power loss need corrective maintenance (CM). Corrective maintenance is mainly performed in the following manner:

- Fault observation: to locate or identify the fault.
- Isolation and temporary repair: Preliminary repair to restore the system temporarily, though permanent repairs need to be done later. The identified fault location or component should be isolated in case the fault has potential to create a safety issue.
- Repair: for resolving the fault permanently.

O&M scheduling include planning of O&M activities (Chapter 7) and checks to be performed at predetermined intervals. These activities need to be performed in order to identify any shortfall in the plant's operation during a specified time span. The maintenance frequency will vary for each component/activity, e.g. PV string voltage current checks for utility scale power plants needs to be performed every week, but MMS torque checks need to be done once a year for ground-mounted plants and within 6 to 8 months for rooftop power plants. The process of O&M scheduling depends on a number of factors, such as:

- Type and capacity of power plant: Utility scale power plants need frequent O&M activities compared to small scale power plants.
- O&M team: Asset owner, O&M contractor.
- O&M agreement terms and conditions.
- Financial feasibility: Depending on the O&M resource availability, scheduling may change. e.g, schedule of PV modules' cleaning may need to be changed depending on water availability.
- Monitoring arrangement: As per the accuracy class (Chapter 4), the monitoring of a power plant will change followed by the O&M schedule.

Detailed O&M scheduling procedure as per the above listed points has been described in Chapter 7.

5.4 Solar PV O&M contract management

A solar PV plant has different O&M strategies according to the factors mentioned above. O&M contracts and contract management varies with the type and capacity of the solar PV power plant, as well as the number of contracts/parties involved. Table 5.1 explains this:

Table 5.1: Industrial practices in O&M as per solar power plant capacity

Type of user	Capacity of system	Industrial practices in O&M
Residential	Small scale (<10 kWp)	● Cleaning of PV strings will be done by the asset owner/third party appointed by the asset owner. ● EPC contractor/equipment supplier may give 1-5 years operational O&M warranty.
Commercial	Medium scale (<100 kWp)	● Cleaning of PV strings will be performed by the asset owner/third party appointed by asset owner. ● EPC contractor/equipment supplier may give 1-5 years operational O&M warranty (sometimes includes cleaning), or ● Complete O&M solution will be carried out by a third party from the time of commissioning.
Industrial	Medium scale (<10,000 kWp) Or a few hundred kWp	● Cleaning of PV strings will be done by the asset owner/third party appointed by him. ● EPC contractor/equipment supplier may give 1-5 years operational O&M warranty (sometimes includes cleaning), or ● Complete O&M solution will be performed by a third party from the time of commissioning
Utility scale-commercial	Large scale (>1 MWp)	● EPC contractor/equipment supplier may give 1-5 years operational O&M warranty, or ● Complete O&M solution will be performed by a third party from the time of commissioning.

Note: In case a power plant is operated under BOOT model, O&M will be under the scope of the company owning the power plant. O&M can be executed either by a third party or by the RESCO company.

In the case of a solar PV power plant being operated by a third party, it is recommended to execute a contract between the asset owner and O&M service provider. Scope of work will vary according to the asset owner's requirement. With increased plant capacity, O&M requirements including scheduled maintenance, troubleshooting, predictive analysis, corrective actions, etc., will become more complex.

Any operational mismanagement during the O&M period will not affect the plant's performance immediately. For example, a technician walking on the PV modules may create micro-cracks on PV cells, so even-though there is no immediate effect on the plant's performance the event may lead to significant damage/module failure in future. Therefore, it is recommended to ensure that the O&M contractor is following standard operating procedures/instructions as per best practices.

Considering that the expected operational life of a PV power plant is 25 years, there will be multiple changes in the O&M team and contracts. Usually during the initial few years (initial 5 years), the O&M activities are performed by an EPC contractor or third party appointed by the EPC contractor/asset owner. A new independent O&M service provider may come into the picture after the completion of 5 years of the initial O&M contract.

Points to be considered while preparing terms and conditions (T&C) of O&M contracts are as follows:

- O&M activity should include scope of PV module cleaning, water quantity and quality requirement.
- PV module cleaning schedule updation methodology.
- Methodology for documentation.
- KPIs and its calculation methodology: KPIs should take into consideration the degradation of components and the same should be updated as and when required.
- Downtime or uptime calculation methodology (if it is included in KPI), and exclusions in downtime (e.g., grid availability, factory shutdown, etc.).

- Reporting formats and their schedule.
- Power plant monitoring data security and storage of data (non-disclosure agreement can be included as part of the O&M agreement).
- Scope of meter and sensor calibration.
- Warranty terms (with EPC contractor and OEMs).
- Power plant performance audit span and entity who will execute the audit (asset owner or O&M service provider).
- Spare parts management.
- O&M team and qualifications, at site (if required).
- Frequency of maintenance activity (if the O&M service provider is not stationed at the site).
- Exclusions in activities by the O&M company.
- Additional support activities by asset owner.
- Asset owner's rules and regulations to be followed by the O&M team at the site (e.g. if the asset owner is a factory and they have certain EHS rules to be followed at the site by their workers, the O&M team working on that factory's premises should also follow the same).
- Commercial: Under-performance penalty clauses, and other commercial T&C.

In case of large power plants, proper O&M transfer procedures from one O&M service provider to another should be spelled out. It is recommended to describe all documents and data management procedures in the O&M contract for smooth transition. The O&M contract's T&C should be a win-win agreement for both parties. Points to be considered are given in a sample O&M contract in Annexure IX.

5.5 Regulatory compliance management

The O&M contractor has to ensure that the solar PV power plant operates within the given limits and complies with local rules and regulations. This is usually applicable in the case of utility scale power plants, where the plant has to comply with all local rules and regulations, like any other industry, and has to maintain the same. The asset owner has to share all required details with the O&M contractor before executing the O&M contract, especially the power purchase agreement (PPA), grid interconnection permissions, short term or long term open access permissions (if any), duties/tax payments, etc. Some of the following points to be considered by an O&M contractor are as follows:

- Liasoning with DICOMs, SLDC, TRANSCO for PPA/open access/grid connectivity/meter testing/ meter calibration, etc.
- Liasoning with electrical inspectorate for taxes/duties on captive generation/safety audits, etc.
- Liasoning with DISCOM/SLDC for grid code compliance, forecasting and scheduling compliance, power quality-voltage regulation, active and reactive power management, harmonics, etc.
- To get local-body clearances before major tree trimming activities, etc. (if any).

5.6 Solar insurance

A solar power plant is subjected to various hazards and risks. Risks, which cannot be mitigated or protected should be insured adequately. Insurance can be taken for the following two phases of project activities:

5.6.1 Insurance during installation & commissioning phases

- **General liability insurance:** This type of insurance covers death or injury to persons, or property damage suffered by a third party. This is extremely important for solar EPC contractor during the installation phase when the risk is high. In such cases, he may require additional liability insurance and premium due to the risks involved in working at heights, etc. Ground-mounted installations may have fewer risks compared to rooftop installations and may therefore have a lower premium.

- **Environmental risk insurance:** This kind of insurance compensates asset owners in the event of any environmental damage caused by their activities or if any pre-existing damage exists at the site. The different types of insurances are listed below:
  - Pollution legal liability policies: This insurance covers the power plant owner from unknown pollution conditions and any harm caused to persons due to that pollution. This doesn't cover long term cleanup efforts but usually takes care of covers business interruption.
  - Cleanup cost cap or stop-loss policies: These cover the cost of continued cleanup efforts and are customized insurance policies.

  As per the site's environmental conditions, the right type of insurance cover needs to be taken by the plant owner.

- **Employers Liability:** Provides cover against workplace accidents such as falls from heights and manual handling injuries.
- **Transit insurance cover:** Provides cover against any loss of goods or loss due to delay in shipment through marine/road transport.

5.6.2 Operations and maintenance phase

- **PV module warranty insurance:** This covers the solar plant owner against performance degradation of PV modules, under-performance due to faulty manufacturing, material defects and material ageing.
- **Property risk insurance:** This insurance provides protection against external hazards like flood, fire, theft, vandalism, sabotage, earthquake, overload, operational mistakes, hail damage, snow load, lightning strikes, water logging and animal bite. The solar owner has to make sure that all possible hazards at the site are covered under this insurance.
- **Business interruption insurance:** Business interruption insurance is often required to protect the cash flow of the solar power plant and covers the operational downtime due to PV module or any other equipment damage. Tax incentives lost due to the project not being built as per deadlines are also covered under this insurance. This is required for third party investors or plants built under the RESCO model, to protect their cash flow.
- **Solar generation shortfall insurance:** This insurance covers losses in generation due to lack of sun cover or solar radiation vis a vis the targeted production. The insurance company compensates for the energy shortfall during a policy year when reported before certain predefined days.

A solar plant O&M contractor, asset owner or representative of the asset owner can manage the required insurance claims and documentation. It is recommended to describe the insurance related responsibilities in the O&M contract itself. In case of large utility scale power plants, asset owners can deploy an insurance expert to analyze the risks at the site and customize the insurance accordingly. All insurance claims and communications need to be properly documented. In case of transition from one O&M contractor to another, it is the asset owner's responsibility to take care of documentation.

5.7 Warranty management

Since the solar power plant is an integration of a number of different components from multiple OEMs, warranty terms will vary. The general arrangement in warranty management can vary based on a plant's capacity and type of consumer, as given in Table 5.2.

Table 5.2: General warranty practices

Type of user	Capacity of system	General warranty practices
Residential	Small scale (<10 kWp)	• Plant component warranty can be enforced through EPC. • EPC contractor usually provides workmanship warranty (usually from 1 to 5 years). • After workmanship warranty period issued by the EPC contractor ends, the plant component warranty can be enforced either through EPC, O&M contractor, or asset owner. • Asset owner may not have direct contact with OEMs. • Component warranty-related information needs to be given to the asset owner before handover of the plant.
Commercial	Medium scale (<100 kWp)	• Plant component warranty can be executed either through the EPC contractor or asset owner. It depends on who procured the component. • EPC contractor usually provides workmanship warranty (usually from 1

		to 5 years). ● All warranty related documents need to meet QAP.
Industrial	Medium scale (<10,000 kWp) or a few hundred kWp	● Plant component warranty can be managed either through the EPC contractor or asset owner. It depends on who procured the component. ● EPC contractor usually provides workmanship warranty (usually from 1 to 5 years) ● Asset owner should have contact details of OEMs. ● All warranty related documents need to meet QAP.
Utility scale-Commercial	Large scale (>1 MWp)	

The main objectives of having a proper warranty management system are as follows:

- To manage and keep track of warranty enforcement processes.
- To reduce downtime of the power plant.
- For documentation of complaints and communication with OEMs.
- Managing warranty renewal activities.
- Analyzing costs incurred during the warranty period.
- To analyze component fault reports from the O&M team and for deciding warranty claims before the fault becomes significant. For example excess temperature inside the inverter may be due to failure of the exhaust fan inside it. The O&M team should inform the OEM for service and replacement of the failed component, because if the situation is allowed to continue for a prolonged period, the excess internal temperature can consequently cause the failure of other major components.
- To ensure that O&M activities do not violate the warranty conditions of the equipment. Some string inverter's OEMs clearly specify that the warranty will be void in case of opening/tampering with the inverter cabinet.

As described above, generally EPC contractors provide a workmanship warranty for the initial 1 to 5 years of the power plant's operation. In case of small scale residential power plants, if any error occurs under this warranty period, the EPC contractor will either repair it or claim warranty from the OEM. In case of medium, large scale or utility scale power plants this works in two ways:

- If the EPC contractor is continuing the O&M, then warranty management will be done as for small scale power plants.
- If any third party agency, other than the EPC contractor, is involved in O&M activity, warranty management will be looked after by the O&M contractor in coordination with the EPC contractor.

Warranty offered by OEMs can be bifurcated into product warranty and performance warranty. Product warranty covers material and workmanship, especially manufacturing defects. In case of PV modules, most OEMs give product warranties between 5 and 12 years. Performance warranty guarantees a certain output within a particular window, and the output may degrade linearly in a predefined fashion, e.g. OEM's of PV modules specify natural degradation in the performance up to 80% of rated capacity at the end of 25 years, as shown in Figure 5.1.

Of all power plant components, PV modules have unique warranty features like 25 year long-term performance and 10 - 12 years product warranty. If the degradation of a PV module is found to be outside the specified level, the asset owner can claim warranty. Currently, all inverter manufacturers are providing 5 to 10 years warranty and apart from this, additional years of warranty are also been offered at an added cost.

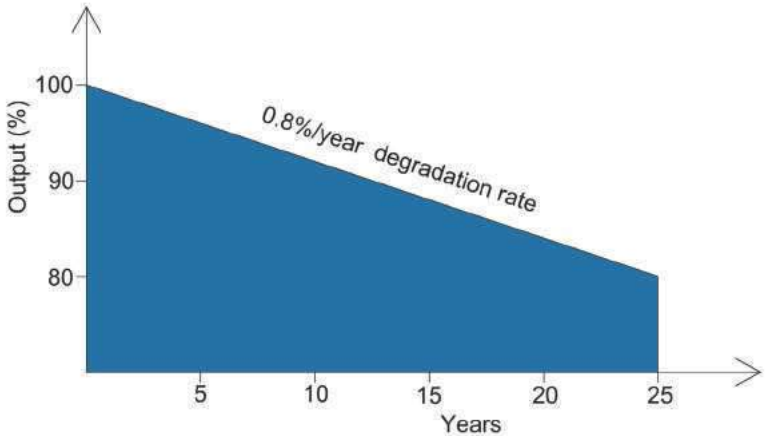


Figure 5.1: PV module degradation over 25 years of performance warranty period

Further, there are certain risks involved with component warranties, such as:

- Warranty may get void under certain predefined circumstances:
  - Mishandling or improper operations: E.g. ARC coating degradation due to use of chemical agents in the water used for cleaning.
  - Accelerated PV module degradation due to even or uneven soiling, shadow, or prolonged mismatch effect.
  - Glass broken due to mishandling, etc.
  - Failure to provide adequate ventilation may void an inverter's warranty.
- OEM going out of business: With increased demand for PV plant components, there are numerous new manufacturers entering the sector. The long warranty periods, increasing liabilities and changing business environment has led to liquidation of reputed manufacturing companies. In such cases it will not be possible to claim the warranty.
- Uncertainty in proving PV module failure: PV module failure has multiple reasons (Chapter 6.6.10), which makes it difficult to prove that the failure is due to issues with the OEM's quality or due to improper O&M. For example micro cracks on PV modules can occur during transportation to the site (which is in the OEM's scope) or during the installation (which is in the EPC contractor's scope) or during O&M (which is in the O&M contractor's scope). Micro-cracks can initiate other PV module failures such as discoloration, delamination, bubbling, etc., which may be due to material quality or micro-cracks. Hence, inability in proving the exact reasons will lead to rejection of warranty claims.
- Uncertainty in testing the failure: In small scale power plants, if one or two PV modules are under-performing and are removed from the string, closing of the entire power plant's operation is likely (in case of non-availability of spares). This prevents the asset owner from testing the panel for identifying the reasons for degradation or under-performance.
- The OEM's warranty might cover replacement, but not labour to remove, ship, transport and re-install an under-performing PV module. Hence, it may not be economically feasible to transport a few PV modules for claiming warranty.
- Difficulty in availing warranty in case of any dispute on imported components.

5.8 Spare parts management

Spare parts management is an important tool which is used for reducing the downtime of a solar power plant. Generalizing spare parts management is difficult in solar power plants because of the wide range of plant capacities, types of O&M contracts and varying requirements of asset owners. By executing a perfect spare parts management system, an O&M company or contractor can control downtime by performing corrective maintenance in a timely manner. Following are the main considerations:

- Type and capacity of power plant.
- Spare parts storage location: Distance from the power plant, environmental conditions.
- Type of O&M contract.

- O&M contractual requirements: Downtime/uptime, response time, rectification time.

As per current industrial practices, spare parts management can be divided into the following types:

On site spare parts management:

In the case of large scale utility power plants, the plant failure rate will be greater than other power plants and if the power plant is down for a few hours it will cost more units or money. Therefore, it is required to perform corrective maintenance without any delay. On-site spare parts management allows the O&M contractor or company to store the required minimum components at the site making them available on hand.

Warehouse based spare parts management:

If the O&M contractor is looking after the projects in profilo level, he can keep the required spare parts in his warehouse or at any plant which is easily accessible from sites under his control. This type of spare parts management is used mainly in case of plants other than utility scale power plants.

EPC contractor controlled spare parts management:

If the O&M is executed by the EPC contractor and if he does not have a specific spare parts management plan, he may utilize surplus project materials as spare parts. This will normally depend on the following points:

- Contractual terms in O&M contract: This is important because the EPC contractor has to give the same importance to the O&M as the power plant under him.
- Downtime or uptime: Downtime-based performance guaranty or KPI will force the contractor to keep the system up and running by providing timely corrective maintenance.

There are certain concerns that need to be addressed while preparing the spare parts management section in an O&M contract, such as:

- Spare parts ownership: Who owns the spare parts and who bills the spare parts?
- Business model for spare parts: If the O&M contractor owns the spare parts and is taking care of site spare parts management, how will the billing for spares be done?
- Storage methodology for spare parts: On-site facility or off-site warehouse.
- Methodology for procuring spare parts outside the minimum spare parts list.
- Downtime of power plant.

Minimum spare parts required at site:

- PV modules: Since the cost component of adding more PV modules to the spare part's list is high, it was observed that only large scale utility power plants keep a certain number of PV modules as standby. O&M contractor/EPC contractor/asset owner should keep a track of the PV module's OEM because if the OEM stops manufacture, it will be difficult to get PV modules of the same specification.
- PV module bypass diode: PV module's bypass diode (normally Schottky diode) as per the specification given by the manufacturer.
- DC connectors: both male and female.
- PV fuses: for AJB, MJB and inverter.
- Fuses: for AC components including ACDB (if any).
- Monitoring system or SCADA communication spares.
- Distilled water for auxiliary inverter's battery (if any).
- Cable ties (plastic or metal), insulation tapes.
- Office stationary items: required for control room or office use.
- Transformer or switchgear spares.
- Spares of measurement devices.
- Battery/cells for measurement devices.

- Safety PPE: Helmets, safety shoes, etc.
- PV module cleaning equipment.

5.9 Human resource management

A confident and knowledgeable O&M team will make O&M activities more effective. An efficient human resource management should make sure that the employees working are satisfied and safe at the work site. Solar PV industry is one of the fastest changing sectors as new technologies and components are coming into the market rapidly. Updation in PV technologies, manufacturing methods, power plant installation methods etc, to avoid known failures may introduce new failure in future. So O&M employees should be knowledgeable about changes in standards, best practices, failure modes, etc. This can be achieved by frequent capacity building of employees. The following points need to be considered while managing O&M team training programs:

- The O&M company shall maintain a training program schedule that includes training identified to be critical to success, including familiarity with basic standards to be followed at site, new technical concepts, etc
- If the O&M company is not able to provide training to all O&M team members, then selected personnel should undergo training. This trained manpower should pass on knowledge internally.

Human resource management needs to ensure workers safety by following the points given below:

- O&M team or company shall perform risk assessment at site before commencing the O&M.
- O&M team should have EHS rules to be followed at site.
- O&M team should be medically fit to work at the site and also undergo periodic health checkups.
- O&M team should wear proper PPEs as per the hazard involved. “No hazard situation or no accident site condition” should be consider a EHS friendly site.

Technical content to be addressed when training to workers as per IEC 63049:2017

O&M engineer / supervisor

- IEC 62446-2: Photovoltaic (PV) systems – Requirements for testing, documentation and maintenance – Part 2: Grid connected PV systems – Maintenance of PV systems.
- IEC 62109: Safety of power converters for use in photovoltaic power systems.
- IEC 62446-1: Photovoltaic (PV) systems – Requirements for testing, documentation and maintenance – Part 1: Grid connected PV systems – Documentation, commissioning tests and inspection.
- IEC TS 61724-2: Photovoltaic system performance – Part 2: Capacity evaluation method.
- IEC TS 61724-3: Photovoltaic system performance – Part 3: Energy evaluation method.
- IEC TS 61836: Solar photovoltaic energy systems – Terms, definitions and symbols.
- ISO 19011:2011, Guidelines for auditing management systems.
- IEC 60364-7-712: Low voltage electrical installation – Part 7-712: Requirements for special installations or locations – Solar photovoltaic (PV) power supply systems, if applicable.

O&M worker

- IEC 62446-2: Photovoltaic (PV) systems – Requirements for testing, documentation and maintenance – Part 2: Grid connected PV systems – Maintenance of PV systems.
- IEC 62109: Safety of power converters for use in photovoltaic power systems.
- IEC 62446-1: Photovoltaic (PV) systems – Requirements for testing, documentation and maintenance – Part 1: Grid connected PV systems –Documentation, commissioning tests and inspection.
- IEC TS 61836: Solar photovoltaic energy systems – Terms, definitions and symbols Tools and test equipment training as required in 5.3.4 .
- IEC 60364-7-712: Low voltage electrical installation – Part 7-712: Requirements for special installations or locations – Solar photovoltaic (PV) power supply systems, if applicable.

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Chapter 6

Performance Evaluation and Key Performance Indicators

Performance Evaluation and Key Performance Indicators

Solar PV power plants are expected to deliver estimated power generation and to ensure that the value of the asset and its longevity are protected.This can be ensured by keeping track of its performance evaluation (PE) and following the best operations and maintenance (O&M) procedures. All solar power plants are intended to perform at certain predicted levels to get the expected benefits from them. However, there are various factors, like design errors, material quality and manufacturing defects, local climatic changes, soiling, O&M issues, etc., which may affect energy generation. These factors may not have been considered during the initial stage of design or they may deviate from the initial considerations leading to under-performance. Hence, regular performance evaluation/ monitoring are required to identify any shortfall in the power plant output. This can be done by keeping track of key performance indicators (KPIs) which can be calculated based on the plant's O&M and techno-commercial data. Different sized power plants will have different monitoring mechanisms and hence, analysis of KPIs will vary with availability of data. Keeping this in mind, stakeholders need to agree on certain KPIs that should be used to analyze the power plant's performance, and the frequency of KPI analysis needs to be mutually agreed upon by the stakeholders.

The first part of this chapter describes various key performance indicators (KPIs) used in the solar industry, and their definition. All power plants should be monitored by following some predefined set points (KPIs), which quantify the performance of the power plant. The second part of this chapter deals with various performance evaluation tests that need to be performed to identify performance shortfall and routine tests that need to be carried out during plant O&M activities.

6.1 Performance evaluation (PE) of a solar PV power plant

Performance evaluation of a solar PV power plant is a continuous process which is required to ensure resource optimization and for keeping track of the expected plant outputs. It starts with monitoring the plant's operational parameters. IEC 61724 describes solar PV performance monitoring which includes measurement details, resolution and frequency of data gathered, and analysis. It also describes how to derive the performance ratio from raw data. Performance evaluation of a SPV power plant varies with scale and mainly depends on the availability of a monitoring system, parameters collected, and their accuracy, etc.

For example, PE required for two 10 kW rooftop power plants with measurement accuracy Class B and C will differ in terms of depth of evaluation. Similar is the case for different capacity power plants. Following are a few factors which decide the PE method required for a solar PV power plant:

- Capacity of the power plant.
- Monitoring accuracy class.
- O&M contractual terms and conditions.
- Key performance indicators.
- PE test boundaries.

The process of the solar power plant's performance evaluation has to start from the AC side and should move to the next lower level as per requirement and issues. Primary performance evaluation compares the actual generation with the theoretical estimation, and in case any reduction is observed a more detailed analysis will be required. Performance evaluation of a solar PV power plant can be done on three levels, as follows:

Portfolio level: This performance evaluation level of solar PV power plants includes generation, PR and KPI monitoring of multiple power plants/assets which are being maintained by a single owner or O&M contractor. This surface level monitoring and evaluation of power plants can be done on a single platform which will enable comparison with the performance of each of them.

Plant level: Here the performance evaluation is done at plant level by the Plant Incharge/O&M Incharge. Apart from generation and PR, various technical parameters are considered for this analysis.

Inverter level: The performance evaluation of all the components next to the inverter which may affect the plant's performance are analyzed in detail. A single power plant may have multiple inverters and the generation of each inverter is compared to identify issues for further analysis of DC components present in the system. Inverter level analysis/performance evaluation is conducted by the O&M team.

Portfolio level and plant level performance evaluation of a solar PV plant is done by analysing different KPIs. While analysing actual generation of a solar plant with the theoretical estimates, the year-on-year deration factor is

considered while setting benchmark/references for generation-related KPIs. Portfolio level and plant level performance evaluation are done based on the availability of data and its accuracy for calculation of required KPIs. Reduction in generation below that of estimates may be due to plant level or inverter level issues which need to be evaluated at a micro level to identify faults and to take necessary corrective action to improve plant performance.

6.2 Solar power plant monitoring parameters

The main step in a SPV power plant's performance evaluation is the monitoring of desired parameters which will be used further to calculate KPIs and performance evaluation. The installed capacity of the SPV power plant can be calculated from cumulative installed DC capacity of the PV module connected. The rating of each string is dependent on the number of solar PV modules connected in series. A typical schematic diagram of a solar PV power plant with monitoring parameters is shown in Figure 6.1. Evaluation of a SPV power plant can be done on the basis of cumulative power generation at the point of injection/interconnection to the utility grid. In case the actual generation is less than the estimation, further detailed analysis of power loss needs to be undertaken. For that, solar power generation at module level, string level, inverter level, need to be verified based on the expected values. The expected power generation, voltage and current from the PV module depend on the rating of the individual module and irradiance (kW/m^2) at that point of time. Rated parameters of the PV module can be known from the datasheet/nameplate attached on the rear side of the module.

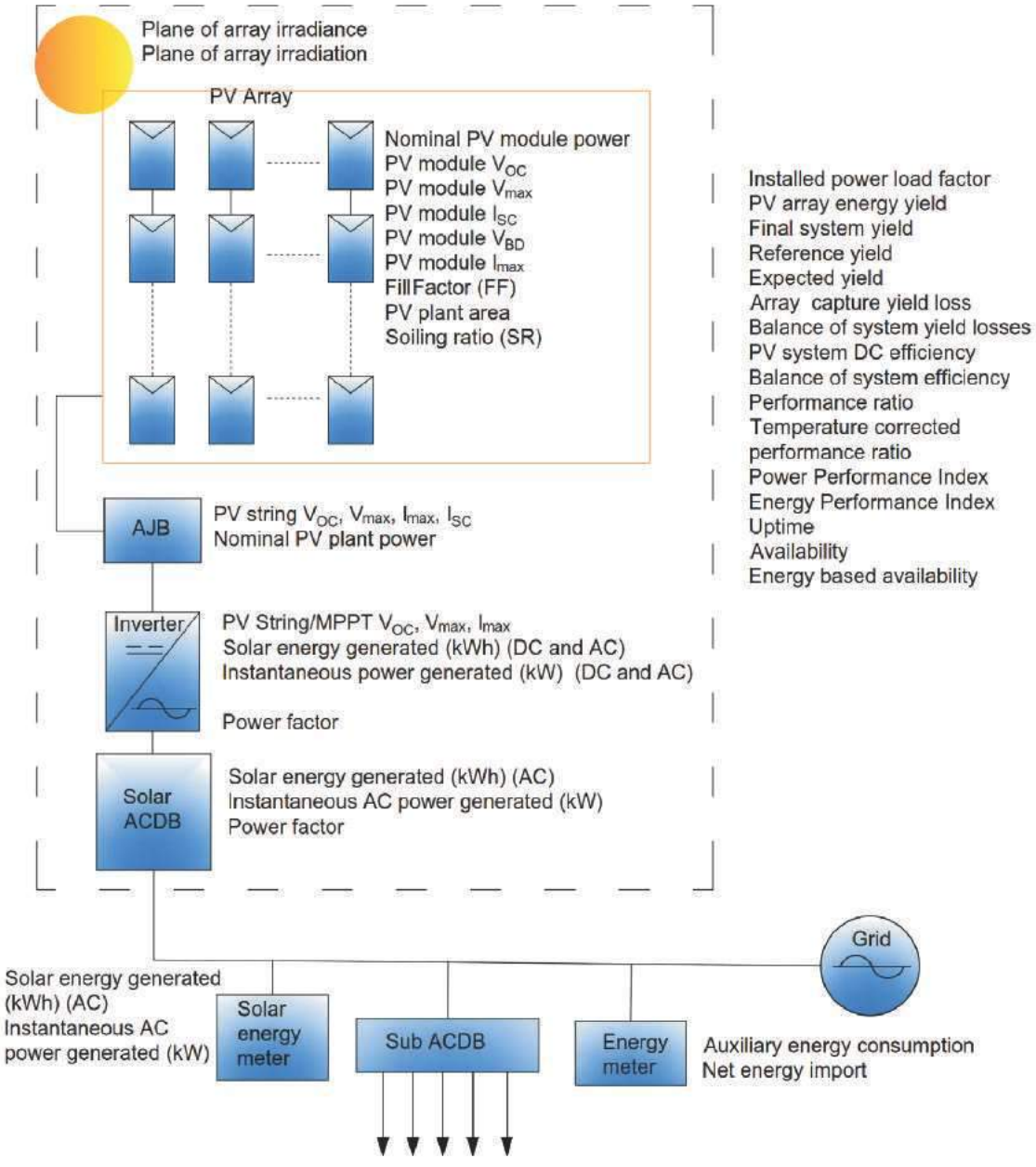


Figure 6.1: Schematic diagram of a solar PV power plant

6.3 Key performance indicators

The main objective of key performance indicators (KPIs) based evaluation of solar power plants is to identify a drop in power plant performance from the expected values. The KPI is calculated based on actual performance and the results will be used for comparing with reference KPIs to analyze performance, investigate the root cause for under performance, planning and/or updating of the O&M plans, etc. KPI based evaluation can be started immediately after the commissioning of the power plant. In some cases, it is recommended to analyze the power plant's performance for 3 to 6 months before freezing the reference KPIs and for identifying the errors related to design, installation and material quality, etc.

KPI's used in solar power plants are bifurcated into technical and operational. The main objectives of technical KPIs are to assess the power plant's performance, identify root causes for reduction in energy yield, investigate issues and faults, and find out effectiveness of O&M. Operational KPIs include indirect factors related to the plant's O&M that affect its performance.

Selection of KPIs will vary depending on multiple factors, such as power plant, capacity, type of power plant monitoring and accuracy class, requirements from the asset owner, etc. Main objectives for introducing KPIs are as follows:

- To analyze performance of a power plant or portion of the plant, in comparison with the desired output.
- To analyze short-term and long-term performance of a plant for given design, site location and baseline performance.
- To compare performance with similar plants within the same climatic zone.
- To compare plant performance with earlier assessment period.
- To update KPIs after commissioning, re-commissioning and developing metrics in support of accurate prediction of future energy yields, and ROI for reliable investment assessment.

6.3.1 Technical KPIs

There are around eighteen technical KPIs discussed here. Reference value of KPI, duration/frequency shall vary based on plant capacity, technology, site conditions and the asset owner's requirement.

A. Average power

Average power is the ratio of total energy produced over a certain period to power plant runtime. This indicates the average power produced by a power plant or inverter, irrespective of downtime. This can be used for comparing the performance of power plants or sub-parts of a power plant within the same climatic zone. Total plant runtime can be calculated from runtime of all the inverters.

Average power, $P_{avg} = E_{Solar} / t$ ---------- (1)

E_{solar} - Energy generated from solar power plant, kWh

t - Total runtime of power plant or inverter (only uptime)

> **Note:**
>
> Since the ratio depends on local meteorological parameters, it is recommended not to use it for comparison of power plants located in different climatic zones or locations.

B. Installed power load factor

Installed power load factor is the ratio of average power to installed power plant capacity. This factor indicates the degree of deviation or degradation. Since meteorological parameters influence the ratio, it is recommended to use it for comparison of power plants or sub-parts of power plants only within the same climatic zone.

Installed power load factor, $K_u = P_{avg} / P_{plant}$ ---------- (2)

C. PV array energy yield

The PV array energy yield is the ratio of DC array energy output to installed power plant capacity.

PV array energy yield, $Y_{array} = E_{DC} / P_{plant}$ ----------(3)

E_{DC} - PV array DC energy , kWh

D. Final system yield

The final system yield is the ratio of AC energy output of the power plant to installed power plant capacity.

PV array energy yield, $Y_{final} = E_{Solar} / P_{plant}$ ----------(4)

E. Reference yield

Reference yield is the ratio of total in-plane irradiation to modules' reference plane of array irradiance. Reference yield represents the number of hours during which solar irradiation would need to be at its reference irradiance level in order to generate same incident solar energy as monitored during the reporting period when the utility grid and/or local grid were available. If the reference yield is calculated for one day, it would represent the equivalent sun hours at the reference irradiance per day.

Reference yield, $Y_{ref} = H_i / G_{i.ref}$ ----------(5)

$G_{i.ref}$ - irradiance at which DC rated capacity of array is determined (normally it is 1000 W/m^2)

F. Expected yield

Expected yield is the product of reference yield to expected PR; it indicates the expected final system yield.

Expected yield, $Y_{exp,final} = PR_{exp} \times Y_{ref}$ ----------(6)

PR_{exp} - Average expected performance ratio (PR of power plant based on simulation with actual meteorological parameters)

Note:

Yield is the ratio of energy generated to the rated power; it indicates the performance of the power plant with reference to rated array capacity. The ratio shows equivalent hours required by the power plant to operate at its rated capacity, i.e. P_{Plant} to generate a particular amount of energy.

These measurements normalize plant output over a selected time frame. This will allow us to compare the production of power plants with different nominal power capacities or technologies.

G. Array capture yield loss

Array capture yield loss represents the time required by the array to operate at its rated power to provide for respective losses (DC) during reporting period. This loss includes all losses on the DC side of the system, such as: PV module efficiency and failures, soiling losses, DC wiring losses, etc.

Array yield capture loss, $L_C = Y_{ref} - Y_{array}$ ----------(7)

H. Balance of system (BOS) yield loss

Balance of system yield loss represents the time required by the array to operate at its rated power to provide for the respective losses (other than DC) during reporting period. This loss includes all balance of system losses (except DC), such as: inverter, AC wiring losses, ACDB losses, etc.

Balance of system yield losses, $L_{BOM} = Y_{array} - Y_{final}$ ----------(8)

I. PV system efficiency (DC)

PV system DC efficiency is the ratio of DC energy produced to reference energy at plane of array. This efficiency includes all DC losses of PV array.

PV system DC efficiency, $\eta_{DC} = E_{DC} / (H_i \,.\, A_{PV})$ ----------(9)

J. PV system efficiency (AC)

PV system AC efficiency is the ratio of AC energy measured to reference energy at plane of array. This includes all DC and AC losses.

PV system AC efficiency, $\eta_{AC} = E_{solar} / (H_i \,.\, A_{PV})$ ----------(10)

E_{solar} - In case of captive power plant, it can be measured after inverter or before evacuation point; in utility power plants it can be measured either in main meter or inverter level.

K. Balance of system efficiency

Balance of system efficiency is the ratio of DC energy measured at the inverter to energy measured at evacuation point. This includes all losses other than DC losses.

Balance of system efficiency, $\eta_{AC} = E_{solar} / E_{DC}$ ----------(11)

L. Performance ratio

Performance ratio (PR) is the ratio of final system yield to reference yield. PR is a most widely used KPI in the solar power industry. The performance ratio indicates the quality of power plants since it captures the overall effect of losses of the PV plant right from DC to AC. This includes soiling, PV module failures and degradation, DC cable losses, inverter losses, AC cabling and BoS losses.

Performance ratio [1] , $PR = Y_{final} / Y_{ref}$ ----------(12)

Eq. (4) and (5) into (12)

$$= (E_{solar} / P_{plant}) / (H_i / G_{i.ref})$$

Performance ratio (PR) can be calculated instantaneously, hourly, daily, etc. as per the requirement. Instantaneous PR calculation is as follows:

$$PR = \left(\sum_{k} P_{solar,k} \times T_k / P_{plant} \right) \Big/ \left(\sum_{k} G_{i,k} \cdot T_k / G_{i,ref} \right) \text{----------(13)}$$

K - recording interval

$P_{solar,k}$ - Power generated at k^{th} interval

T_k - Time span between two interval

$G_{i,k}$ - Solar in-plane irradiance on k^{th} interval

Note:

Performance ratio (PR) can be used for comparing the performance of power plants irrespective of location. Since PR depends on incident irradiance on PoA, any error on irradiance sensor will affect the PR value - for example, soiled sensor will read less measurements of irradiance which will increase the PR even if the plant is under-performing.

Because of the temperature effect on solar PV modules, there will be difference in PR as per the PV module surface temperature variations. For example, in winter PR will be better than summer even though the plant performance is the same. To avoid this ambiguity, temperature corrected PR calculation is introduced.

M. Temperature corrected performance ratio

The above mentioned seasonal variation of PR can be avoided by calculating temperature corrected performance ratio, in which power rating is adjusted as per temperature variation.

Eq. (13) can be rewritten as follows:

$$\text{Performance ratio [1]}, PR = \left(\sum_{k} P_{solar,k} \times T_k \right) \Big/ \left(\sum_{k} P_{plant} \cdot G_{i,k} \cdot T_k / G_{i,ref} \right) \text{----------(14)}$$

$$\text{Temperature corrected PR [1]}, PR = \left(\sum_{k} P_{solar,k} \times T_k \right) \Big/ \left(\sum_{k} (P_{plant} \times C_k) \cdot G_{i,k} \cdot T_k / G_{i,ref} \right) \text{----------(15)}$$

Where

$$C_k = 1 + \gamma \cdot (T_{mod,k} - 25^0 C)$$

γ - Relative maximum power temperature coefficient ($^0C^{-1}$)

$T_{mod,k}$ - Module temperature (^0C)

Usually, reference PR for the power plant will be set during the post-commissioning testing of the power plant. This is recommended to calculate temperature corrected PR to avoid seasonal temperature fluctuations.

N. Power performance index

Power performance index is the ratio of instantaneous actual power to expected AC power output. The instantaneous expected AC power depends on factors like, PoA irradiance, module temperature, and expected degradation of the module.

Power Performance Index, PPI= P_{actual}/ $P_{expected}$ ----------(16)

O. Energy performance index

Energy performance index is the ratio of generated energy to expected energy output; it is regularly recalculated for the respective assessment period (daily/monthly/yearly or as per the agreement between O&M contractor and asset owner) using actual weather data as input to the model each time it is calculated. Energy performance index can also be defined as the ratio between final system yield and expected yield, which is equivalent to temperature corrected PR [2].

Energy Performance Index, EPI= E_{solarl}/ $E_{expected}$ = Y_{final}/Y_{exp}= Temperature corrected PR --------(17)

$E_{expected}$ - Is calculated with the same specific performance model as that used in the predicted energy model, using actual weather data collected at the site during operation of the system for the year.

P. Uptime

Uptime is the ratio of total time in which the inverter was producing power to the total useful irradiance time. This parameter indicates the time during which the power plant was generating power, but total useful time will not exclude any plant non-operating conditions. Generally, uptime is measured at the inverter level.

Uptime, U_{time}= (T_{useful} - T_{down})/ T_{useful} ----------(18)

Uptime can be represented as percentage.

T_{useful} - All inverters need a minimum array voltage and power to initiate their operation, which is directly proportional to the available in-plane irradiance. T_{useful} indicates the total time period in which useful irradiance is available; it can vary as per the inverter rating, number of PV modules in series, DC to AC ratio, PV module technology, climatic conditions, etc.

T_{down}- Time period inside T_{useful} where the power plant is down or not producing power.

Q. Availability

Availability is the ratio of total time in which the inverter was producing power to total useful irradiance time, excluding some of the plant's downtime which was mutually agreed to by the stakeholders in the agreement. For example, external factors like grid non-availability are not within the control of the O&M contractor and hence, plant down time due to grid outages can be excluded from the total useful time. Thus, availability represents the time in which the power plant was operating over the total possible time it is able to operate.

Availability, A= (T_{useful} - T_{down}+ $T_{excluded}$)/ T_{useful} ----------(19)

$T_{excluded}$ - Excluded time; Stakeholders need to be agreed on certain plant down conditions such as:

- Grid failures, low grid voltage, low grid frequency.
- Environmental impacts — flood, earthquakes, plant down due to lightning.
- Communication system failures, or data acquisition system failures.
- Delays of approval by the asset owner to conduct any necessary work.

R. Energy based availability

If the plant is down and not producing power during sunny days or cloudy weather, the energy loss contribution will differ. Therefore, this loss contribution needs to be considered during the availability calculation. Energy based availability considers the availability in terms of amount of energy wasted during plant down. It takes into consideration - an hour in a period of high irradiance is more valuable than in a period of low irradiance.

Energy based availability, $A_{energy,i}$ = E_i / (E_i+$E_{loss(i)}$) ----------(20)

$A_{energy,i}$- Energy based availability for period I

E_i- Energy produced in the time period I

$E_{loss(i)}$ - Estimated energy loss during the time period i

6.3.2 Operational KPIs

Operational KPIs have an indirect impact on a solar power plant's performance and are used to assess the effectiveness of O&M.

A. Acknowledgment time

It is the time between fault detection/alarm and the acknowledgement of fault.

B. Response time

Response time = Time taken for acknowledgment by O&M contractor + time for technician to reach the site.

C. Rectification time

Is the time required to resolve the issue, starting from the technician reaching the site.

It is not practical to give assurance in terms of rectification time since the depth of work involved is different for every problem and site. However, keeping a track of this will help to undertake corrective action to reduce the downtime.

D. Mean time to repair

Is the average time it takes for repair to be completed. This measures the maintainability of the solar PV plant and its components.

Total time for corrective maintenance divided by total number of tickets for repair will give the mean time to repair. For example, if issue 1 took 10 minutes for repair and issue 2 took 2 minutes for repair, the mean time to repair will be = (10+2)/2 = 6 minutes.

Root cause analysis of faults needs to be done for the faults which took a longer time to repair. This KPI also helps to identify issues/components for undertaking preventive maintenance to avoid occurrence of such faults.

E. Mean time between failures

Is the mean time between system failures and represents the reliability of the power plant.

For electronic devices, the mean time between failures is counted in hours/days, but for solar modules and components it can be typically measured in years. It is useful to measure it over long periods of time and it also represents the likelihood of failure. However, it should not be used as a prediction for when the parts will fail.

F. Reporting and documentation

Timely reporting and documentation of the plant's performance and operational activities shows the professionalism of the O&M contractor. Strategic documentation is necessary for the smooth working of the power plant. This KPI can be monitored for compliance and non-compliance.

G. Environment, Health and Safety

Power plants that follow all good practices in environment, health and safety (EHS) have fewer interruptions due to safety related problems, which in turn improves workmanship quality. This parameter is treated as a major KPI that is followed internationally and the O&M contractor should display the achievements on a notice board to show commitment and track record (Figure 6.2).

Figure 6.2: Notice board showing statistics of accidents/non compliances under EHS

Apart from the above technical and operational KPIs discussed, some KPIs listed below can also be monitored as per requirement:

- Annual capacity utilisation factor (CUF).
- Net power import.
- Reactive power consumption as a percentage of active power export.
- Grid non-availability factor.
- Percentage auxiliary consumption.
- Soiling ratio.
- Tonnes of CO_2 saved per annum/since commissioning of plant.
- No of trees saved per annum/since commissioning of plant.
- Annual gross revenue realization.
- Annual net revenue realization etc.

6.4 Implementation of KPIs

The previous section of this chapter describes the most commonly used technical and operational KPIs in the solar industry. Adoption of appropriate KPI(s) is very critical in performance analysis of solar PV power plants. Unlike power plants operating on other technologies, SPV power plants will differ in capacity, type of installation, monitoring system and its accuracy, requirement of the customer, etc. This diversity makes the selection of appropriate KPIs crucial and requires mutual agreement between the stakeholders for its selection.

Key performance indicators (KPIs) can be calculated instantaneously or with short-term/long-term assessment periods. Long-term assessment periods can be weekly, monthly, quarterly or annually, based on energy yield and requirement. Major KPIs, like yield and PR, are independent of the PV model. However, PPI and EPI are the actual performance parameters divided by the calculated expected performance and therefore are dependent on an accurate PV model. Considering the simplicity in PR calculation, most power plants are following PR as a primary KPI, however, asset owners who need more accurate analysis on plant performance can select PPI or EPI. It should be noted that the PV module used for calculating the predicted energy and expected energy should be the same as those deployed in the plant. Summary of technical KPIs and their general implementation is as follows [2]:

Table 6.1: Summary of technical KPIs and their general implementation

Performance indicator	Purpose	Uncertainty
Unit energy production (kWh)	Maintenance	High - 15% to 20%
Yield	Financial only	Low - 5% to 10%
PR-Performance Ratio	Maintenance	High - 15% to 20%
Temperature corrected PR	Maintenance	Moderate - 10% to 15%
Power Performance Index	Commissioning & Troubleshooting	Low to Moderate - 5% to 15% (model and measurement dependent)
Energy Performance Index	Maintenance, Commissioning, Financial	Moderate - 10% to 15% (model dependent)

6.5 Errors in performance evaluation

Errors in measurement of technical parameters can result in errors in performance evaluation, followed by undetected problems in the power plant. Plant data collection can be divided into three categories: directly measured, continuously measured, and visual inspection.

Directly measured: Measurement of electrical parameters is described in Chapter 4.2.2. These parameters are required for regular monitoring of the power plant and for troubleshooting.

Continuous measured: These are metered generation and weather parameters, generally recorded digitally by the monitoring system and used for calculating KPIs.

Visual inspection: This can be done by an experienced person only. Visual inspection done by a person without proper knowledge is likely to ignore failure or its indications which may lead to failure of the power plant.

6.5.1 Errors in directly measured parameters

The main errors in this category are instrument error, communications error, recording error and human mistakes. If the instrument is not calibrated as per requirement, it may lead to an error in measurement. It is recommended to calibrate instruments as per the manufacturer's recommendations. Apart from this, human error can occur in various forms, such as:

- Recording error: Solar plants have multiple strings and there is a likelihood of mistakes in recording measurements manually. The person taking the measurements should note down the string number and location, carefully.
- There should be unique numbering for each string and inverter. All measurements should be recorded by using this numbering so that the measurements can be referred to in future (maintenance of string identification ferrules is important in this case).
- If the irradiance is fluctuating due to cloud cover, it is recommended not to undertake PV string measurements during that time because comparison of string voltages will be difficult.
- If the technician is not using proper PPE, he may be distracted due to safety concerns which may lead to errors in measurement.

6.5.2 Errors in visual inspection

Visual inspection is a main activity in overall O&M because it involves all technical and non-technical parameter analysis of the SPV power plant. Usually, there is no specific instrument used for visual inspection (except IR imaging), and so only an experienced person or a person who is regularly observing the power plant, can identify abnormalities. This requires knowledge of different failure modes of a solar power plant's components as described in Chapter 6.6.10. Technicians should prioritize the problems/issues for urgent attention based on its impact on plant performance. For example, some PV modules affected by a nearby tree's shadow may cause generation loss from that MPPT. Further the time slot of shadow needs to be observed to analyze generation loss before taking a call for seeking permission to trim the branches.

6.5.3 Errors in continuously measured parameters

Continuously measured parameters are used for calculating the performance of a power plant, and are directly linked to data acquisition and recording system. Data acquisition will be done by using energy meters, sensors, or by using any other systems. The main sources of error can be divided into internal factors and external factors.

Internal errors are due to errors in meter or sensor calibration or error in data transmission. This can be avoided by the following measures:

- Calibrate the meters and sensors as per the manufacturer's recommendations.
- Check the data acquisition system connections once a month (in case of utility scale power plants), once in 6 months (in case of large rooftop power plants), along with scheduled maintenance (in case of small rooftop and ground-mounted power plants).
- Filtering data to specific conditions: Instantaneous recorded data may contain values like null value or extremely high/low value; data processing system must have facility to flag and filter the errors on the basis of weighted average values of prior data sets (Figure 6.3).

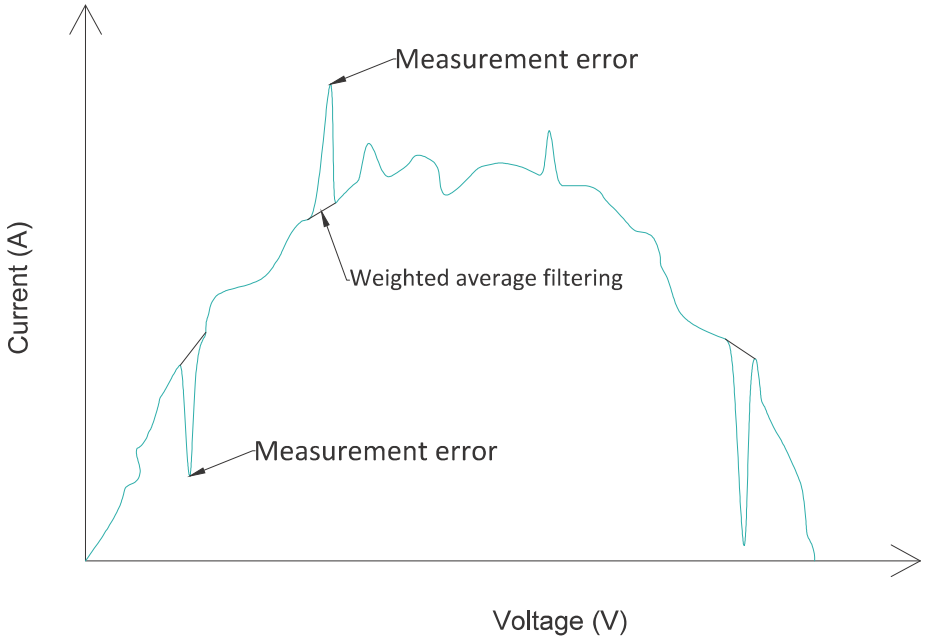


Figure 6.3: Distorted generation curve due to error in measurement and weighted average filtering to avoid error in analysis

External factors which influence errors in continuously measured parameters:

- Shadow or soiling on irradiance sensor: This makes the sensor measure less value and the performance analysis result may shoot up to high value even if the plant is under-performing. Cleaning frequency of irradiance sensor should be less than the cleaning frequency of PV strings, and the location of the sensor should be easy to access.
- Irradiance sensor installed at a different tilt angle than plane of array (PoA) : If the sensors are not installed at PoA, measured irradiance and the irradiance falling on PV modules will be different, which will lead to error in measurement.
- In case of large scale utility power plants located in hilly areas, the cloud cover will be different within the project's boundaries and will lead to error in measurement. Hence, it is recommended to install multiple sensors within the project boundary in line with specified accuracy class (Chapter 4.1).
- Reflections from nearby planes can impose error in irradiance measurements.
- If the temperature sensor is installed at a location near a hotspot area or non-working PV module, it may affect the measurement.

6.6 Component level performance analysis and testing

Based on observations from the KPIs and portfolio/plant level performance analysis, further detailed analysis of various components is undertaken to identify the root cause of performance degradation. In order to do that, component level testing and analysis is required. Different component level test procedures and visual inspections are discussed here. Selection of required tests depends on the issue and site conditions. Some of the tests explained below are also listed in scheduled maintenance activities (Chapter 7.4).

6.6.1 Testing of solar PV string/module

A solar PV string accumulates the power generated from each solar module connected to that string. Such strings are connected in parallel to one MPPT. If any of the strings connected to a particular MPPT is under-performing, then the output of the complete MPPT will get affected. Hence, string level testing is undertaken to identify faults within the strings. Following are different tests conducted on strings:

A. Voltage measurement tests

The purpose of these tests is to check whether the strings are connected properly, expected numbers of PV modules are connected and functioning, etc. To conduct an open circuit test, a multimeter or clamp meter can be used for measuring open circuit voltage. In case the strings are connected through AJB to the inverter, initial testing can be done at AJB level. Procedure for testing is as follows:

I. Set the voltage range of the multimeter as per the rated string voltage. Take the measurement across the positive and negative terminals of the string.

Working voltage measurement

II. In case of AJB with parallel string connection (central inverter), individual string voltages should be the same as that of the AJB.

III. In case of AJB without parallel string connection (string inverter), all string voltages should be same at stable irradiance.

Open circuit voltage measurement

IV. Switch-off the inverter and open the AJB isolator (in case multiple AJBs are connected to one inverter, then once the AJB isolator is opened the inverter can be switched on to avoid generation loss).

V. Open the string fuses or isolate the strings. In case of cylindrical fuse, pull the top end of the fuse cabinet, first (Figure 6.4). An arc is very common when breaking the connection, therefore, it should be done quickly.

Figure 6.4: AJB Isolator and string fuses are opened

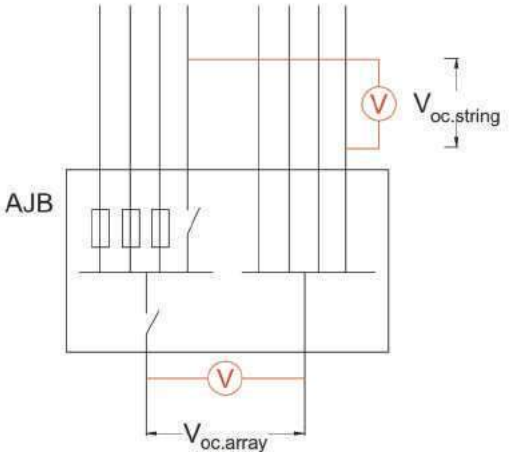


Figure 6.5: Measurement at AJB in open circuit (OC) condition

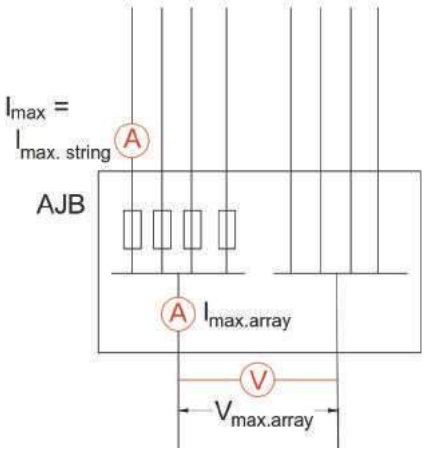


Figure 6.6: Measurement at AJB under working condition

VI. Measure open circuit and voltage of individual strings including the working voltage of the AJB (Figures 6.5 and 6.6).

VII. The resulting open circuit voltage measurement shall be assessed to ensure that it matches the expected value (typically within 5%) in one of the following ways:

- OC voltage of string, $V_{OC.string}$ = OC voltage of array, $V_{oc.array}$= V_{oc} across a PV module × number of PV modules.
- If voltage difference is more than the tolerance limit, then it may be due to a number of different fault conditions, e.g., fewer numbers of PV modules are connected on string, or part of the modules are out of circuit, or there is string interconnection failure, or shorted bypass diode (BD), damage and/or water accumulation in conduits or junction boxes, wrong polarity, etc.

VIII. In case any string shows measurement other than the expected value (more than 5% difference), measure individual module's V_{OC}, $V_{OC,BD}$, and continuity of bypass diode (Figure 6.7).

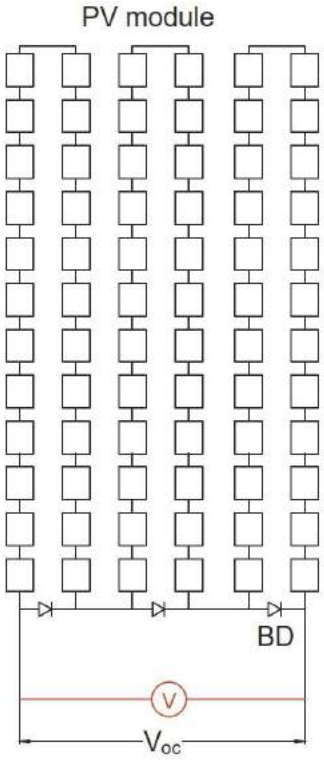


Figure 6.7: Voltage measurement across individual module

Issues observed in measurement with probable cause are as follows:

Reverse polarity: Voltage measurement shows negative reading.

Cause: Positive and Negative wiring leads are reversed between modules or AJB.

Solution: Identify the string with reverse polarity; swap the wiring between each connection point for correct polarity reading; re-test to confirm correct polarity after changing.

Wiring open/short circuit: If the voltage measured is too low (near zero) then it indicates either an open circuit in the wiring or a short circuit.

Cause: Bad or loose connections in the module junction box, or DC connectors, or wiring short circuit, etc.

Solution: Trace wires to find open/short circuit; Correct problem (tighten or repair wire) between bad connection points.

Low /high voltage: Voltage measured is higher or lower than expected.

Cause: Following are the possible causes:

- The number of PV modules connected in series is less or more.
- Some PV modules may have been bypassed in the circuit due to bypass diode malfunction (Chapter 6.6.9).
- Short circuit inside the PV junction box.
- Mismatch effect due to shadow or soiling (Chapters 6.6.4 and 6.6.5).
- PV module failures (Chapter 6.6.10).

Solution: Brief solutions are as follows:

- Check system design and voltage drop calculations to verify enough voltage is passing through from the array to the AJB and that the voltage matches expected values.
- Trace the module to find failures, short circuit or mismatch effect.
- Bypass/replace the faulty PV module and check the voltage again. If the voltage is equal to the number of modules in series, then find the cause of PV module failure.

Note:

- Make sure that soiling on PV modules is less than average, because thick soil deposition may affect measurement. If the soil deposition on PV modules in a string varies, mismatch effect may lead to measurement uncertainties.
- While comparing, make sure that the selected strings are identical in terms of PV module rating and number of PV modules in series.
- While comparing the voltage between strings, make sure the irradiance is stable.
- In case of unstable irradiance conditions, multiple meters can be used to take readings of different strings so as to get all the readings at the same time for comparison purposes.

Safety note:

Make sure all safety measures are taken before doing tests.

While using normal multimeter, make sure that the probes are of adequate rating and polarity. If the multimeter setting is at current measurement and used for voltage measurement, it will result in a short circuit which could lead to electric spark followed by electrocution.

B. Current measurement tests

Although the open circuit voltage test is a good technique for detecting many common issues in arrays and modules, the current measurement test is required for identifying additional problems. However, current measurement cannot be taken as a measure of PV module/array performance, as its output depends on irradiation and inverter load parameters. Two current measurement test methods are: short circuit current and operational current measurement. Since the current will vary with respect to irradiance, it is recommended to perform the test when the irradiance is stable. In case of fluctuating irradiance conditions the following tactics may be adopted:

- Measurement may be delayed.
- Multiple meters may be used to measure current of different strings and compare them at the same time.
- Measuring irradiance and current at the same time can be used to validate the current measurement during its comparison.

String short circuit current measurement

The test should be done on a sunny day and the measured value should be linear with the sunlight conditions available. An insolation or solar radiation meter can be very helpful in determining sunlight conditions.

I. Ensure that the string is completely isolated from the circuit.

II. Ensure that the instrument used for testing has a rating higher than the potential short circuit current and open circuit voltage.

III. Follow any of the given methods for I_{sc} measurement:

- Using test instrument with short circuit measurement function.
- Using a load break switching device already present in the string circuit.
- By using a temporary short circuit test box or additional switching device with short circuit conductor, the technician can connect the string to the test box having an isolator and once the string is connected, the isolator can be closed and measure I_{sc} taken using a clamp meter or ammeter.

String operational current measurement

I. Ensure the strings are connected to circuit as per the SLD or normal operating conditions (Figure 6.9).

II. Ensure the inverter is switched on and is in working condition.

III. Ensure minimum irradiance is available (greater than 650W/m^2).

IV. Measure each string's current using a clamp meter (make sure that the irradiance is stable).

V. Compare the measured values with expected value (after taking into account the degradation) ($I_{max.array} = I_{max}$). Measured string current values should be the same (typically within 5% of the average string current for stable irradiance conditions [3]).

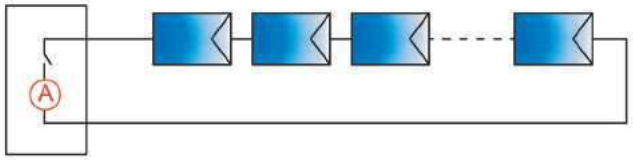


Figure 6.8: Short circuit testing of string

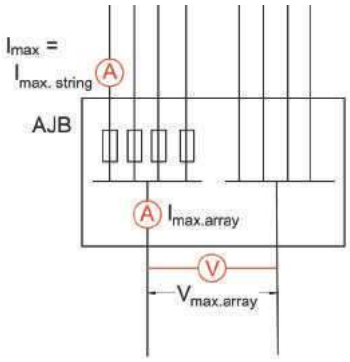


Figure 6.9: Operational current measurement

Issues observed in measurement with probable cause are as follows:

No current: Measured current is zero.

Cause: Open circuit in the wiring, a bad or loose connection, incorrect wiring, or an internal problem with the solar module. It's possible the connection point is sufficient enough for full voltage reading, but has limited current.

Solution: Trace and fix wiring mistake or loose/bad connection issues.

Less than expected current: Measured current value is less than expected.

Cause: The reasons could be:

- Degradation of PV module: Refer to the datasheet of the PV module in which the degradation level of the module will be mentioned. For example, 2.5% for the first year and 0.80% every year thereafter.
- If the measured value is less than estimated after considering expected degradation, it can be because of the following:
  - Mismatch effect due to shadow or soiling
  - PV module failures

Solution: Determine if the current loss is appropriate for the age of the module. If not, the module may be degrading faster than expected. Undertake I-V test to verify degradation.

Safety note:

Ensure that all safety measures are taken before carrying out tests.

While performing the short circuit test, confirm the maximum current to be measured is less than maximum current rating of the meter.

C. Junction box testing

A single power plant may contain multiple AJBs and MJBs. Reverse polarity due to a single string connection can lead to fault condition. Especially in case of larger power plants, this situation may lead to significant consequence because of multiple often interconnected combiner boxes. Error in AJB can occur during the following conditions:

- During installation phase: interconnection issues during first charging.
- During operational phase: fault can occur due to aging of components, or during re-connection of strings/arrays after testing/shutdown.

The main purpose of this test is to ensure that all the strings interconnected at the junction box are connected correctly. The test procedure is as follows:

I. Set the digital multimeter voltage range to at least twice the maximum expected string $V_{OC,String}$.

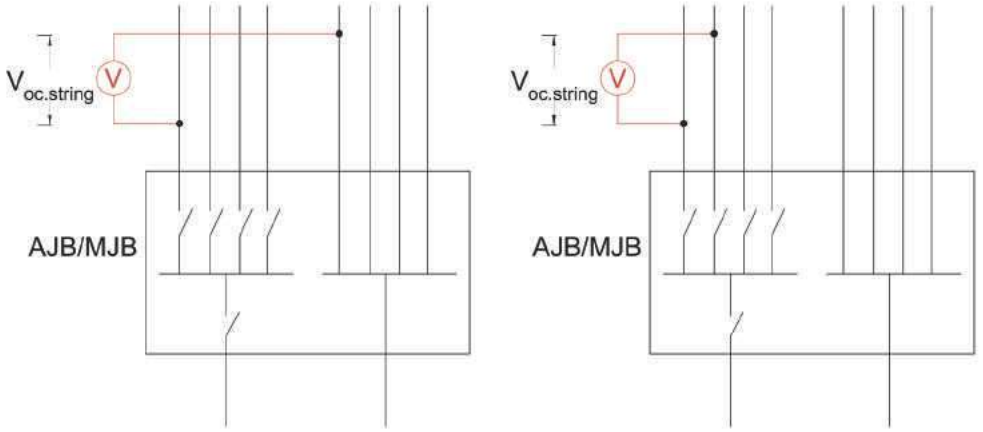
II. Connect all the negative ends of strings/arrays to the junction box. Do not connect positive end of the strings/arrays.

III. Measure $V_{OC,String}$ of the first string by inserting positive lead of multimeter in positive end of first string and negative of multimeter to common string/array negative.

IV. Ensure, measured $V_{OC,String}$ is equal to expected $V_{OC,String}$.

V. Leave positive lead of multimeter on first string's positive end, then insert the other lead of the multimeter to the next string as shown in Figure 6.10.

VI. Because the two strings share a common negative reference, the voltage measured should be near zero, with an acceptable tolerance range of ±15 V.



Voltage between first string positive with common negative

Voltage between first string positive and second string positive with common negative

Figure 6.10: Junction box polarity testing steps

VII. Continue measurement on subsequent strings, using the first positive circuit as the meter common connection.

VIII. In case of reverse polarity condition, measured voltage will be twice the expected $V_{OC,String}$.

IX. If the reverse polarity is found, remove the positive and negative end of that string/array and insert positive and negative lead of the multimeter in the disconnected string or array.

X. If the multimeter shows negative $V_{OC,string}$, mark the string polarity correctly using string identification ferrules as shown in Figure 6.11.

Figure 6.11: String polarity marking using ferrules

D. Ground fault testing

PV power plants may get grounded in different parts. Factors like, type of grounding, fault level, inverter topology, etc., will influence a system's fault tolerance and its response to ground faults. There are two reasons that current will flow through ground conductors. They are leakage current and ground fault current.

Ground faults can result from failure of insulation which removes constraints to the flow of electrical energy from live parts to the conductive surfaces. In normal grounded systems, ground fault will lead to current flow in the equipment's grounding conductors and grounded equipment by creating a parallel path for the current. Consider Figure 6.12 which shows ground fault where some portion of the string current flows in the intended circuit conductors and some portion flows in the parallel ground circuit between the array and the ground connection in the inverter. Since the combined impedance of the ground fault and the ground conductor is higher than the circuit impedance, ground fault current will be low.

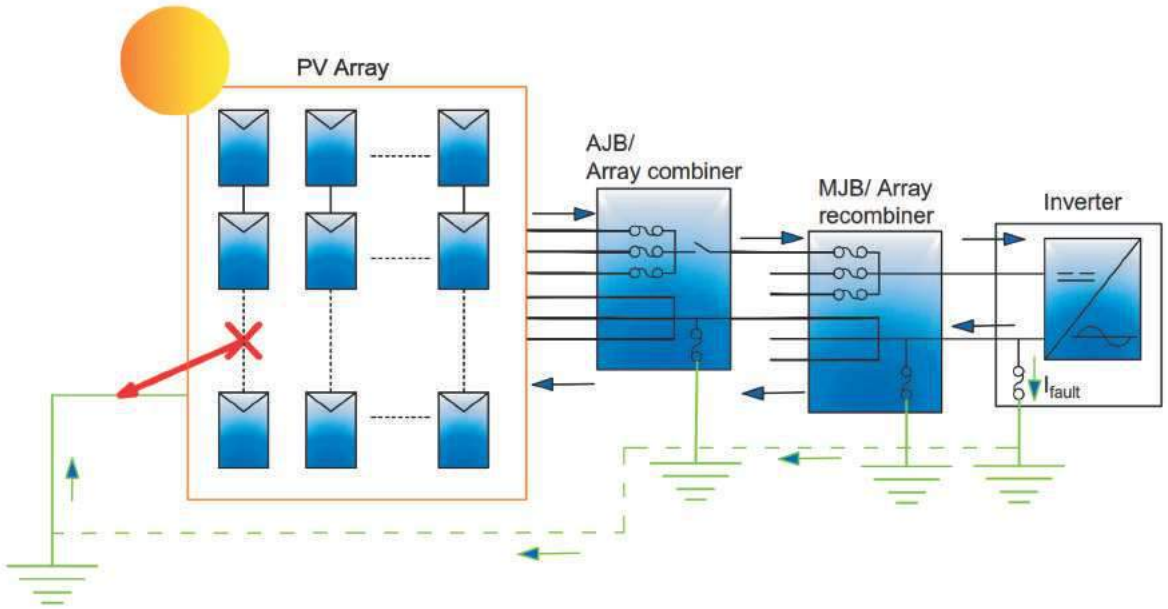


Figure 6.12: Circuit showing ground fault current path

In case of a ground fault between the AJB and MJB or inverter, the fault current might be enough for triggering the over-current protection device, but in some cases, fault impedance may still be sufficient to keep the fault current below the trip rating. Consider Table 6.2 which specifies the maximum ground fault current for required protection to detect and interrupt the PV inverter as per UL 1741 standard.

Table 6.2: Maximum ground fault current for different inverter DC rating

Inverter DC Rating	Maximum ground fault current for activate the protection (A)
0-25	1
25-50	2
50-100	3
100-250	4
>250	5

If the ground interrupt fuse or over-current protection device's rating is higher than the fault current, then fault remains undetected. For example consider a ground fault in a string which carries current 9A. Due to high impedance of parallel circuit formed by the ground fault less than half (<4.5A) is flowing in the ground circuit back from the inverter. In this example, with a large inverter and a 5A ground fault interrupt fuse, the fault can exist indefinitely without blowing the fuse. Presence of this undetected fault can result in current flow through ground conductors and

can lead to electrocution [4]. The presence of this undetected fault can result in arcing and fire if a second, subsequent ground fault occurs in the ungrounded conductor.

There are two PV module frame fault scenarios most likely to present shock or safety hazard. They are the DC circuit ground fault and leakage current. However these fault can also occur on other conductive surfaces that rely on the module frame for a conductive path to the ground circuit.

Conductor Fault to Frame

This fault can be generally termed as short circuit fault, which can occur if a damaged ungrounded string conductor is exposed and electrically connected to a PV module frame. Consider Figure 6.13 (PV system has a negative-grounded circuit) in which, positive string conductor shorted to grounded frame. The path of the fault current is as follows:

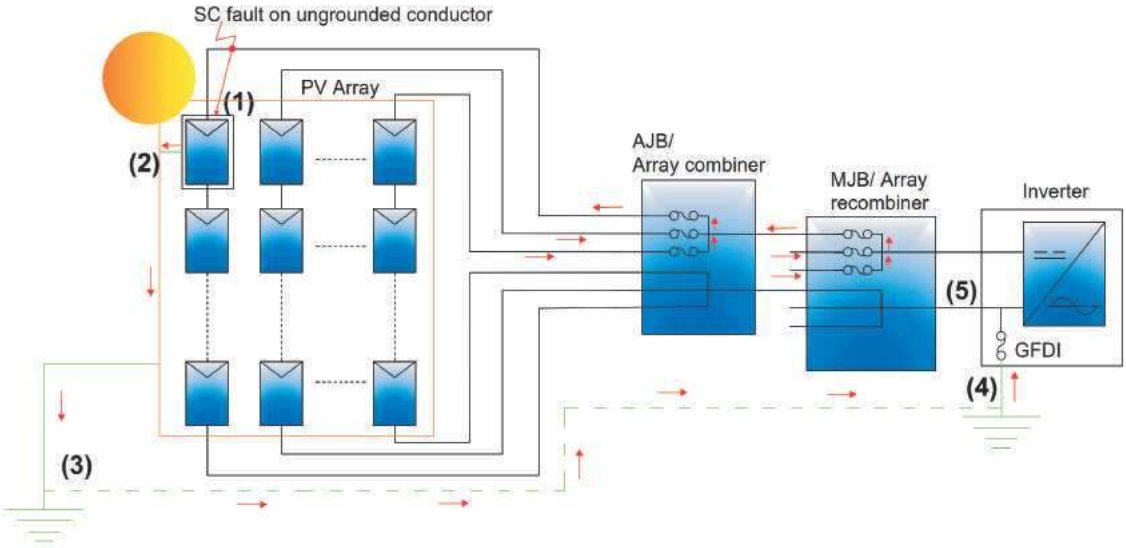


Figure 6.13: Ungrounded string SC fault to PV module frame

1) Short circuited positive polarity conductor to the module frame.
2) PV module frame to the MMS ground circuit (equipment grounding conductor).
3) MMS ground circuit to the equipment grounding path followed by inverter ground bus.
4) Inverter ground bus to the inverter negative bus (location of negative to ground bond through the ground fault detector interrupter [GFDI]).
5) Negative ground bus to the negative conductor of the faulted string.

From the above Figure 6.3 it is obvious that the fault current is not limited to the single faulted string. The entire array's positive pole is grounded via this connection to the frame, so most of the fault current is backfed from the positive bus at the combiner box and the recombining fuse bridge feeding the inverter. These currents will flow through this fault connection until either the GFDI or the faulted string fuse blows. Generally string fuse rating is typically between 10A to 15A, but due to the entire array's current circulating through the parallel circuit, the faulted string fuse will blow. In this case of low string current due to low irradiance and the fault current being below string fuse rating, the string fuse will not operate. Any factor limiting the current in the fault circuit will prevent or delay over current protection device operation including resistance in the ground path from module frames to the ground circuit. However GFDI at inverter level usually detects and isolate the system much before the fuse gets blown.

Leakage Current to Frame

It is normal for SPV power plants to have small leakage currents (mA) flowing between the PV cells and the ground. The magnitude of the current depends on factors such as the capacity of the module, type of PV module construction (amount of conductive surface), moisture ingression, amount of conductive media, damage to the integrity of the circuit, etc. Example: leakage of current in a PV system with thin film PV module (glass to glass construction) will be less than that in crystalline modules. Assuming the frame is properly grounded, the leakage current travels from the frame to the ground circuit and returns via the grounded polarity conductor to the modules. Under normal conditions,

there is no safety hazard. If the grounded PV module frame has a poor or discontinuous ground connection,however, the frame voltage relative to earth potential can be significant (especially on a 1000VDC or 1500VDC PV string) and a person touching the frame can become the path for the leakage current. Even though small leakage currents are not dangerous, abnormal leakage currents to a PV module frame at a high voltage (1000VDC or 1500VDC) cause enough of a voltage potential and energy to injure or kill anyone who comes in contact with the ungrounded PV module frame. This abnormal leakage current flow can be due to aging or defective PV modules with broken glass or delamination, or due to wet conditions.

Following are cases when the ground fault can turn to become dangerous:

- When a person touches ungrounded MMS part which in live SC condition
- PV module frame has a poor, high impedance ground connection with live SC condition.
- Low resistance between the body and the return path to ground, which can be through the earth or other grounded metal such as an adjacent PV module or mounting frame.

Procedure for locating ground fault

I. Ensure all safety precautions are taken.

II. Record inverter display details: In case of existing earth fault, note down the information/error message shown in the inverter display. If the testing is under scheduled maintenance, check the inverter event logs for previous ground faults.

III. After recording all available information, isolate the inverter from power source by referring to the inverter manual. Open ACDB switch before isolating the inverter.

IV. Apply lock-out-tag-out procedures to secure the disconnections.

V. Wait for 5 to 10 minute for the internal capacitor of inverter to discharge (as per inverter manual).

VI. Ensure the inverter is isolated, by checking the voltage using digital multimeter.

VII. Test for current in ground circuit (inverter) by using ground fault detector.

VIII. If no ground fault current is measured and inverter is showing ground fault then (a) open ground fault fuse and check continuity, (b) proceed to test the AJBs, step X

IX. If ground fault current is measured

(a) Record the current level.

(b) To locate the source of the current, open all DC disconnectors other than string fuses of AJBs as shown in Figure 6.14 (this will eliminate the leakage current due to variations in V_{oc} among strings).

(c) Measure the ground conductor current at the MJB. The conductor with current on the grounded conductor that matches the current measured at the ground fault protector at inverter level is the conductor/AJB with the fault. Measure all conductors even if you have found the conductor with the fault. This is because there are chances of multiple fault. Then proceed to the AJB connected with faulty conductor (step X)

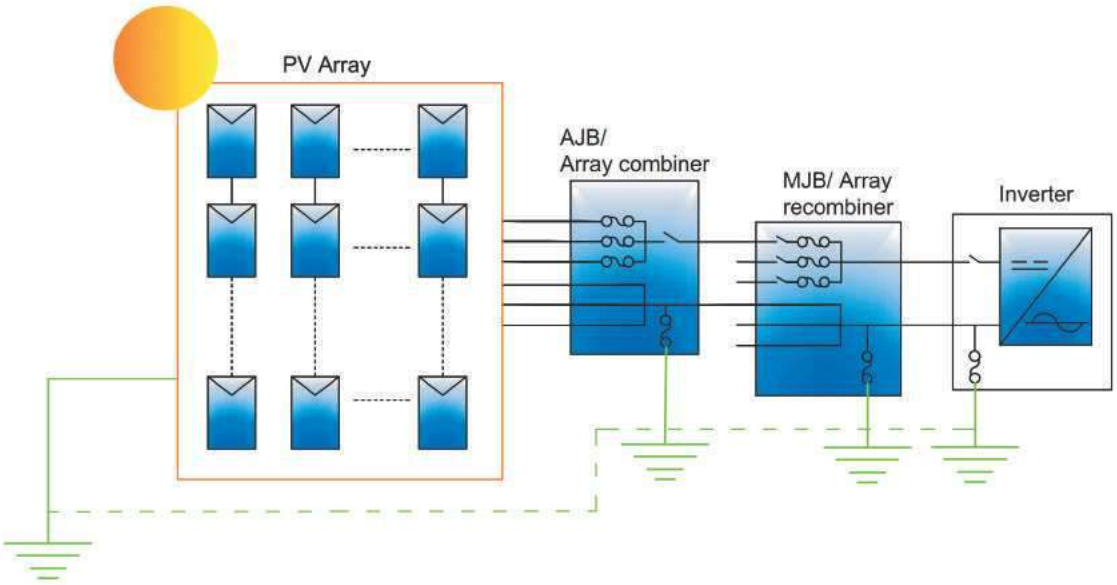


Figure 6.14 : Location of DC disconnectors at MJB to be opened

X. At selected AJB, test and record the ungrounded conductor current.

XI. Measure the current at each string if all strings having significant current flow; identify the faulted string (step XII) or open fuse holder of strings carrying current less than 1A (small current flows in the circuit because of slight difference in V_{oc}).

XII. If all strings have significant current, the faulted string will generally show higher current value. Open both ends of the faulted string and isolate it from AJB. Once the current flow stops and is verified, open all fuse holders.

XIII. Test the fuse for continuity test, blown fuse is an indication of faulted string

XIV. Record V_{oc} of all strings under fuse open condition, V_{oc} of the faulted string will shows lower than the expected value (i.e. PV module V_{oc} × number PV modules connected in series). Foe example if the V_{oc} of a faulted string is 400VDC and each PV modules nominal V_{oc} is 40VDC, 400/40=10 PV modules, fault location could be 10 modules back from the high voltage side of the string.

XV. Test all the AJBs as per step X to XIV (to identify undetected ground faults).

XVI. Remove and replace the damaged PV module or conductor, replace the blown fuses.

XVII. Reconnect the strings one by one and check the ground current after connecting each string. Verify the current once again after connecting the strings.

XVIII. Reconnect the opened fuses at AJB and MJB level and measure and record the ground current

XIX. Turn on the inverter and measure the ground current again (normally it is less than 10mA for 5000kW array)

E. Insulation resistance testing

One of the main reasons for ground faults is the insulation resistance failure of PV modules. It is recommended to perform insulation resistance test at regular intervals for identifying insulation resistance issues during the initial stages so as to prevent them from becoming significant. Electrical insulation is provided to prevent human exposure to hazardous voltages and currents and to reduce the risk of fire.

Ideally, there will be small residual or some earth leakage current in every PV system. The residual current consists of partial fault currents from individual components like PV modules, DC cabling and inverters, etc. The insulation resistance of the components can be considered as a parallel connection to earth. Figure 6.15 gives the effective insulation resistance of different components.

Insulation resistance, $$R_{iso} = \Big/ \frac{1}{\frac{1}{R_{iso,\mathrm{module_array}}} + \frac{1}{R_{iso,DC_cable}} + \frac{1}{R_{iso,inverter}}}$$

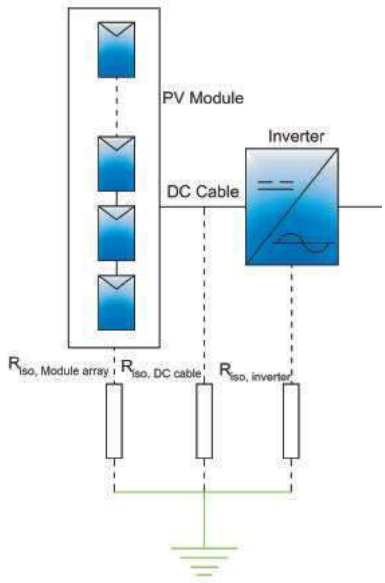


Figure 6.15: Effective insulation resistance of different components

It is expected that PV modules are designed, tested and verified to withstand harsh climate during their 25 year life cycle. However, it was observed that many PV modules installed at different sites have shown low insulation resistance compared to expected values. This can be because of low quality materials, aging effects, mechanical damage, damage due to exposure to corrosive chemical compounds, etc. Any of these listed issues may lead to dielectric breakdown of insulating material and allow potentially damaging or dangerous leakage currents to flow.

Insulation resistance test for PV string/module

According to IEC 62446-1:2016, there are two methods used for performing the insulation resistance measurement test. Testing procedure is as follows:

I. Check if the module mounting structure (MMS) is connected to the ground or not.

II. Ensure all personnel safety measures before performing the test.

III. Isolate ACDB, inverter and array junction box (AJB).

IV. Disconnect over voltage equipment like SPDT from AJB if the test point is between the inverter and AJB.

V. **Method 1**- Connect insulation resistance measuring tester between array negative and earth and repeat by connecting array positive and earth. If the MMS is grounded, measurement can be made by connecting the device to the MMS or frame.

VI. **Method 2** - Test between earth and short circuited array positive and negative (typically this would be achieved by an appropriate short circuit test box).

VII. Verify the measured value with previously recorded values (from last scheduled maintenance record, commissioning reports). Minimum values of insulation resistance are given in Table 6.3.

Table 6.3: Minimum values of insulation resistance

System voltage (V_{oc} (STC) × 1.25) V	Test voltage V	Minimum insulation resistance MΩ
<120	250	0.5
120 to 500	500	1
>500	1000	1

Insulation resistance measurements can take an entire PV array offline for the duration of the test. The larger the PV array, the greater the difficulty in identifying and correcting an electrical insulation problem and the greater the

economic loss associated with the value of power that would otherwise have been generated. Conventional methods for insulation resistance creates economic and safety disincentives for regular monitoring of insulation resistance throughout a PV array. Simple PV insulation resistance measurement devices are available in market and most of I-V curve tracers are coming with an insulation measurement feature. To avoid generation losses during tests and due to corrective maintenance activity, it is suggested to perform the test on a scheduled basis along with other regular tests. If insulation resistance is not monitored sufficiently often, problems with electrical insulation may not be found before a destructive fault occurs.

Wet Insulation-Resistance Test

This test is to evaluate the module's electrical insulation system under wet operating conditions and to verify moisture ingression in the active part of the PV modules circuitry where it may cause corrosion, ground faults, or pose an electrical safety hazard to personnel. This test can be used to identify:

- Ground defect such as wiring damage.
- AJB water ingression and other similar installation issues.
- PV module manufacturing defects including polymer substrate punctures.
- PV module junction box failures.
- Improper connector installation and water ingression.

The procedure for wet insulation test is almost the same as that of a standard insulation resistance test but with the additional step of wetting the PV module array. Selected PV array or string needs to be thoroughly wetted with a mixture of water and surfactant. Following steps need to be considered while performing the test:

- Ensure all required safety precautions are take care.
- Ensure that all parts are wetted, including front, rear and edges of the module along with all junction boxes and cables.
- Minimum two persons are required to perform the test. While doing the test one person should ensure all the parts of the array/ string are wet.
- Perform the test procedures as per standard insulation procedure as given above (step I to VII).

Safety note:

- Make sure all safety precautions are taken before doing the test.
- There is a potential for electric shock while performing the test and hence basic safety measures should be followed. The person who is performing the test should wear proper personal protective equipment and avoid direct metallic contact.
- Surge protection devices (SPDs) must be removed from the circuit to avoid damage. These SPDs may be wired directly to the fused bus of the combiner box or may be wired to a tilt-out fuse holder, or may be a plug-in device.
- Lower testing voltages are necessary if the SPDs are not removed. Insulation testers are now available with 50V settings that will not damage the SPDs. The added benefit of a low-voltage insulation test is that it can detect problems with SPDs. Leakage in SPDs are common in older PV plants.

F. I-V Curve testing

I-V curve can be treated as a basic performance indicator of a PV module or string. It represents all the possible operating voltages and current points of a solar PV module or string for weather conditions (irradiance and temperature) present at the time of testing.

I-V Curve at STC: The curve starts at the rated I_{sc} and ends at the V_{oc} (at controllable ambient conditions). The maximum power point (MPP)(located at the knee of the I-V curve), is the operating point that delivers the highest output power (Figure 6.16). Parameters which are measured from I-V curve under STC conditions are presented as the nominal rating of the PV module.

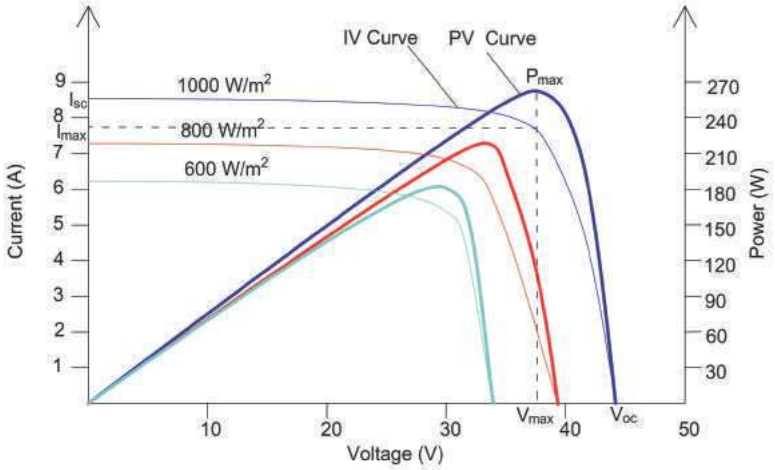


Figure 6.16: I-V and PV curve of PV module under different irradiances

Series (R_s) and shunt (R_{sh}) resistance of solar modules

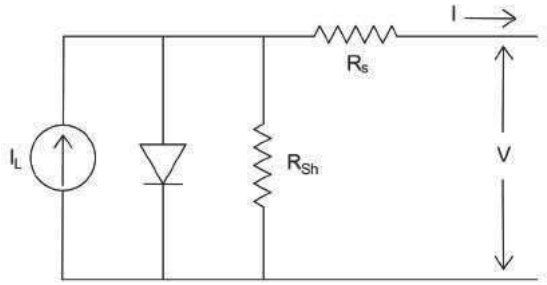


Figure 6.17: Equivalent circuit of solar cell

$$I = I_L - I_0 \exp\left[\frac{q(V + IR_S)}{nkT}\right] - \frac{V}{R_{Sh}}.$$

In Figure 6.17, I is the cell output current, I_L is the light generated current, V is the voltage across the cell terminals, T is the temperature, q and k are constants, n is the ideality factor, and R_{Sh} is the cell shunt resistance [5].

Series resistance (R_s) in a solar cell is mainly due to the movement of current through the emitter and base of the solar cell. Other causes are the contact resistance between the metal contact and the silicon, or the resistance of the top and rear metal contacts and additional resistance caused by a mismatch of the individual cell characteristics. The main impact of series resistance is to reduce the fill factor, although excessively high values may also reduce the short-circuit current. Slope of X intercept in the I-V curve will give value of R_s. High value of R_s will change the I-V curve pattern from the ideal curve (Figure 6.18).

Shunt resistance (R_{sh}) illustrates a shunt path for the current flow bypassing an active solar cell. If R_{sh} is low, then shunt path leakage current will be high. Lower R_{Sh} is typically due to manufacturing defects, mismatch effect or hotspot caused by PV module failure.

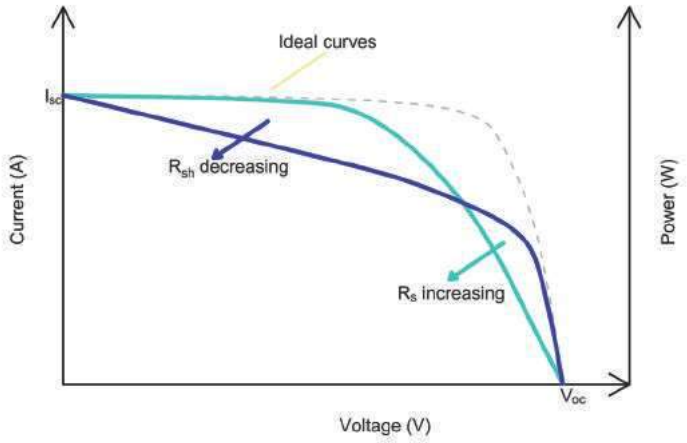


Figure 6.18: Variations in I-V curve as per changes in R_{sh} and R_s

I-V Curve in site condition: Since the input parameters are not controllable in actual site conditions, I-V curve will not be in line with that of STC conditions (Figure 6.19). I-V curve can get distorted due to reasons like:

- Variation in irradiance and angle of incidence.
- Variation in temperature.
- Shadow on the PV module.
- Soiling of the PV module.
- Degradation or aging of PV module.
- Other PV module failures which may affect the performance (Chapter 6.6.10)

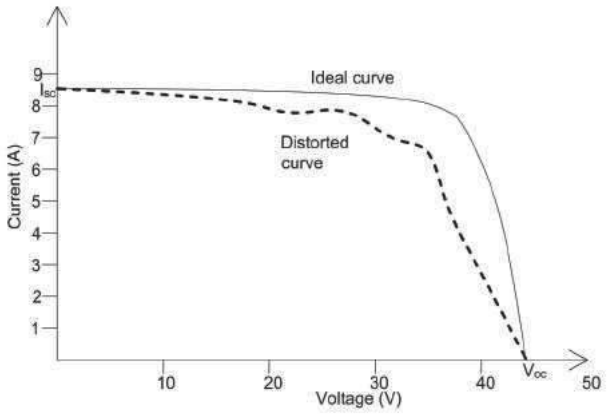


Figure 6.19: Ideal I-V curve and distorted curve

- Open circuit voltage (V_{oc}), short circuit current (I_{sc}).
- Maximum power (P_{max}), maximum voltage (V_{max}), maximum current (I_{max}).
- Performance of PV module or string; fill factor.
- Identification of PV module or string defects, shadow issues, soiling.

If the test requirement involves both V_{oc} and I_{sc} measurements, it is recommended to conduct I-V curve tracing rather than doing separate V_{oc} and I_{sc} test. Any good quality I-V curve tracer can be used to plot I-V curve and following are the common features provided by I-V curve tracer manufacturers:

- Plotting I-V curve according to given input conditions.
- Facility to plot I-V curve of individual PV module and PV strings (voltage range up to 1,500VDC).
- Storing multiple test results.
- Insulation resistance test.

- Real-time monitoring of output by connecting laptop or mobile to the I-V tracer.
- Software for plotting the test output — I-V and PV curve.
- Facility to convert test data to STC condition (for degradation calculation).
- Facility to export the test data in .csv or any other usable format for further analysis.

Procedure for performing I-V curve tracing is as follows:

I. Ensure all PPE and safety precautions are taken.

II. Ensure the PV module is cleaned properly (no need to consider this step in case of soiling analysis).

III. Open ACDB isolator, switch off inverter, open MJB and AJB.

IV. Check whether the irradiance is stable or not. It is recommended to perform the I-V curve test when the irradiance is >400 W/m^2 as measured in the plane of array[3]. However, I-V curve tracer manufacturer's recommendation is for more than 650 W/m^2. Practically, it was found that if the irradiance is less than 650 W/m^2, the error content in the analysis will be high.

V. Isolate the string from AJB and make sure that no current flows through the circuit.

VI. Mount the irradiance sensor plane equivalent to plane of array (PoA) (Figure 6.20).

VII. If a reference cell device is used, this should be checked to ensure it is of the same cell technology as the array under test, or suitably corrected.

VIII. Ensure that no nearby or far shadow is cast on the irradiance sensor.

Figure 6.20: I-V Curve test set up for measuring irradiance at PoA

Procedure for installing temporary temperature sensor

IX. The sensor type and attachment method can have a significant impact on the measured temperature, leading to significant measurement error. Main causes of error are the contact between the sensor and the module's rear surface, amount and type of insulation placed over the sensor and the amount of adhesive used.

X. Clean the module's rear surface and allow it to dry completely.

XI. Select the sensor's location at the centre of a cell, close to the centre of the module to avoid boundaries between cells [1].

XII. For crystalline modules select the centre of the centre most cell; in case of even numbers of rows or columns select the cell which is nearest to the centre most point.

XIII. For thin film modules, place the sensor within the boundaries of a cell near the centre of the module, avoiding scribe lines between adjacent cells if possible.

XIV. Follow installation steps provided in the sensor manual for connection of the sensor.

XV. Connect module and ambient temperature measurement sensors. While installing module temperature sensors make sure there is no hotspot on the selected cell (Figure 6.21). If a hotspot is found, select another cell which is nearer the centre (but not adjacent to the hotspot).

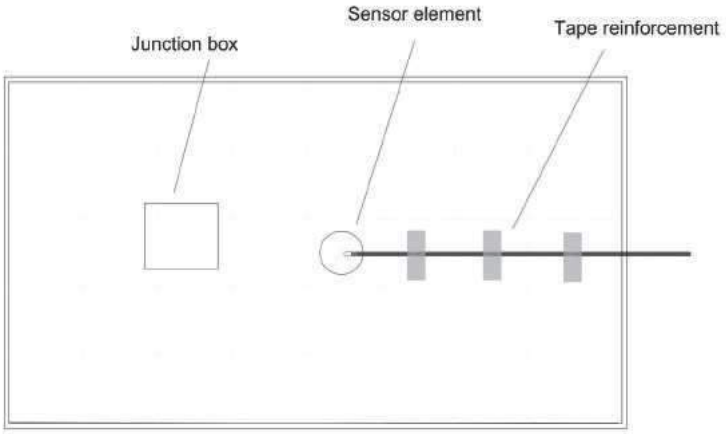


Figure 6.21: Ideal position of PV module sensor

XVI. Connect the sensors to the I-V tracer's main equipment (wireless facilities also available).

XVII. Check whether all the sensors are transferring data correctly (verify the instantaneous irradiance sensor readings with the help of another sensor reading or visual verification).

XVIII. Connect all the required probes to the I-V tracer's main equipment (in some systems I-V tracer standard connectors would be MC4 and PV modules have MC3 or others). The required connectors need to be arranged prior to the test.

XIX. Check the string voltage and current before connecting the string to the I-V tracer (string current and voltage must not go beyond the I-V tracer's maximum value).

XX. I_{sc} value of most industrial PV modules is less than 12A, therefore, string current also become less than 12A. SLD of the power plant needs to be verified to check whether the string has been paralleled any where before the connecting point. If so, remove the parallel connection and continue to the next step. In case of individual module testing, over current issue will not occur.

XXI. Check $V_{oc,string}$ and set the I-V tracer settings as per the expected maximum $V_{oc,string}$. If the $V_{oc,string}$ voltage is higher, divide the string in two halves before proceeding with the test.

XXII. Connect the I-V tracer's probes to the string and connect the reference earth probe to a nearby grounded conductor or MMS or module frame.

XXIII. Ensure the irradiance again, as per step IV.

XXIV. Perform the I-V tracing as per the instructions give in the I-V tracer manual.

XXV. In case of performance analysis, if there is no significant change found in recorded I-V curve from expected results, proceed towards the next string for testing.

XXVI. If any deviation is found from the expected I-V curve, first perform visual inspection of the string (to identify shadow, soiling, etc.).

XXVII. Clean the PV string again in case of shadow or soiling on the PV module and perform the test once more.

XXVIII. If the issue still exists, check the I-V tracer and string connection and verify the V_{oc} value.

XXIX. If there are no connection issues, proceed with individual module I-V curve tracing.

Figure 6.22: Testing of I-V curve

Note: Instrument connection, ratio and measurement methods, may vary from manufacturer to manufacturer. It is recommended to read the instrument's instruction manual carefully before proceeding with measurements.

Interpreting the plotted I-V curve

Recorded I-V curve shall be studied for any deviation from the nominal curve for identifying significant faults within the PV array. I-V curve can be used for identifying the following critical defects:

- Damaged cells or modules.
- Short circuited bypass diodes.
- Local shading.
- Mismatch losses.
- Presence of shunt resistance.
- Excessive series resistance.

Ideal I-V curve

A normal I-V curve has three parts, as shown in the following graph Figure 6.23. Ideally, these parts should be smooth. The slope and shape of the knee depends on the cell's technology and changes in series and shunt resistance. In case of thin film modules, curve knee would be rounder than that observed for crystalline PV modules.

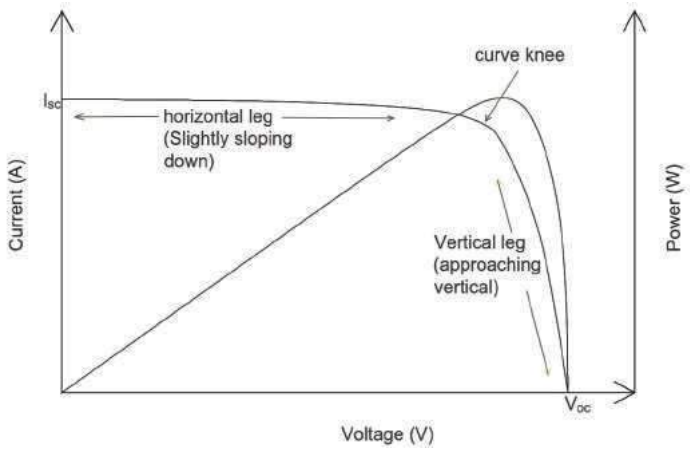


Figure 6.23: Ideal I-V and PV curve

In a normal PV module manufacturing line, all PV modules undergo a flash test and I-V curve tracing is carried out at the last stage of the manufacturing process. The recorded maximum values should be used for comparing the performance of the PV module. However, under normal operating conditions (I-V curve at site conditions mentioned above), the curve will be different from the ideal. In case of I-V curve of string, there will be additional DC connectors and cable losses. An ideal PV curve would be measured under STC. Since site conditions differ, it is not possible to conduct an apples-to-apples comparison of the curve plotted at site with the STC's I-V curve. But by analyzing the curve's shape it is possible to interpret the defects.

Stepped curve

Stepped curve or notches in the I-V curve represents the mismatch effect (Figure 6.24). Mismatch can be due to many factors, like shading, non-uniform soiling, bypass diode failure, etc. Multiple maxima produced in the I-V curve will mislead the inverter's MPPT, thereby reducing its efficiency.

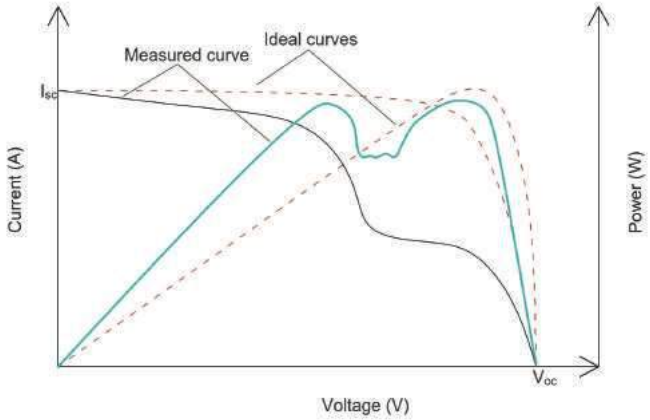


Figure 6.24: Stepped -I-V curve

Low current

This can be due to uniform soiling, thick shadow or hard soiling on the lower length edge cells of a PV module (will bypass the sub-string on module, Chapter 6.6.5), aging or degradation of the PV module (Figure 6.25).

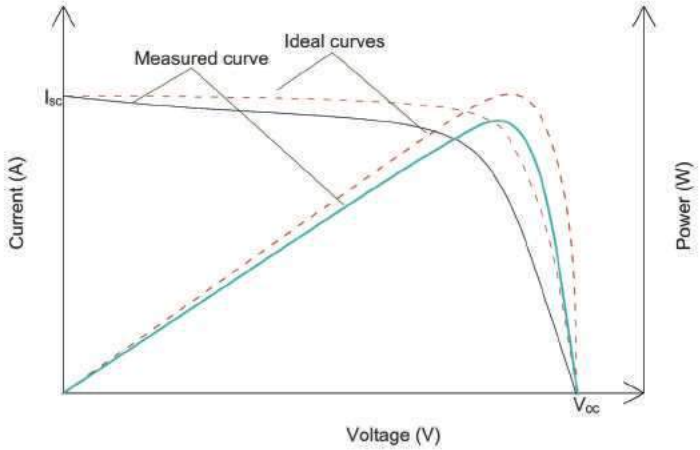


Figure 6.25: Low current shown on I-V curve

Other reasons

- Wrong information given to the I-V curve plotting software (changes in PV module rating or model, changes in array information like number of strings in series)
- Issues with I-V tracer irradiation sensor (calibration issues, short time variation in irradiance due to cloud change, shadow on sensor, sensor misalignment, measuring at low irradiance)

Low voltage

This can be caused by conducting bypass diode (Chapter 6.6.5), or the wrong number of modules in PV string, potential induced degradation (PID), thick or dark shadow on the module which enables the bypass diode, or ground fault (Figure 6.26).

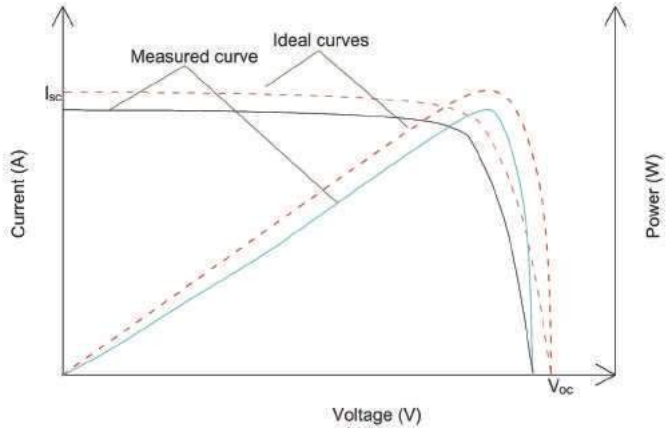


Figure 6.26: Low voltage shown on I-V curve

Other reasons

- Wrong information given to the I-V curve plotting software (changes in PV module rating or model changes in array information like number of strings in series).
- PV temperature sensor error will lead to error in internal calculation. Sometimes, due to a loose contact between sensor and the module's rear surface, measured values would be lower than the actual or higher than actual or there may be measurement errors due to a hotspot near the sensor. In such conditions, check the sensor connection or module temperature using other instruments. These measurement errors can even show higher voltage than expected, if measuring lower temperature than actual.

Rounder knee

This can be due to ageing of the PV module, or due to change in series and shunt resistance (which will change the slope of the vertical and horizontal legs), or PV module failures (Chapter 6.6.10) (Figure 6.27)

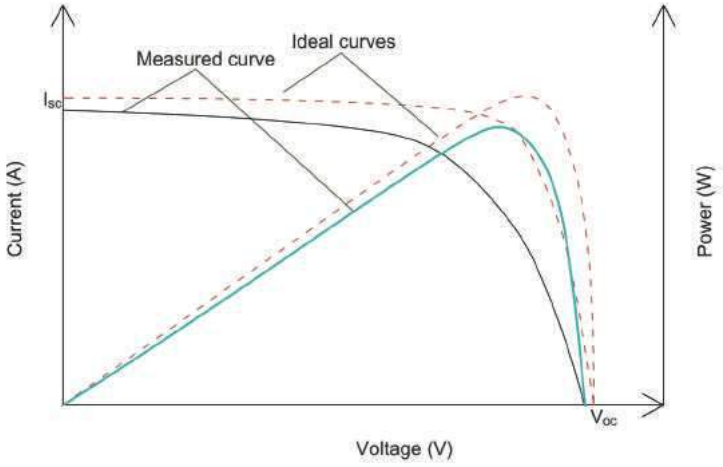


Figure 6.27: Rounder knee I-V curve

Increased slope in vertical leg

This may be caused by the increase in series resistance (R_s). Increase in series resistance is due to PV module faults/failures (Chapter 6.6.10), fault in DC interconnection. Special attention needs to be given in this case, because an increase in series resistance can increase hotspots in wiring or connections which can lead to severe fire hazards. Perform IR imaging to identify hotspots (Figure 6.28).

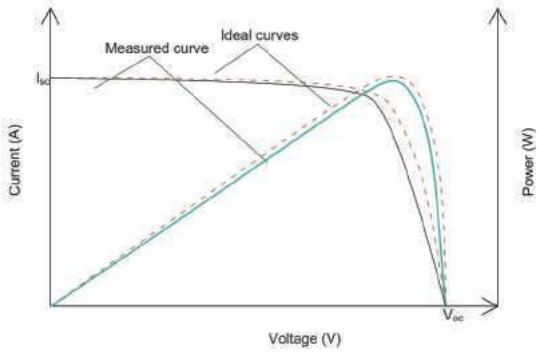


Figure 6.28: Increased slope in I-V curve vertical leg

Other reasons

If the measurement is carried out on string with a long run cable, the series resistance may increase. In such cases, repeat the test after bypassing the long run cable.

Increased slope in horizontal leg

This is due to shunt current paths in PV cells, module I_{sc} mismatch (in case string I-V curve tracing), or/and soiling and shading on PV module (Figure 6.29). Usually shunt current path can occur due to any localized defect in either cell or cell interconnects. This can lead to local hotspots.

The main reason for module I_{SC} mismatch in a string is due to manufacturing discrepancies or uneven degradation of PV modules. If the mismatch is small and randomly distributed across the string, steps or notches may not be present in I-V curve.

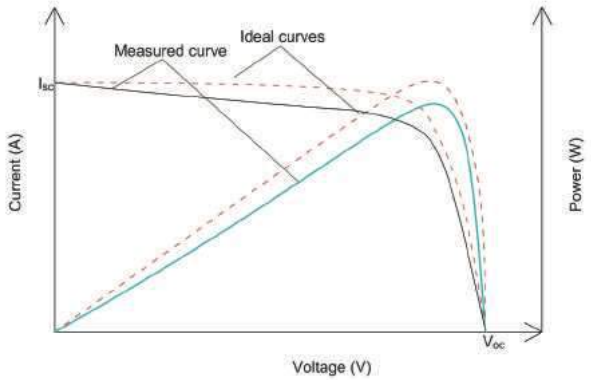


Figure 6.29: Increased slope in I-V curve horizontal leg

Fully distorted curve

May be caused by the non-uniform shadow on string (tree shadow), or a combination of soiling, shadow and other causes of mismatch effect (Figure 6.30).

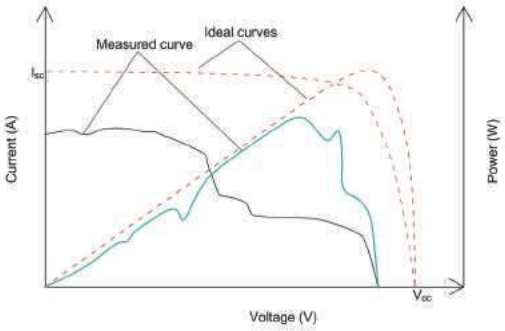


Figure 6.30: Fully distorted I-V curve

Other reasons

- Measurement error (as discussed above).
- Low irradiance or instantaneous change in irradiance.

6.6.2 Infrared or thermal imaging of solar PV modules

Thermal imaging allows analysis of the PV power plant's components without interrupting the power plant's operation. The basic principle behind the fault identification using thermal (or IR) imaging analysis is that any error or losses in power plant components will cause unusual temperature variations compared to normally operating parts. For example, micro cracks or cracks in a solar PV cell will reduce the power generation of that cell and this can lead to power dissipation followed by hotspot formation. Thermal imaging can be used to identify such hotspots in a large number of modules without making direct contact.

Selecting camera for thermal imaging: Thermal imaging is not a specialized technology for solar PV applications. Therefore, when selecting an IR camera it is suggested to check the application first. IR cameras of different resolutions will vary in cost from a few thousand to lakhs of rupees. Hence, the following points need to be considered while selecting a camera to meet the purpose and for cost of optimization:

- Resolution - In solar power projects, IR imaging is usually done over a small distance range (IR imaging using drones is coming up with high resolution cameras).
- Budget - IR cameras are considered costly equipment and the cost will increase with higher resolution.
- Handling - It is recommended to use handy cameras especially while carrying out rooftop solar plant inspections.
- Scale of PV project - Undertaking the thermal imaging of small scale projects is easy and can be done with the help of hand-held cameras. Since utility scale large projects are spread over a large area, drone-based IR imaging solutions will be helpful in completing the task in a shorter amount of time.
- Availability of manpower - The technical team available on site should have adequate knowledge to operate the IR imaging camera and identify issues. In case of non-availability of such manpower, the help of independent agencies providing dedicated services can be sought.

The following figures show some thermal imaging cameras and drone-based thermal imaging solutions.

Figure 6.31: Gun type IR camera (Source: FLIR IR cameras)

Figure 6.32: Small hand held IR camera (source: FLIR IR cameras)

Figure 6.33: IR camera which can connect to mobile phone (Source : FLIR IR cameras)

Figure 6.34: Drones with IR imaging camera

IR imaging test procedure:

I. Ensure all site specific safety measures are undertaken.

II. Ensure array/inverter is working in normal operating mode.

III. Check the irradiance level - irradiance in the plane of array should be relatively constant and greater than 600 Watts/m^2 (as per IEC 62446-1:2016) (there should be sufficient current to cause temperature difference).

IV. Solar PV module IR imaging can be done either from behind or from the front of the module.

V. IR image from behind the PV module is always better. However, in case of rooftop projects, on sheet roof structure test can be conducted from the front of the PV module.

VI. While capturing images, ensure that the angle of view is set as close as possible to 90^0 but not less than 60^0 to the module glass plane, and 90^0 to 45^0 if the image is captured from behind (Figures 6.35, 6.37).

VII. Set emissivity values as 0.85 for the glass and 0.95 for the polymer backsheet[6].

Figure 6.35: IR imaging of PV module at site

Figure 6.36: IR imaging of SPV plant BoS

VIII. Technician should be aware of reflections like buildings in the neighbourhood, clouds or self radiation of operator or camera (Figure 6.37). In case of indoor IR imaging, chances of such reflection is less and hence image capturing can be done from anywhere indoors.

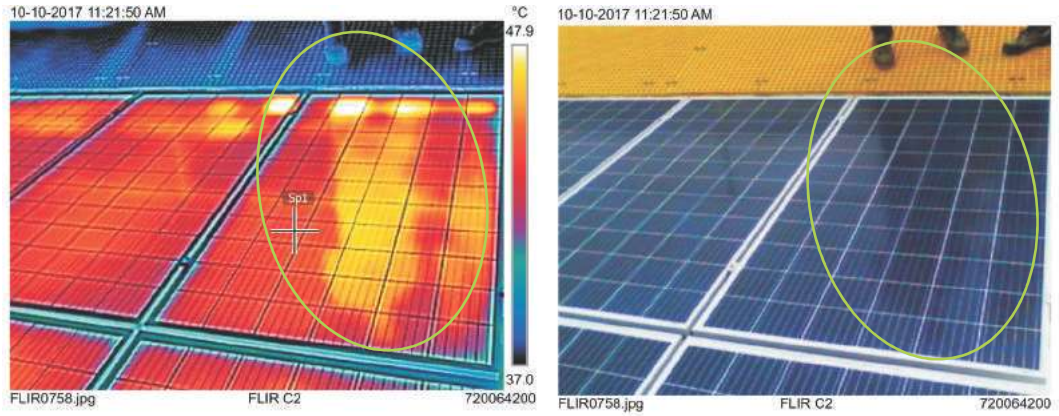
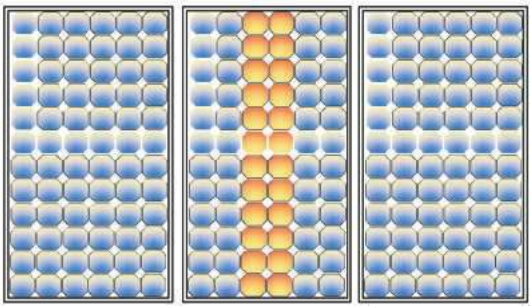
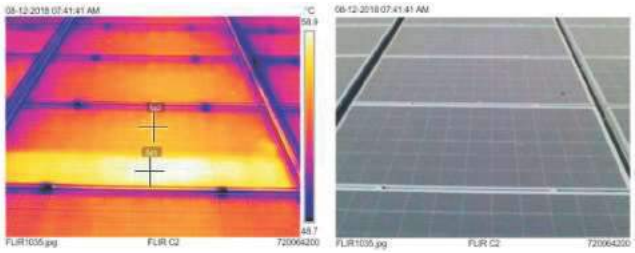
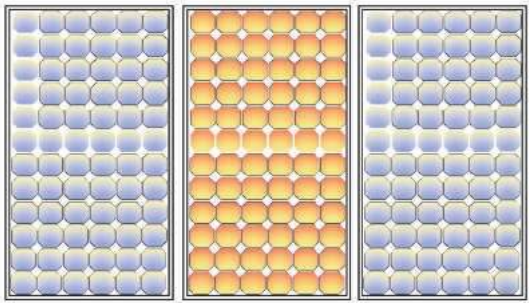
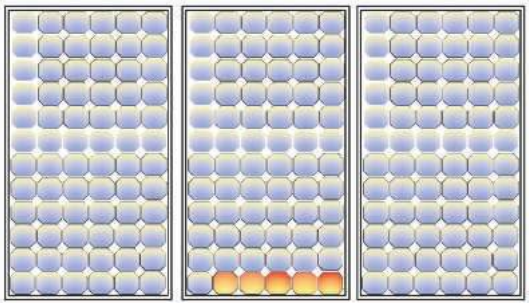
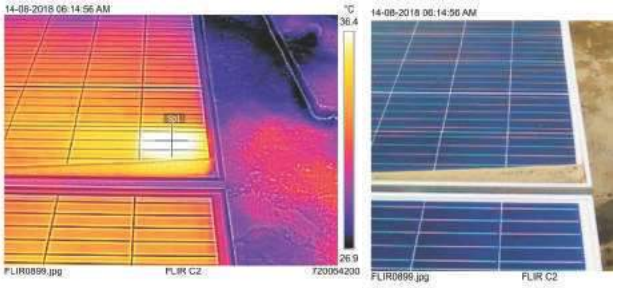
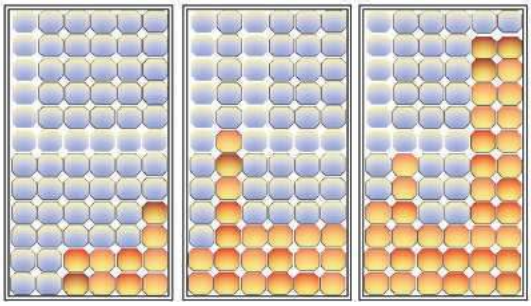
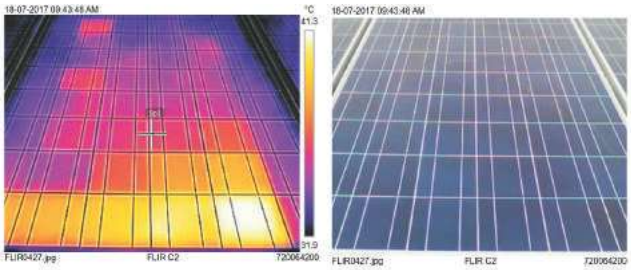


Figure 6.37: Error in IR imaging due to reflection from person standing nearby

IX. In case of PV module imaging, if the irradiance is less, then there could be less variation in temperature. In such cases terminals can be shorted for 5 minute and thereafter the image may be taken. Short circuit should not last more than 15 minutes for high irradiance (>700W/m^2) conditions.

IR imaging will indicate any failure at the initial stage and the technician should identify the failure using image patterns. Some images with possible failures are shown for ready reference in Table 6.4:

Table 6.4: PV module failures and IR image representation

IR image representation	Reason/ Causes
Significant temperature variation in PV module sub-array.  Figure 6.38: Sub cell string hotspot (representation)	Short circuited bypass diode: This can be caused by continuous thick shadow/hard soiling on solar module (Chapters 6.6.4 and 6.6.5). Or short circuit inside the module junction box.  Figure 6.39: Sub cell string hotspot (actual)
Significant temperature variation in PV module.  Figure 6.40: Whole module hotspot (representation)	Bypass diode short circuit/failure: This can be due to continuous thick shadow/hard soiling on solar module. Short circuit inside the module junction box. In case the PV module is disconnected or isolated from the circuit, those modules will show higher temperature than normal modules.
Hot spots at bottom edge of the module (towards lower end)  Figure 6.41: Module bottom edge hotspot (representation)	Shadow caused by soiling scale formed because of improper cleaning  Figure 6.42: Module bottom edge hotspot due to soiling (actual)
Increased hotspot towards negative end of the string  Figure 6.43: Hot spot due to PID (representation)	Shunting caused by charge accumulation on cell surface or PID effect (Chapter 6.6.8)  Figure 6.44: Hot spot due to PID (actual)

Shattered hotspot.

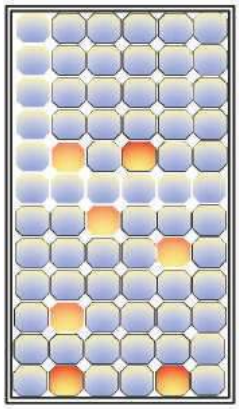


Figure 6.45: Hot spot due to multiple cell failure (representation)

There could be bypass diode failure or uneven soiling.

PV cell failures: Hot spots can occur due to any severe failure or a combination of failures (Chapter 6.6.10).

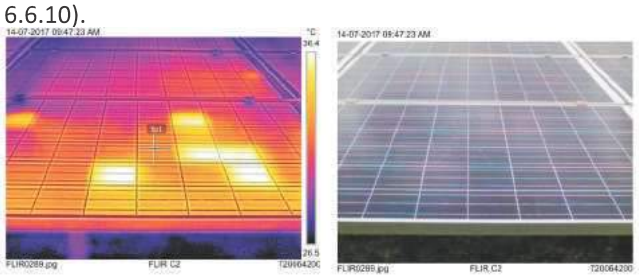


Figure 6.46: Hot spot due to multiple cell failure (actual)

Partial hotspot cell/s.

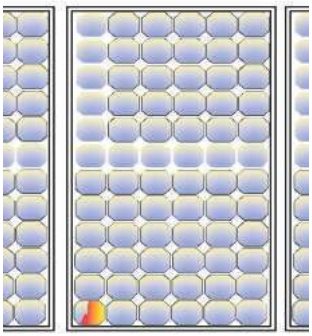


Figure 6.47: Partial cell hotspot (representation)

Bubbling effect on the rear side of the cell, active cell cracks (Chapters 6.6.6 and 6.6.10).

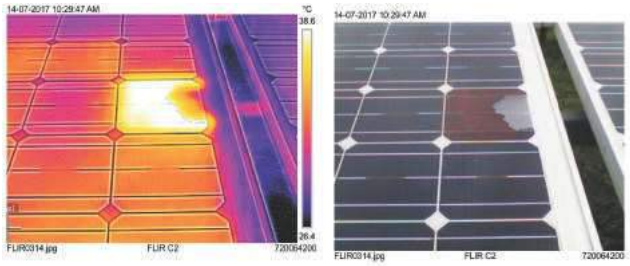


Figure 6.48: Hot spot due to bubbling effect(representation)

Pointed hotspot.

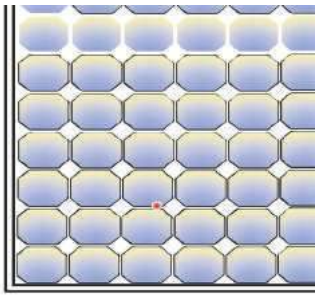


Figure 6.49: Pointed hotspot (representation)

Interconnection ribbon failure or corrosion. Abnormal increase in temperature (~150^{0}C) i.e. 2 to 4 times the temperature of a normal cell.

Note: Don't touch the point with bare hands.

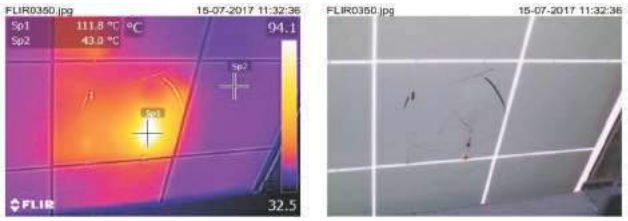


Figure 6.50: Hot spot due to Interconnection ribbon failure or corrosion(actual)

Hot spot on cable interconnection (AJB), warm cable.

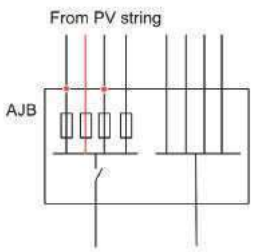
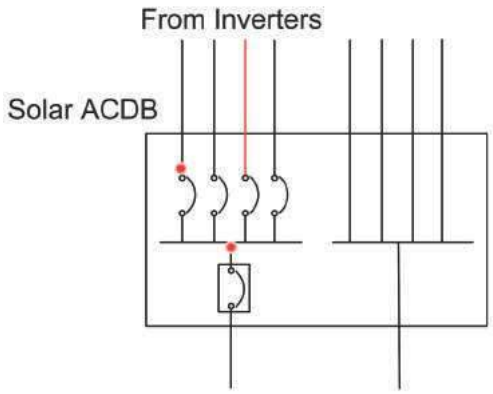
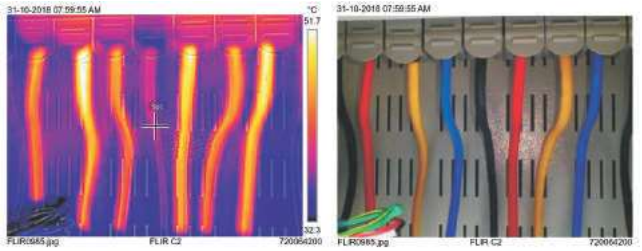
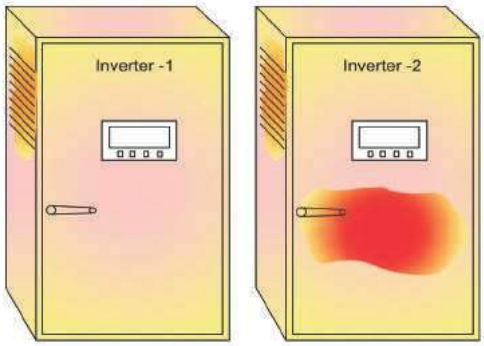


Figure 6.51: Hotspot on cable interconnection (AJB) (representation)

Interconnection hotspot may be due to improper cable termination or due to corrosion at interconnection point. This issue may occur in case of MC4 connectors also and may lead to high hazard situations (Chapter 6.6.7).

Interconnection hotspots can be observed at the inverter too. If the cable is warm, it may be due to improper cable sizing, ageing of cables, etc.

Hotspot on cable interconnection (ACDB), warm cable.  Figure 6.52: Hot spot on cable interconnection (ACDB)(representation)	Interconnection hotspot may be due to improper cable termination/ bending radius or due to corrosion at interconnection point. If the cable is warm, it may be due to improper cable sizing, ageing of cables, etc.  Figure 6.53: Hot spot on ACDB cable termination (actual)
IR imaging of Inverter  Figure 6.54: Hot spot on inverter cabin (representation)	If the IR image of an inverter is showing increase in internal temperature of the cabinet it may be due to: • Interconnection failure in any power electronic component. • Inadequate ventilation or ventilation fans are not working. • Space between inverters is not in line with manufacturer's specifications or exhaust of first inverter is entering the second inverter leading to increase in temperature in the second inverter.

It is recommended to carry out plant SLD and layout during IR imaging. In case of any issue found during the imaging, identify the area in the layout and SLD for further analysis. Drone-based IR imaging can be utilized for analysing large areas in a short span of time; it is recommended to conduct nearby IR imaging if any issues are found. Since the I-V curve tracing is a time consuming process, it is recommended to conduct IR imaging before I-V tracing. If temperature irregularities are found in IR imaging, then detailed visual inspection of strings may be undertaken.

Safety note:

- Do not touch the PV module with bare hands to confirm the temperature difference, physically.
- Watch your step while simultaneously walking and capturing IR image.
- Use proper PPE while testing.
- Place the IR camera in a safe position while climbing onto rooftops (your life is worth more than the instrument).

6.6.3 Electroluminescence (EL) imaging

Electroluminescence (EL) imaging is an indoor testing activity and is commonly used for detecting cell cracks. It is based on the working principle of light emitting diode, i.e. diode will emit radiation when current is applied to it. A solar PV cell is similar to a diode and when controlled current is applied, radiative recombination of carriers causes infrared radiation near 1150 nm. It can be detected by a silicon-charged coupled device camera, which is similar to a digital camera but optimized for sensitivity to near-infrared and cooled to reduce thermal noise.

Normally, EL imaging is performed in a dark environment to avoid radiation emitted by the background lighting noise. All commercial solar cells and modules undergo multiple EL testing during the production phase. PV cell parts, in the case of physical separation or cracks in those areas will not emit radiation and will appear as dark lines (Chapter 6.6.6). Now, EL imaging test kits or mobile PV module testing laboratory set-ups are available. Operational/working PV

modules which are not performing well can be tested in detail at the site to identify the root cause of generation loss. Such PV modules can be taken out separately in one particular string/MPPT so that other strings/MPPTs can deliver power effectively. Figure 6.55 shows an EL image of a module:

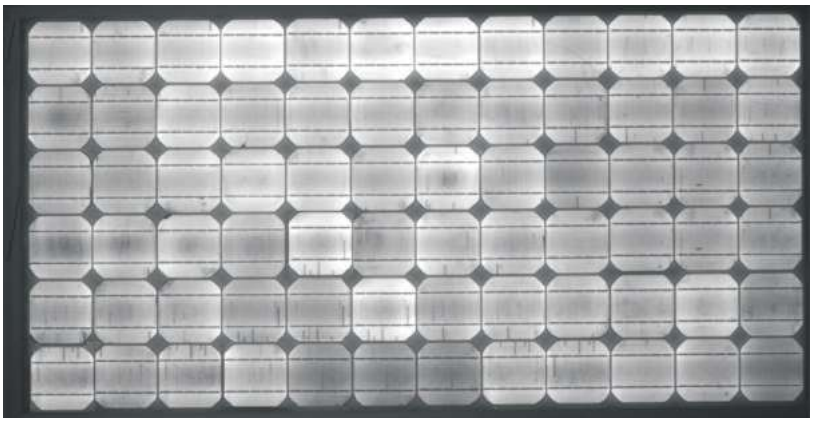


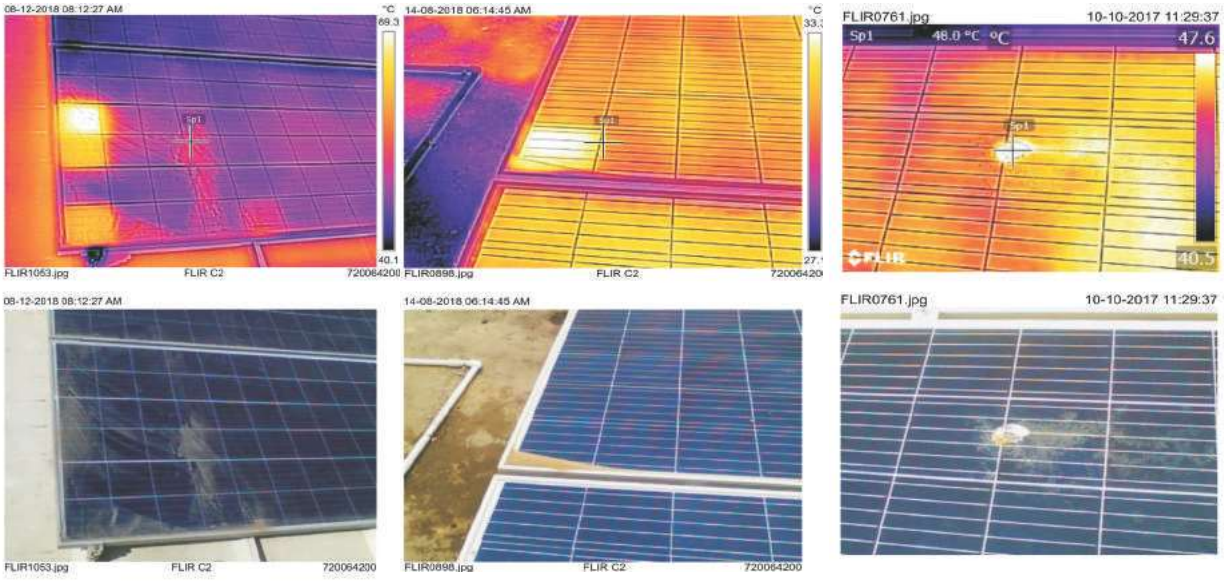
Figure 6.55: EL image of a module

6.6.4 Analysis of soiling

Soiling on PV modules is accumulation of dust particles or any sticky materials, like bird droppings, which will lead to power reduction. Soiling leads to reduction in transmittance and hence the effect of soiling is comparable to continuous shadow on a solar PV module [7]. From our study it was observed that rooftop PV power plants are more prone to soiling losses compared to utility scale power projects. This is due to reasons such as difficulty in accessing the roof. This results in ineffective cleaning of modules or an increase in the time span between two cleaning cycles which in turn leads to dense soiling; a lower tilt angle in some cases leads to greater soil deposition, etc. Soiling will affect the plant's performance adversely and the output will be lower than the estimation made during the plant's designing. Improper cleaning of modules will lead to scale formation on the bottom edge, as shown in the Figure 6.56.

Figure 6.56 : Scaling at bottom of modules

Uneven soiling has greater adverse effects than evenly distributed soiling. Continuous shadow and soiling will not only reduce power generation but create hotspots. Further, it will accelerate degradation of PV modules that eventually will lead to module failure [8]. Hot spot effects due to uneven soiling in newly commissioned power plants can be seen from the following IR images (Figure 6.57). Results shows that uneven soiling, bird droppings and scaling at the bottom of modules will lead to local hotspots.



(a) Hotspot due to uneven cleaning

(b) Hotspot due to uneven cleaning and shadow due to bottom scaling

(c) Hotspot caused by bird droppings

Figure 6.57: IR images of PV module affected by uneven soiling

These hotspots can increase PV cell degradation, hence, proper cleaning of the PV module not only improves the efficiency of the power plant at that point of time, but also extends its overall life. In O&M of PV power plants, PV module cleaning is a highly manpower consuming activity. Further, frequent cleaning increases consumption of water and manpower resulting in increased O&M costs, which is not desirable. Cleaning of solar modules involves technical, economic and environmental factors like selecting the period of cleaning cycle, manpower requirement, water usage, method of cleaning, weather conditions, etc. Therefore, cleaning of PV modules requires a scientific approach rather than a fixed cleaning cycle. Detailed analysis of selection of cleaning methodology for SPV power plant is given in Annexure X.

There are three methods commonly used for analyzing the cleaning requirement or selection of PV module cleaning span, such as:

A. Visual inspection

Visual inspection is the most commonly used method in small rooftop power plants. Based on visual inspection of soil deposition, the requirement for cleaning is decided. However, in this method there is no direct co-relation between soiling loss/power loss due to soiling and the cleaning cycle selection. Further, it is observed that there are power plants which follow fixed cleaning spans only to simplify the O&M contract. However, for large utility scale power plants this is not a desirable solution.

B. DC input based soiling analysis

This method analyzes soiling ratio (SR) for optimizing the cleaning cycle. It is useful for utility scale projects because it requires more technical tools and analysis. Since this method of soiling ratio analysis uses DC input data, it avoids the losses getting added on the AC side. The soiling ratio (SR) is the ratio of the actual power output of the PV array under given soiling conditions to the amount of power that would be expected if the PV array were clean and free of soiling [1].

There are quite a few methods for calculating soiling ratio. These methods, explained in IEC 61724-1, use I_{sc} and P_{max}.:

SR using short circuit current = $I_{sc,measured}$ / $I_{sc,expected}$

SR using power = $P_{max,measured}$ / $P_{max,expected}$

Key points to be considered are as follows:

- I_{sc} can be measured by using a multimeter or clamp meter.
- P_{max} can be calculated manually or measured by using I-V tracer.
- Of these two methods, SR calculation using P_{max} is more effective as it represents the actual power loss due to soiling.
- From experiments it was found that SR calculated at irradiance above 750W/m^2 is more accurate.

- In the case of rooftop power plants of capacity less than 100 kW, it is difficult to calculate SR regularly using P_{max} method. For utility scale power projects and commercial power plants it is preferable to do the soiling ratio calculations using P_{max} method and the SR can be used for optimizing the cleaning frequency of the PV modules.
- The I_{sc} method of calculation of SR is simpler than P_{max} method. However, I_{sc} method of SR calculation should not be used for partial soiling. There will be a difference of 6% to 8% in SR measurement with I_{sc} method compared to the P_{max} method.

Cleaning cycle optimization can be carried out by comparing the SR calculated by using either I_{sc} or P_{max} method at string level. Further, there are soiling ratio sensors also available in the market which can be used for analysing soiling to optimize the cleaning cycle.(Chapter 4.2)

C. AC output based soiling analysis

Soiling ratio can be analyzed based on the AC output power/energy recorded at inverter or energy meter level. Based on the daily generation, data soiling ratio can be analyzed to optimize the cleaning cycle. Steps to be followed while analyzing SR for two different sized solar plants are given below:

Small power plants using single inverters: In case of small power plants, it is assumed that cleaning of all PV strings will be completed in a single day because the number of PV modules is few.

I. Record maximum power generated per day and/or total energy generated per day from the inverter reading. This can be done from the first day of cleaning.

II. It is recommended to note the weather details for each day. If there is no sensor connected for measuring weather data, data from nearby weather stations can be referred to. This is to avoid comparison of generation data for a cloudy day with that of a sunny day.

III. If linear reduction in energy generation is observed on sunny days, cleaning can be undertaken after visual inspection.

Power plants using multiple inverters: In case of large power plants, it is assumed that cleaning of all PV strings connected to the inverter will be completed in a single day so as to compare the daily energy generation for each inverter.

I. Record maximum power generated per day and/or total energy generated per day from the inverter readings.

II. Try to clean all the strings connected to one MPPT/inverter in a day. Compare the generation data of inverters connected to cleaned modules with that of other inverters.

III. Repeat the process for every cleaning cycle.

Note:

- In case of string inverters with multi MPPT, usually all DC connectors/strings are distributed among the MPPTs. For example, in 2 MPPT inverters with 10 DC strings, each MPPT will be connected to 5 DC strings. These 5 DC strings will be paralleled before MPPT logic is applied.
- Hence, while cleaning the PV module it is suggested to clean all the modules connected to the same MPPT to get the desired result.
- Partial cleaning of modules connected to one MPPT will lead to mismatch effect followed by power loss.

6.6.5 Shadow analysis

Primarily, there are two types of shadows which affect the power generation from a solar module. These are: (a) removable shadows like vegetation and (b) fixed shadows, like building projections (Figure 6.58).

Removable shadows needs to be eliminated at certain intervals based on the visual inspection of the plant. Such shadows may appear due to growth of nearby trees and the sun path. It is observed that rooftop solar plants are more affected by partial shadow and mismatch effect than utility scale power projects. This is because of flexibility in designing since there is large availability of space in utility scale ground-mounted projects. Mostly rooftop projects face partial shadow from nearby buildings, trees, parapets, chimneys, etc. Some of these issues can be solved by repositioning movable objects, trimmings trees, etc. The most frequent cause of mismatch effect, is partial shadow due to trees. Cutting trees to eliminate shadow effect is not always possible because of local regulations and environmental factors.

Fixed shadows need to be considered only during the design stage. If there are shadows developing during project operation, they have to be taken care of by modifying the installation so as to avoid them.

Figure 6.58: Removable and fixed shadow on solar module

Impact of partial shadow on solar modules:

A commercial solar module is a combination of 60 or 72 numbers of solar cells connected in series and such a solar cell can be referred to as a photo diode [9 -12]. If one cell is shaded for any reason, it will generate less current than the other cells in the string, and the unshaded cells will try to pass more current to it than it is capable of handling. Such a shadow affected cell actually develops negative voltage and will starts consuming power instead of generating it [13]. As the power output of the module drops down, it pulls down the rest of the modules in the string because all modules are connected in series. Since strings are connected in parallel to a MPPT in an inverter, drop in string voltage due to shadow will derate or reduce overall power output of the inverter [14].

In addition to reducing the power output, partial shading may cause permanent damage due to hotspots. This is because the solar cell in the shade will starts dissipating power that it received from the unshaded cells. Bypass diodes are used to solve the partial shading problem [15].

The bypass diodes (BD) are installed in the PV module junction box, in reverse biased condition, as illustrated below. In PV modules working under normal conditions, the voltage across the BD will be less than threshold voltage and it will not conduct (will restrict the reverse voltage to less than breakdown voltage of the PV cells). In shaded conditions, the voltage across the BD will increase and start conducting before the reverse voltage reaches breakdown voltage [16-22], thereby bypassing the shadow affected cells or sub-module part and protecting this section from overheating.

Generally, Schottky diodes are used as bypass diodes, because of their lower threshold voltage as well as fast switching speed. These characteristics help Schottky diodes protect the solar cells by operating quickly when small reverse voltage (due to shadow) occurs.

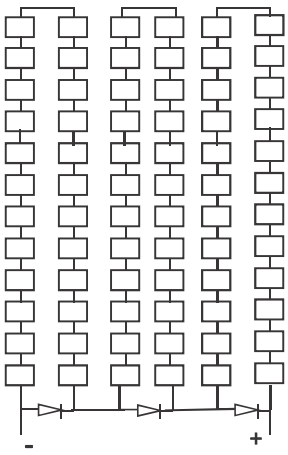


Figure 6.59: Internal connection of solar module

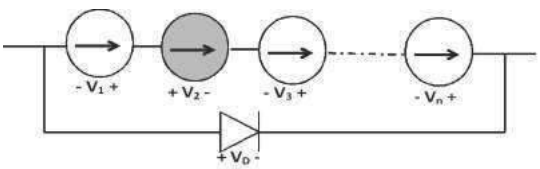


Figure 6.60: Bypass diode across the PV cells where one cell is under shadow

Figure 6.61 illustrates the actual PV and I-V curve of a string affected by partial shadow. This shows multiple maxima due to mismatch effect. This multiple maxima will confuse the inverter's maximum power point tracker (MPPT) and as a result output will reduce.

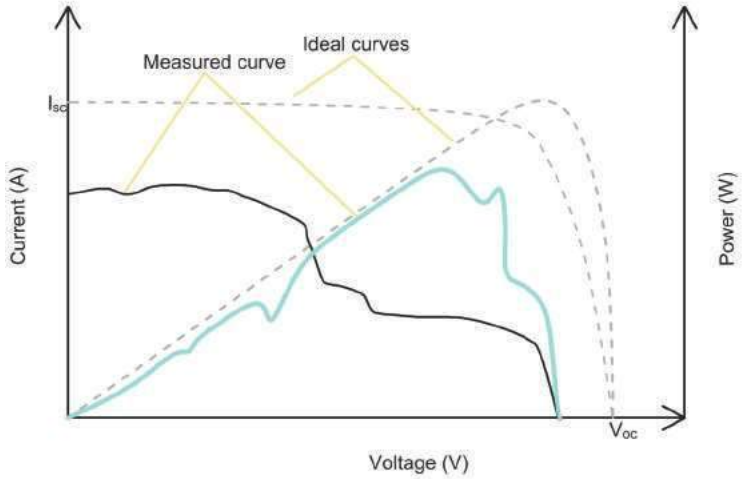


Figure 6.61: Shadow affected string PV and I-V curve with multiple maxima

Mitigation of shadow

Fixed shadows of mountains, trees, buildings, etc., can be avoided only during the design stage. If such shadows are observed during project operation, they can be mitigated by restructuring the plant layout. Also fixed shadows caused by nearby newly constructed buildings during the O&M period, can be avoided by restructuring the plant layout.

Removable shadows are due to growth of nearby trees. Shadows from moving clouds may also affect large projects. These shadows cannot be controlled but shadows from nearby trees can be eliminated by proper tree trimming within the permissible limits of local regulations.

The impact of fixed and removable shadows can be reduced by rearranging the shadow affected strings under one MPPT, so that other MPPTs connected to shadow free modules can perform to full efficiency. The impact of partial shadow can be reduced by installed power optimizers for small scale power plants where their is limited space constraints in plant layout.

6.6.6 Analysis to identify loss of power due to cracks in solar PV modules

Cracks in solar PV modules are ubiquitous and a genuine problem. They are hard to avoid and their impact difficult to quantify on the efficiency of modules during their lifetime.

A. Causes of micro cracks

There are a number of reasons that micro cracks appear in a PV module. They could be from cell manufacturing, PV module manufacturing, transportation, installation, during the operation of the PV module, etc. Apart from these, climatic conditions like snow loads, strong winds and hailstorms might create major cracks on the surface of PV modules [23, 25]. The presence of micro cracks doesn't cause marginal power loss every time but depends on the age of the crack, its position and the type of crack, etc.

Generally, micro cracks can be divided in two: active and inactive cracks. From extensive studies done by researchers it is clear that most micro cracks observed during the production stage of PV modules are of the inactive type [26-28]. During the initial stages, these cracks will be hidden and not easily observed. However, with ageing and due to climatic conditions, these inactive cracks becomes active and lead to significant power loss and accelerated degradation [26],[29].

B. Stages of micro crack production

Cell micro cracks can occur during the production stage or the operations stage of PV modules. During soldering operations in the production phase of a PV module, the cell and wires heat up and expand and later on cooling, contract. These contractions lead to stress on the cell's surface and may cause micro cracks [29]. In the production phases of PV modules, cells with micro-cracks are identified and rejected before they are integrated into the cell string. This is achieved by undertaking tests like ultrasonic, thermal flux thermography or electroluminescence (EL) imaging, etc. (Chapter 6.6.3).

Another stage where micro cracks can materialize is during the lamination process of PV modules. Thermo-elastic residual stress builds up in the solar cells after module lamination which can lead to micro cracks. Usually in the last stage of PV module production, modules affected by micro cracks can be identified by thermal flux thermography or electroluminescence (EL) imaging. Ideally, a three stage micro crack detection exercise should be performed in the production line. Firstly, cell testing before lamination and then two more tests in the final stage. The end user can request for the EL images of the purchased PV modules, for his reference.

Chances of micro cracks developing are high during transportation of the PV module. It is observed that the rate of micro crack occurrence is higher in the case of rooftop power plants than in ground-mounted power plants because of the following:

- Transportation of PV modules to rooftops involves more handling of PV modules.
- There are space constraints for storing PV modules on the rooftop during installation.
- There are greater chances of walking over a PV module during installation and operations.

Working on a PV module is a key cause of on-site micro cracks (Figure 6.62). This issue can be seen at many sites during the installation and operation phases of a power plant. Usually, this will create inactive micro cracks which will gradually become active for reasons discussed earlier.

Figure 6.62 Cell crack formation due to walking on the modules during installation and O&M

C. Effects of micro cracks

When cracks appear in a solar cell, the parts separated from the cell might not be totally disconnected, but the series resistance across the crack will vary as a function of the distance between the cell parts and the number of cycles for which the module is deformed. In the case of full electrical isolation of a cell part, the current produced by the broken cell, and subsequently by all the cells connected in series with it, decreases. When a cell part is fully isolated, the current decrease is proportional to the disconnected area [30]. Apart from direct reduction in performance, micro cracks will catalyze the discoloration effect, snail trails, delamination, etc.

Performance loss in a PV module usually varies according to the orientation of the cell cracks. Several studies have been conducted to analyze the effects of micro cracks on PV modules. One such study indicates that micro cracks on less than 8% of a cell's area does not influence the module's power and the output voltage will start reducing only when the inactive cell area is sufficient to enable bypass diode, thereby bypassing two cell rows in a PV module [31].

Crack orientation has significant influence on performance reduction. Certain studies have divided cell cracks into 6 orientations, as illustrated in the following Figure 6.63 [29]. It was found that diagonal cracks, a crack oriented parallel and one oriented perpendicular to the busbar, have a major impact on the power output of the module. Cracks parallel to the busbar appear most frequently and they separate a large cell area, which may lead to a significant reduction in module power output.

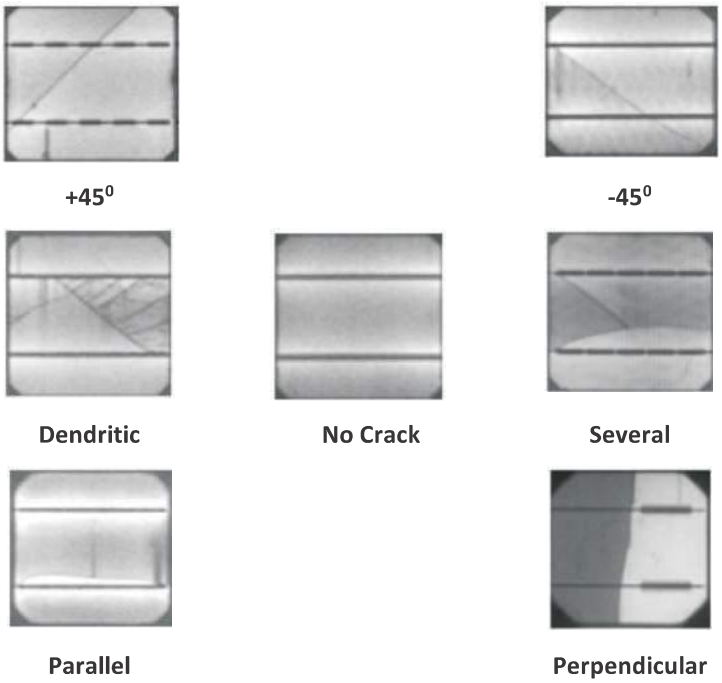


Figure 6.63: Crack orientation [29]

D. Crack identification and monitoring

It is not possible to detect micro cracks in a working power plant, on site. Separate arrangement for EL imaging is needed for detection of micro cracks. A sample EL image showing micro cracks is displayed in Figure 6.64:

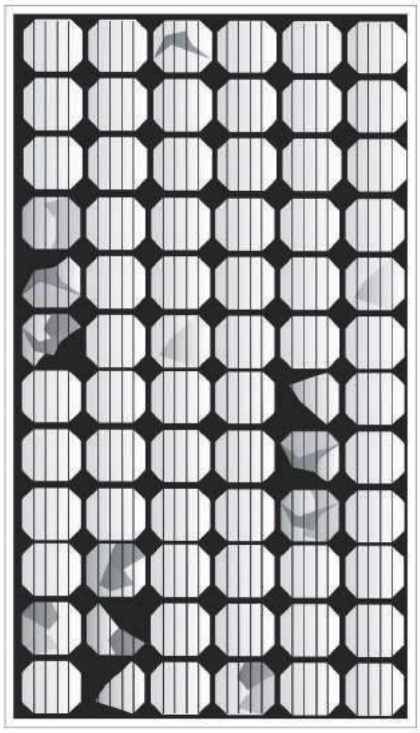


Figure 6.64: Micro cracks in EL image

Snail trails show the crack path. Tracking snail trails is another method for identifying micro cracks, but this will not work all the time. Since snail trails will not play a significant role in power reduction during the early stages, often operators do not pay much attention to them. However, continuous monitoring of affected PV modules needs to be done. Increase in cell temperature due to the effect of micro cracks can be detected by IR imaging.

6.6.7 Faults in DC connectors

DC connectors are a critical parts of an installation with regard to safety and yet they are often overlooked, compromising the performance of the array and putting the system's safety at risk. Earlier, workers used to connect the PV module inter-connection cables to the junction box, separately, but it was a time consuming exercise and sometimes it damaged the junction box. Nowadays, PV modules come with interconnecting cables with MC4 connectors and hence interconnection is much easier, secure, and saves installation time[32].

MC4 connectors are small in size but are a very important component of a solar installation. Inferior quality MC4 connectors will increase the O&M and create safety hazards. Improper DC connections/faults in MC4 connectors can lead to increased contact resistance, DC arcing, power loss, increased down time, and electrocution of working personnel, etc. Overheating of an MC4 connector may also lead to fire. Hence, the selection and use of a proper MC4 connector is of prime importance during the installation and O&M phases. Selection of a connector is dependent on the size of the cable being connected. Parts of an MC4 connector are presented in Figure 6.65.

Figure 6.65: Components of MC4 connector

Faults in MC4 connector

Typical failures are caused by:

- Use of improper connectors of different types which may not fit exactly.
- Inaccurately crimped connectors connected to extension cables used for connecting PV modules to the AJB, or the inverter.
- Use of improper size DC cables which may lead to improper sealing at the end cap of the MC4 connector. This will lead to moisture ingression and further corrosion of contacts.
- Use of different materials or brands may lead to mismatch of connections, resulting in poor connections.
- Use of low quality materials may cause rise in connector temperature, which could result in overheating of the system, possibly causing a fire, or allowing water to enter.

Safety note:

- Do not work on live or load-carrying parts without proper PPEs.
- Do not allow cable with connectors to hang; use proper cable ties to avoid such situations. Do not tighten the cable tie too much else it may lead to cable breakage in future.

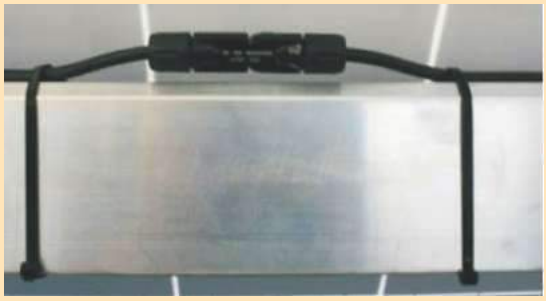


Figure 6.66: Best practices in DC connector installation

(Source: Guide to Best Practice - Connections and Connectors ensuring the best performance of REC Peak Energy solar modules)

- Disconnect AJB or inverter before working with connectors.
- Try to avoid working during peak production time; always follow safety rules before working with connectors.
- Always use proper disconnection tools to disconnect the MC4 connector.
- Connection and disconnection processes are illustrated below in Figure 6.67 [33].

Connection and disconnection

- Align latches of the male plug with receptacles of the female socket.
- Insert the plug into the socket until a firm click sound is heard.
- Check the connectors to ensure they are engaged correctly by pulling them apart.
- Insert the two extended posts on the end of the tool into the side of the female MC4 connector.
- This disengages the locking mechanism on the male connector and allows the two connectors to separate.

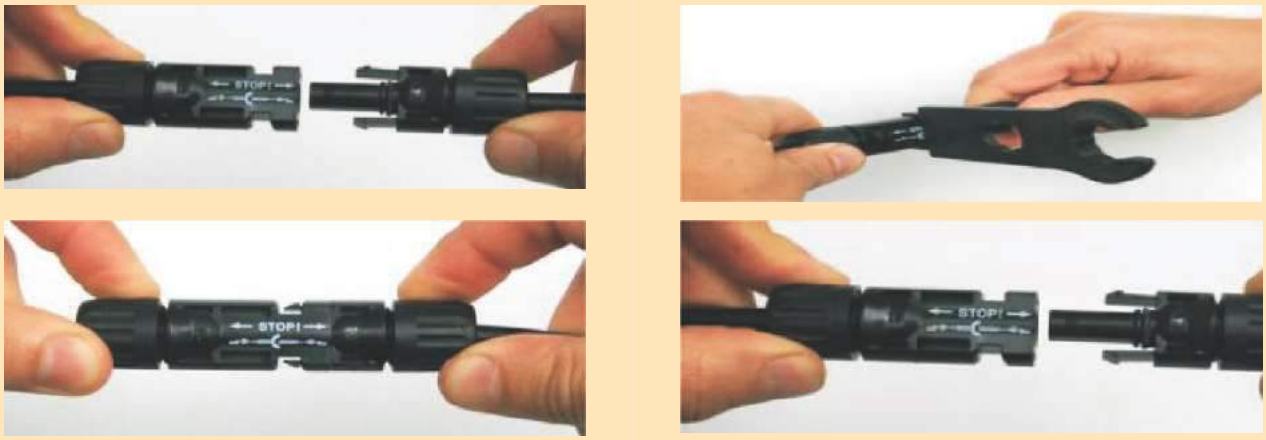


Figure 6.67: Best practice for MC4 connection and disconnection

6.6.8 Analysis of loss due to Potential Induced Degradation (PID)

In recent years many of the newly commissioned power plants have been found to be with exponentially reduced performance ratio (PR). After detailed analysis and studies, researchers found that this is due to potential induced degradation (PID) caused by the introduction of increased module sensitivity and higher system voltages. In June 2011, the Fraunhofer Center for Silicon Photovoltaics published its test results that showed PID causes almost 70% power reduction. During the testing of two-year-old PV power plants, it was found that there was more than 15% degradation in power output.

A. Process of PID

In PV power plants, photovoltaic modules are connected in series to achieve expected voltage. For example, consider a commercial on-grid power plant using 20 numbers of 300 Wp crystalline PV modules in series having $V_{OC,string}$ of around 900VDC. For safety purposes, the module frames are grounded through MMS to earthing. The value of the absolute potential (to the ground) at the positive pole, negative pole, or somewhere in-between, principally depends on the inverter's topology. In addition, absolute potential of an array does not necessarily remain at one level but changes constantly while in operation depending largely on the type of inverter and its internal connection concept. In case of inverters with transformer or magnetic isolation, it is possible to ground the negative part of the DC circuit as per safety regulations. Since the neutral point of the local network transformer is generally grounded, the N conductor has ground potential. In connection diagram (Figure 6.68), a transformerless inverter has the different mains phases alternate between being connected to the array's positive pole and negative pole. The alternating switching states of the bridge circuit result in transformerless inverters being connected to a second ground circuit for at least 25 times per second. For this reason it is not advisable to use transformerless inverters with grounded PV generators. On the other hand, since the PV arrays' DC network can no longer be operated without a ground, ground fault currents can occur. If the negative pole or the positive pole is grounded in a solar power array with a transformerless inverter, the inverter's output stage could be short circuited under certain connection conditions.

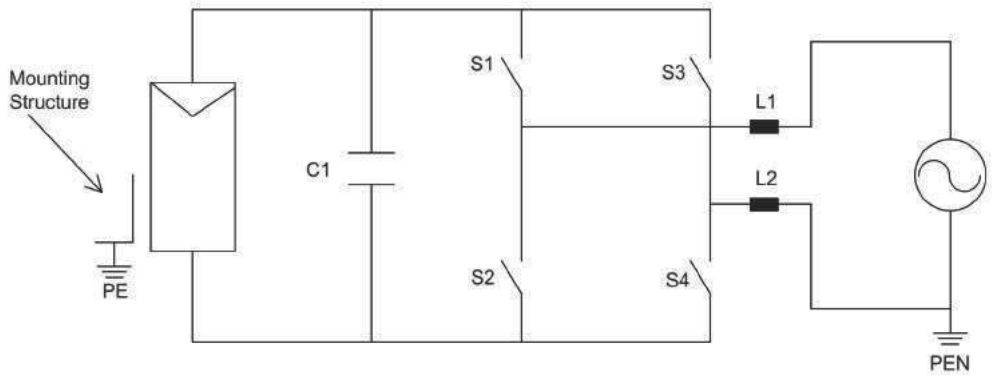


Figure 6.68 : Inverter concept drawing with switches

So along with voltages between an array's positive and negative poles, there are also voltages between individual solar cells and the ground. If an array's substructure is grounded in line with requirements, these voltages are then directly between the cells and the PV modules frames or clamps. This will lead to high negative voltage between the cells of the module (negative end) and the frame. This electrical voltage attracts the electrons from the materials used in the PV modules and discharges them through the grounded frame, resulting in a small amount of leakage current. This unexpected movement of charge carriers disturbs the photovoltaic effect and leads to increased local shunting and drops in the fill factor.

Step by step PID process:

Module frames are grounded.

There is a voltage difference between the frames and the cells with negative voltage.

This voltage may cause a migration of mobile ions through the module either towards or away from the cells.

Mobile positive ions (Na+) contained in the glass substrate can migrate towards the cells.

Crystalline defects permit the ingression of these Na atoms, which results in module degradation.

From previous analysis done by a number of researchers, and from site experiences, it was observed that severity in PID effect is high from the negative end to the positive end of the array. There are a number of factors catalyzing the PID effect other than potential between cell and module frame. The conditions for the occurrence of PID are summed up in these levels:

- **Environmental factors**: These are dependent on the temperature and humidity, and are accelerating agents; they increase the amount of leakage current [34].
- **System factors**: They depend on the system voltage, type of biasing, type of grounding used.

- **Module factors**: These can be used to control leakage current to a large extent by increasing electrical resistivity of insulation by choosing proper materials such as encapsulate, glass type or introducing barrier layer to sodium ions.
- **Cell level**: A major factor influencing the PID resistivity at cell level is the refractive index of the ARC on the cell, homogeneity of ARC and also on the Si to N ratio of ARC (SiNx).

The main effects of PID are reduced R_{sh}, FF, V_{oc}, hotspots towards negative side of the string and ultimately reduced PR even during the initial years of a plant's life. Solar module degradation due to PID will gradually build up w.r.t time, and as PID increases, the above mentioned effects will also rise. I-V curve of PV module which is affected by PID for different time periods is shown in Figure 6.69.

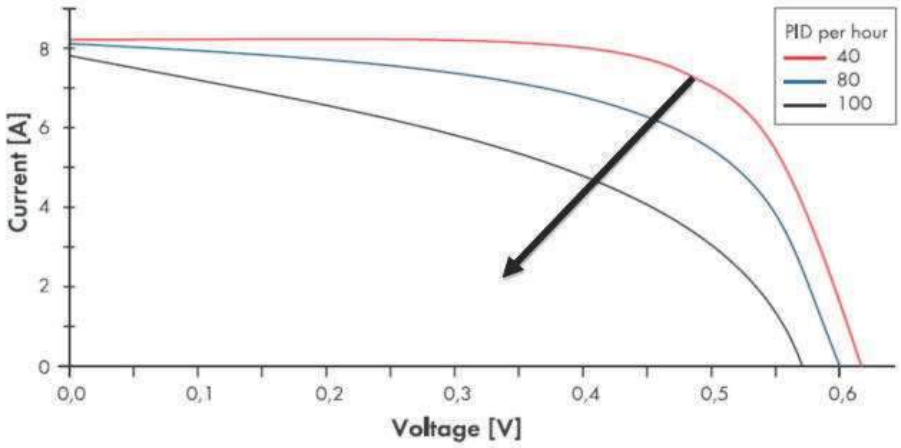


Figure 6.69- Effect of PID [38]

B. Testing to identify presence of PID

If a power plant/array is under-performing, one of the reasons could be the PID effect. Following are some tests for detecting PID effect:

- **Open circuit voltage**: A PV string with PID has a much lower open-circuit voltage than one without PID. The first indications of PID can therefore be found in the comparative measurement of open-circuit voltages. PID typically affects only one end of a string – the positive end for modules with n-doped cells, and the negative end for modules with p-doped cells. Therefore, if you are able to measure the open-circuit voltage for each module in a string and it continues to decrease as you approach the end of the string, you may very well have a case of PID. This is a more practical method for detecting PID with the help of a less expensive tool like the multi-meter.
- **Electroluminescence imaging**: Electroluminescence imaging can be used to detect the PID in the module easily. This is performed with a CCD (couple-charged device) camera, while the module is biased with a current source and without sunlight. A module free of PID has an electroluminescence image with all cells having almost the same brightness, whereas a module affected by PID has dark cells, i.e. shunted cells due to PID. Figure 6.70 shows the electroluminescence images of 20 modules connected in series in a string affected by PID.

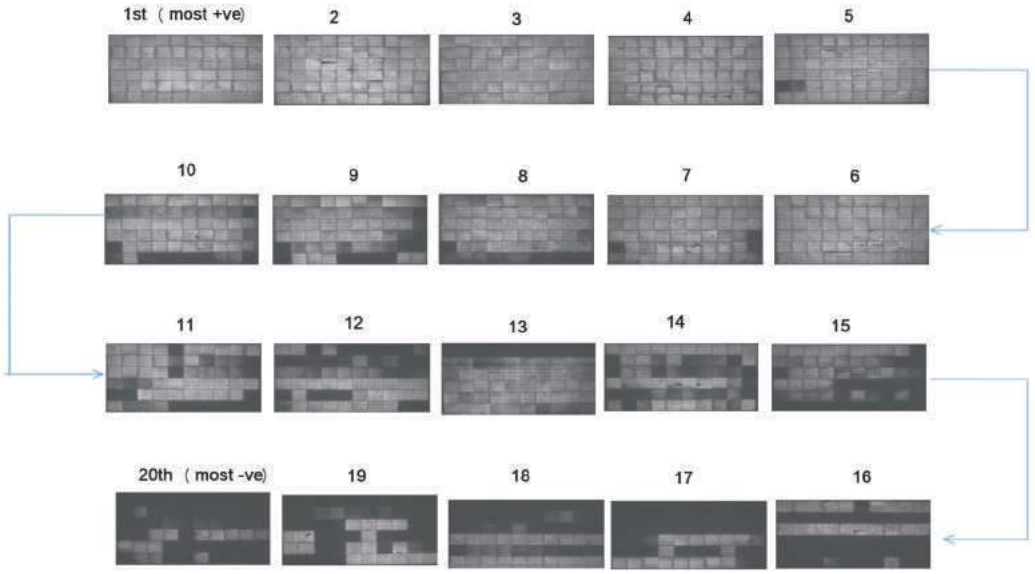


Figure 6.70: Electroluminescence images of 20 modules connected in series in a string affected by PID: The modules closer to the negative pole (module number 20) have dark cells (evidence of PID); the modules closer to the positive pole (module number 1) have cells with almost the same brightness (free of PID). [35]

- **Thermal Imaging**: This test is done on a sunny day with an infrared camera. A module affected by PID has a higher temperature than the surrounding modules that are unaffected by PID. The cells that are hotter (red) than the others (yellow) are potentially infected by PID (Figure 6.71). The infrared test is easy to perform because the installation does not need to be turned off.

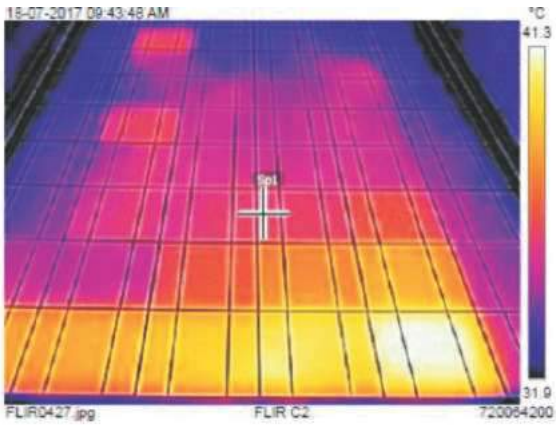


Figure 6.71:Thermal image of PID affected module

- **Operating voltage:** The working voltage of the PV module can also be measured by means of a simple voltmeter. This parameter gives more information about a solar module than the open circuit voltage. Solar modules affected by PID have a lower operating voltage than modules not affected by it. This is because solar modules with PID have higher leakage currents, which creates additional current requirement (leakage + string) with fixed power generation condition. As a consequence, these solar modules work at a lower operating voltage.

  This can easily defined by the following formula:

  $P = V \times I$

  If the power (P) decreases due to PID, and the current (I) remains the same by the other modules in series, the voltage (V) will fall. Moreover, the drop in the operating voltage is proportional to the PID losses.

- **I-V-curve**: To check whether a solar module is PID free, take an I-V characteristic that can be measured by means of an I-V tracer. This makes it possible to observe deviations from the nominal I-V curve. The measurements should be made on a sunny day in order to obtain sufficient accuracy. Consider the following I-V curve of a 305

Wp polycrystalline PV module (Figure 6.72), in which both the voltage and the current have dropped. IR image (Figure 6.71) clearly shows hotspots and it can be concluded that the PV module is affected by PID.

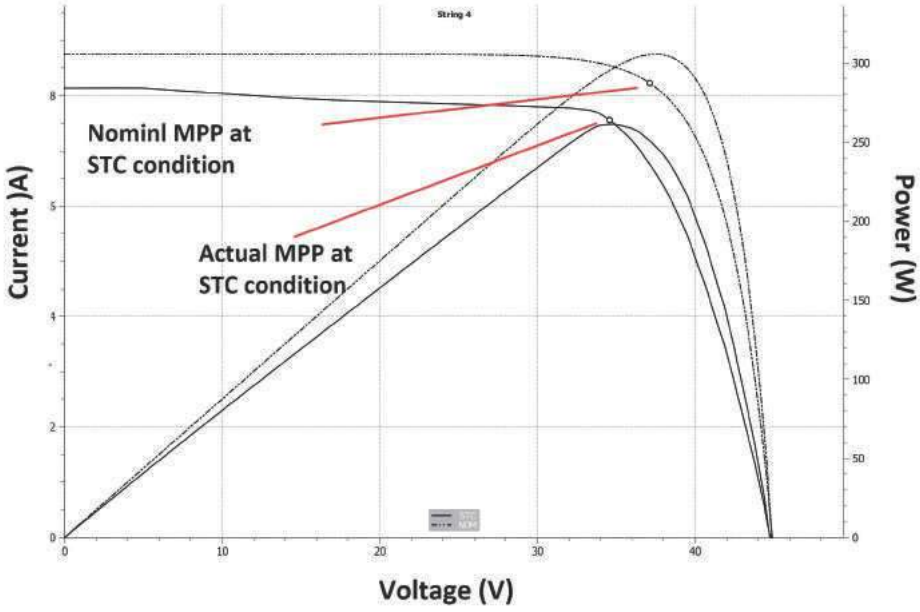


Figure 6.72: I-V curve of two- year old PV module in coastal area at 1037W/m^2

C. PID resistance test

This test is used for checking the resistive capacity of a PV module. There are international standards which describe the procedure of PID testing. However, there is more research going on to refine the test procedure. Since the PID tests are destructive in nature, these tests will be carried out on a sample basis only. IEC TS 62804-1:2015(E) defines procedures to test and evaluate the durability of crystalline silicon photovoltaic (PV) modules for short-term high-voltage stress including potential-induced degradation (PID) [36].

During the test, a voltage bias equal to the system voltage rating of the module (either -1 kV or -1.5 kV) is applied under 85°C and 85% relative humidity conditions for two sessions of 96 hours. This accelerated environment provides the temperature, moisture and voltage bias conditions necessary to evaluate degradation related to increased leakage current [68].

D. PID protection

PID protection is possible at three levels, i.e. system level, module level and cell level.

System level PID correction

- For transformer-based inverter: PID effect can be prevented by grounding the negative string, in consultation with the inverter's manufacturer (Figure 6.73).

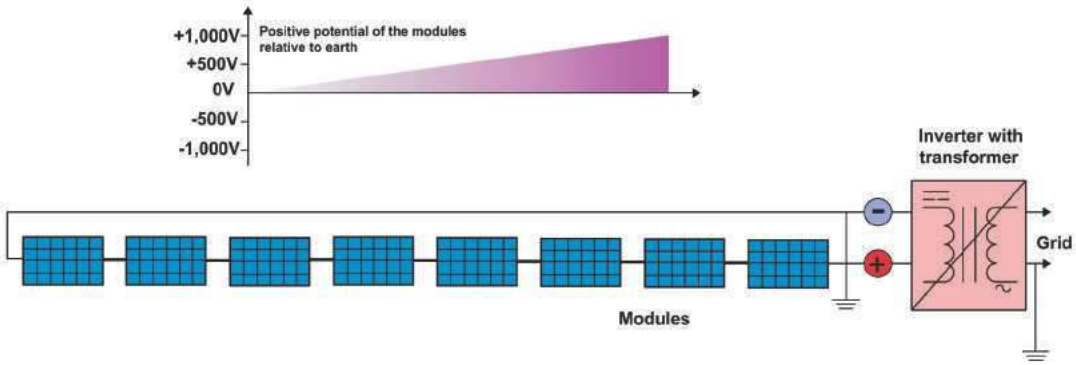


Figure 6.73: Schematic for grounding of –ve terminal of the string for preventing PID in inverter with transformer

- Transformerless Inverter: - Transformerless inverter is lighter, cheaper and most efficient. However, in the absence of galvanic isolation between the AC and DC sides, negative DC grounding cannot be done. But some inverter manufacturers have developed PID recovery solutions and PID free inverters.

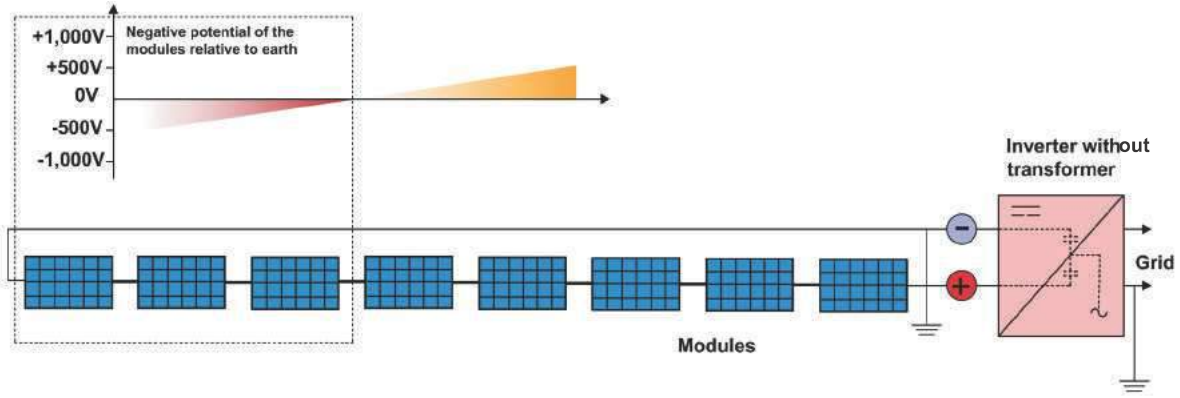


Figure 6.74: Schematic for grounding of –ve terminal of string for preventing PID for Inverter without transformer

Module Level

- Reduce accumulation of water on modules to avoid leakage of charges.
- New technologies in glass can be explored, like quartz glass, potassium based glass by AIS.
- More the resistivity of encapsulate, better the performance against PID.

Nowadays, alternatives to encapsulate, like Poly-olefin, Ionomers, etc., are introduced by various leading solar research laboratories across the world. While selecting PV modules check if OEM offers PID-free modules.

Cell Level: The anti-reflective (AR) coating of the cell is supposed to be in a particular range. Increase in the ARC layer thickness can increase the PID resistivity. It will reduce the light transitivity and vice-versa.

E. PID Recovery

If the system is already installed in the field with PID susceptible cells/modules, the PID issue can still be resolved by applying a reverse potential on the modules during night time so that the cells are positively biased to the frame. There are three practical methods for PID recovery:

- **Exchanging polarity:** In case PID occurs in the field and depending on the grade of degradation, the most economical solution is to reverse the polarity.
- **PID recovery box [30]:** If the array voltage falls below a defined threshold after sunset, the PV Offset Box raises the voltage of the entire PV array to a high positive potential (between +400 V and +1,000 V to earth), thus reversing the polarization effect which occurred in operation. When used on a PV array which has been affected by PID for an extended period, recovery time required is half the time taken for degradation. There are several researches have already been conducted to analyze the effect of recovery by using PID recovery boxes.

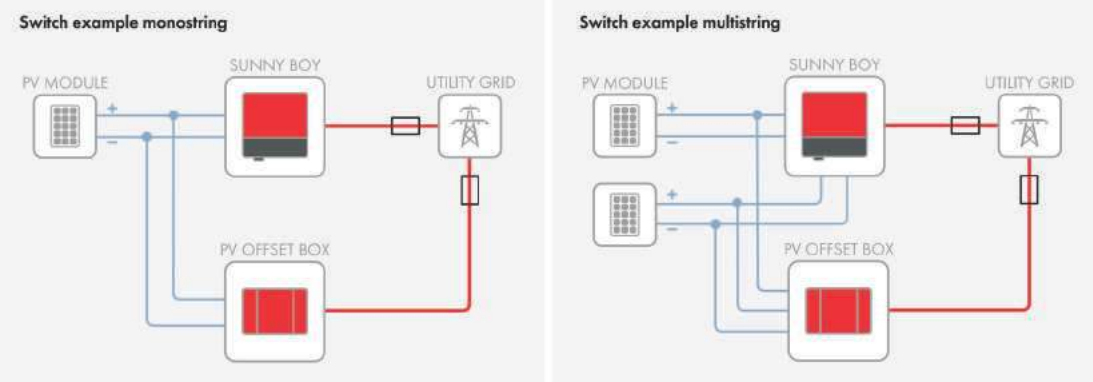


Figure 6.75: Connection diagramtof PV Offse Box [38]

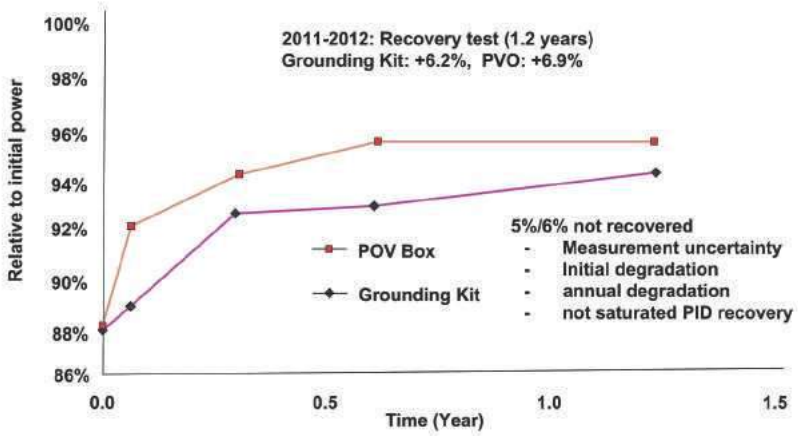


Figure 6.76: Relative recovery of field degraded modules versus time by PVO Box and PV-Grounding [39].

The above experiment was conducted with PID affected modules connected to a PV Offset Box (PVO) and grounding. The experiment was conducted for 14 months and recovery for PVO was ≈95% (+7%) and for Grounding Kit ≈94% (+6%), on average. One of the major observations [39] was that temperature has influence in PID recovery. Increase in temperature and irradiance leads to rapid recovery in both methods and PVO shows better results during winter. Various researchers suggested PVO is better suited for cold climates, whereas grounding the negative terminal using grounding kit is recommended for warm climates.

Energy drawn from the household grid is negligible as the current that flows during regeneration at night is minimal due to the current restriction in the PV Offset Box ($P_{AC\,nom}$ < 3 W).

- **Heat Recovery:** For the recovery of PID modules affected by temperature, storing PID modules at around 100°C for 10 hours leads to a recovery close to 100% (depending on module condition). Even though this is a faster process, the recovery procedure at high temperature stresses the module and its materials and may affect long term stability.

PID free inverters: Most PID-free inverters incorporate a zig-zag chopper circuit (ZCC) to combat PID occurrence in photovoltaic modules. This technology is designed to outperform conventional inverters that use internal or external transformers. Incorporating the ZCC into transformerless inverters allows the negative pole of PV strings to maintain a zero potential to ground and in turn eliminates the possibility of harmful PID effects [35].

6.6.9 Bypass diode failures

A bypass diode (BD) will operate in shadow effect (Chapter 6.6.5) or any mismatch effect condition, and during the operation it will generate heat. This will increase the temperature inside the module junction box. Increased temperature will further lead to increase in leakage current through the BD. This will even increase the junction box temperature and lead to thermal runaway ultimately causing failure of BD. Failure of BD will create permanent short circuit (SC) conditions and will bypass the sub-module part permanently from the circuit. This can be easily identified by measuring open-circuit voltage of the string. Similarly, failure of BD may lead to open-circuit conditions. This open circuit may be because of soldering issues inside the module junction box.

Bypass diode failure may remain undetected until significant power reduction is observed by the O&M team. Detecting the bypass diode failure in a small rooftop power plant is easier than in ground-mounted projects with large numbers of PV modules. Bypass diode failure can be detected in three ways: visual inspection using IR camera, string voltage checking and EL imaging.

IR imaging is the most feasible solution for identifying BD failure. Since bypass diode will isolate the complete sub-module part from the circuit, the IR image will show increased temperature of that part of the module compared to other parts. If the BD is in open circuit condition, temperature of shaded cells or cells with other mismatch effects will increase. This is because in the absence of BD, other cells will try to pass current through the shaded or defective cells. Similarly, when the BD is under short circuit conditions and module is working under normal conditions, there will be no current flowing through the cells in that sub-module part and temperature will be low compared to other areas. If the module is under open circuit condition and BD is under short circuit condition, then the shorted sub-module part will have a higher temperature than other areas. A pictorial view of IR image of these conditions is shown in Figure 6.77.

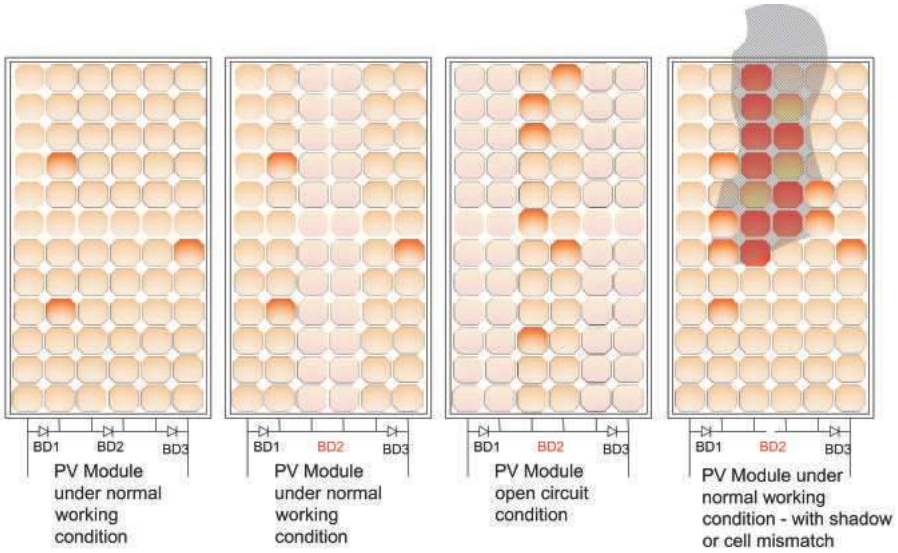


Figure 6.77: IR image of PV module under various BD failure conditions

If significant voltage difference is found during string level voltage testing, consider the following procedure to confirm BD failure:

I. Identify the number of PV modules connected in series, number of bypass diode per PV module, V_{OC} of PV module.

II. Calculate $V_{OC,string}$ and total number of bypass diodes.

III. Ensure all PV modules are cleaned and shadow free.

IV. Measure V_{OC} of all strings.

V. Divide $V_{OC,string}$ with total number of bypass diode.

VI. The resulting voltage is the maximum allowable difference in voltage between two strings with the same number of modules.

VII. Compare the measured voltages using calculated value.

VIII. After identifying the faulty string, open PV module junction box to check the following:

- Connection of diode.
- Voltage across the diode (pass criterion of voltage is between 0.5V to 1.65V [1]).
- Check circuit continuity of all BD even though failed BD is found.

Open circuited BD is not possible to identify by this method. Continuous IR monitoring is required for that. If any module is found with a large number of hotspots, it is recommended to clear the module from shadow and soiling and then proceed with module junction box testing.

6.6.10 Visual inspection of PV power plant

Visual inspection is a most effective, primary, performance evaluation step where keen observation of a plant's components can help identify possible failures and reasons for under-performance. Basic steps in visual inspection are:

A. Scheduling the visit

Visual inspection can be treated as one method of data acquisition during the monitoring of a power plant and can be scheduled based on the capacity of the power plant. In case of small power plants, inspection can be done along with the scheduled maintenance. For utility scale power plants (>1 MW), it can be done along with other regular maintenance activity. There should be at least 2 persons in the inspection team and they should ensure all safety measures are in place before proceeding with the inspection.

In the case of small residential power plants where the owner is undertaking maintenance activities, planned or scheduled inspection will not be possible. In that case, the owner should be adequately trained to identify component failures, e.g. cable puncture, PV module burn marks, etc. These are highly hazardous situations and the person inspecting the plant should keep a safe distance from them. He/she should then contact a skilled person/service provider to rectify the issue.

B. Preparations to be undertaken for visit

The following points need to be taken care of by the technician while preparing for a visual inspection:

- Technician who is carrying out the inspection should be fully aware of the site conditions; new persons should consult the owner/O&M team before going into the field.
- Refer to the last inspection reports for better understanding.
- Technician should carry with him/her the site layout and a camera during the inspection (if possible carry an IR camera).
- While touching the PV modules, be careful about the hotspots.
- In case of large power plants, try to connect with control room personnel regularly to ensure one's safety.

Inspection procedure: Consider the following points while carrying out inspection:

I. Read the plant layout before starting inspection.

II. Plan the inspection points as per plant layout.

III. Walk around the plant area and inspect all plant components as per Annexure XI.

IV. Capture pictures and note down picture nos. (since a power plant's area is symmetrical, it will allow identification of the area/string number during the analysis exercise).

V. Note down any significant issues in plant layout.

C. Reading or analyzing observations

An undetected failure in PV modules continues to reduce power generation and ultimately may stop generation at some point. Unlike other components, PV modules may have multiple failures which can be due to a combination of various external factors or the quality of materials. In case of SPV plant, reading and rectification of faults/failures is easy for components other than PV modules. Some of the common component failures observed during visual inspection are discussed at the end of this section.

D. Proceed to testing (if required) and documentation

The last step of visual inspection is testing and documentation in the form of visual inspection report. A draft skeleton of a visual inspection report is given for ready reference in Annexure XI. Based on identification of issue/fault, the visual inspection report should give clear instructions for the way ahead. Depending on the severity of the fault, testing to confirm such fault needs to be taken quickly. Based on the testing results and on confirmation of fault, necessary steps for rectification should be taken. While preparing documentation and rectification plan, the following points need to be considered:

- Check if the faulty component is under warranty period or not. Check the warranty terms before proceeding with rectification.
- All issues related to PV module may lead to reduction in energy generation and it is therefore recommended to immediately isolate and replace the faulty PV module from the string to avoid mismatch losses.

- PV module failures can occur due to material quality and external factors. Keep a track of similar faults and try to undertake root cause analysis of failures.
- Other issues like vegetation, cleaning of PV modules, cleaning of control room and other areas of the plant, activities related to O&M, can be addressed based on the severity, priority, availability of resources, etc.

Examples of component failures observed during visual inspection

Following are some of examples of component failure observed during visual inspection of a PV plant:

A. Snail trail on PV modules

Snail trails or snail tracks that occur in PV modules within several months of installation may highly impact performance. Snail trail or snail track is actually an optical illusion of grid finger with discoloration (Figure 6.78).

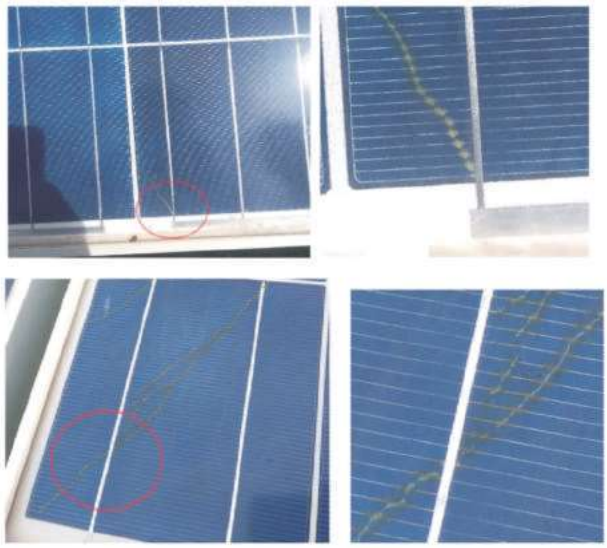


Figure 6.78 :Pictures of snail trail / snail track on PV modules

Snail trails appear as brownish discolored contact fingers on solar cell surfaces especially around the cell edges and/or micro crack areas. The presence of micro cracks is considered to be an essential condition for the formation of snail trails, along with moisture and oxygen. Snail trail/tracks can be of three types [40]:

- Type I: Spreads back and forth across the solar cell along micro cracks.
- Type II: Found on edges of cells (called framing).
- Type III: Appear near the rim of cells.

Process of grid finger discoloration

The probable reason for the onset of grid finger discoloration is moisture entering the PV module from behind (through the backsheet) and entering the sunny side of the cell through cell cracks or between single cells. This assumption is supported by the observation that glass-glass modules seems to be completely resistant to grid finger discoloration, since the glass at the rear is a much better barrier to moisture than the usual backsheet foils. Moisture diffuses through cell edges or micro cracks of a cell [41 - 43]. When the module is under operational conditions, Ag^{+} ions migrate from the contact finger into the polymer encapsulant and are reduced to silver nano particles by electrons. Therefore, micro-cracks not only provide a path for moisture to enter from behind the cell to the front, they are also responsible for the formation of a local electric field in which ions can migrate (Figure 6.79). The silver nano-particles are then oxidized into silver oxides by the peroxide residues in encapsulants which causes the brownish colour to be eventually visible [44].

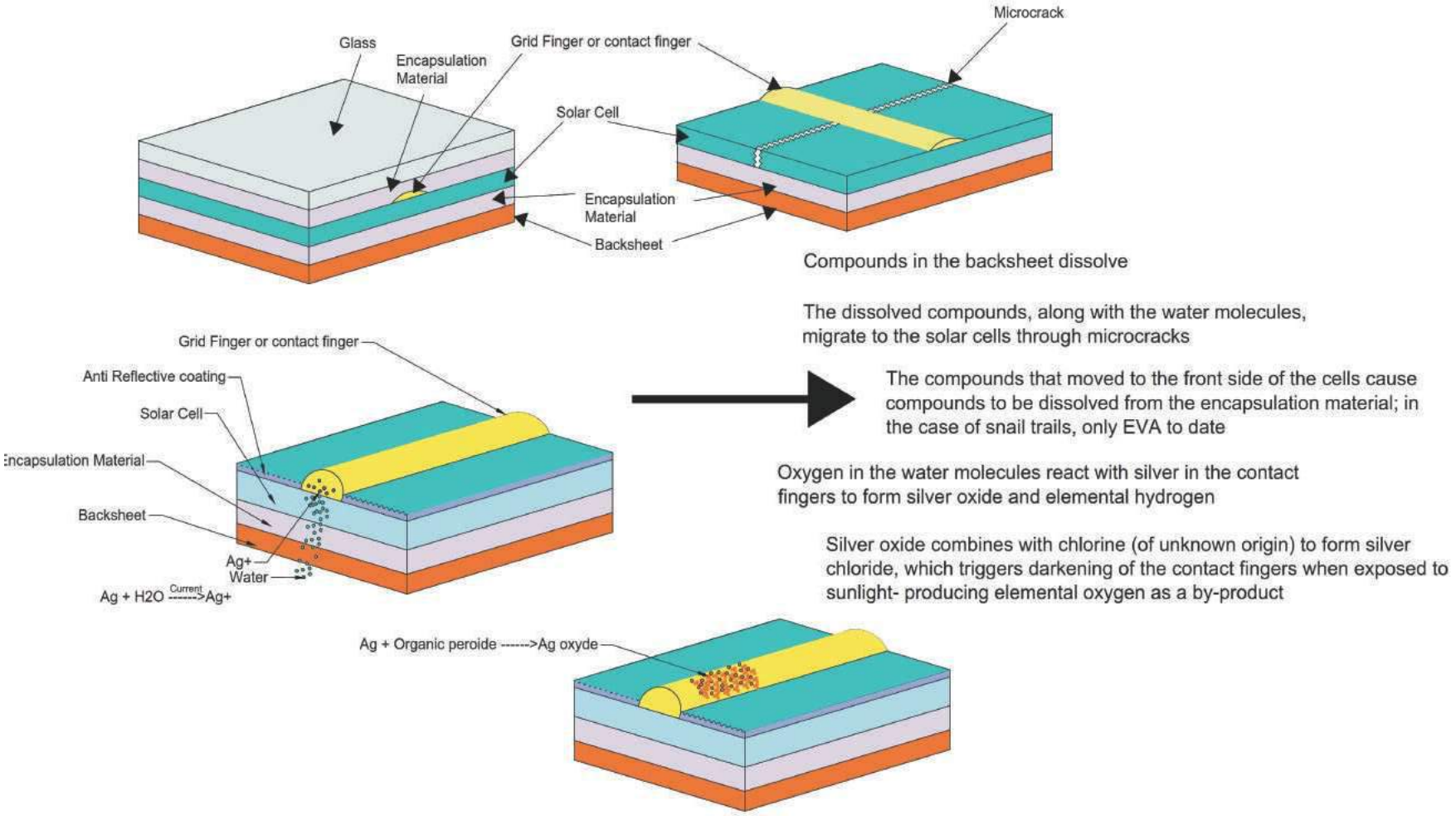


Figure 6.79: Snail trail formation

This explanation is the most commonly accepted theory for grid finger discoloration. Apart from this there are several other researches going on in this field to identify the main cause of grid finger discoloration. Some researchers indicate that the discoloration of snail trails is due to the formation of silver acetate ($AgC_2H_3O_2$) as well as its reaction with the encapsulant [45]. *Canadian Solar Inc.,* found some evidence that the additives like glass frits of silver paste and peroxide additives in the EVA (ethylene vinyl acetate) were the root cause of formation of snail trails. As per their opinion, in order to avoid snail trails, solar module manufacturers need to select the appropriate type of silver paste and additives contained within the encapsulation polymer [46].

The electroluminescence (EL) image shows that the cell below has a characteristic pattern of cracks [47]. This pattern is completely identical to the pattern of the discoloration seen in the photograph of the same solar cell, as illustrated in Figure 6.80.

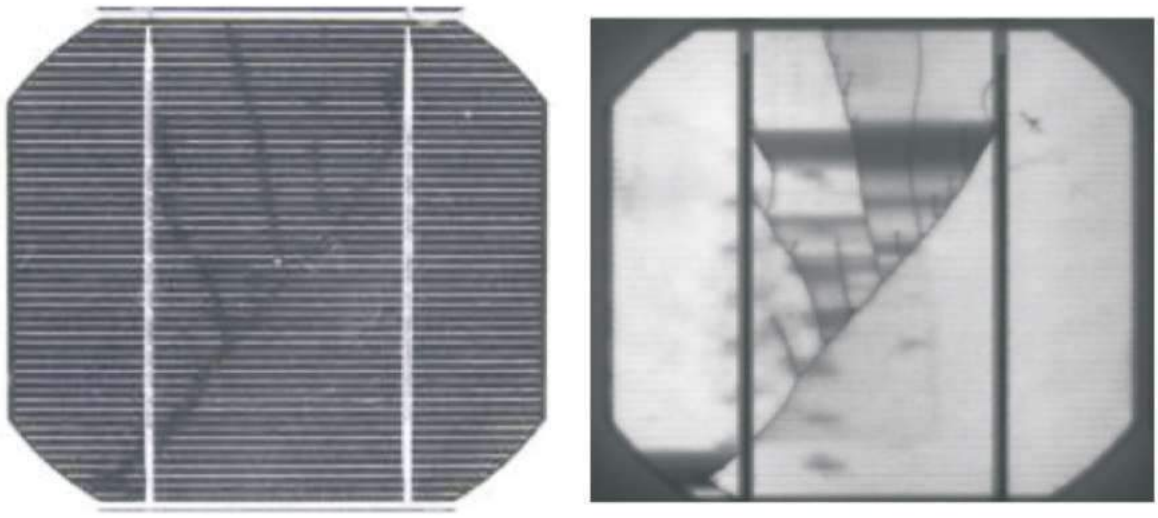


Figure 6.80: Cell with snail trail observed with micro cracks in EL image [48]

Power reduction due to snail trail

Various researchers have conducted studies on the performance of PV modules with snail trails. After the analysis of grid finger discoloration it was clear that the active cell surface is not impaired and, hence, the discoloration does not lead to reduced light harvesting. Furthermore, electron microscopic studies on the affected grid fingers showed that there is no significant change in material structure or cross-section which might have an influence on the conductivity [49]. Thus, snail trails by themselves do not cause a reduction in electrical performance. Tests which found power reduction in PV modules with snail trails do not concluded the main cause to be snail trail. This issue can be attributed to micro-cracks, and a snail trail can be treated as an indicator of the presence of micro-cracks.

Type testing of PV modules will not reliably and completely cover snail tracks because field specific external factors play a major role in their formation. Generally, it is important to minimise the number of modules with macroscopic cracks already in the cell during module production. However, not every crack immediately leads to a power loss and one has to distinguish between electrically active and inactive cracks. Active cracks cause electrically isolated cell areas and result in a power loss which is detectable in the standard sun-simulator test. On the other hand, inactive cracks hardly affect cell or module power but can become electrically active later on during the module's operation in the field. This means that even if the snail trail has no implication in power reduction, these micro cracks can become active in future and lead to isolation of that part from the circuit.

B. Cell interconnection failure

Structure of a conventional wafer-based crystalline silicon PV module contains a number of solar cells, with gridlines or grid fingers which make up the finest level of metallization directly on the cells and consist of an array of lines <0.4 mm thick. Current from the gridlines is collected in the 'busbars', which are also directly connected to the cells. Each cell is interconnected in a series with cell interconnect ribbons to obtain higher voltage. These cell interconnect ribbons are connected from the front to the rear of solar cells. A series of interconnected cells is called a cell string. These cell strings themselves are typically interconnected in series or sometimes in parallel by string interconnect ribbons. Figure 6.81 shows a typical structure of C-Si cell and interconnection within a module.

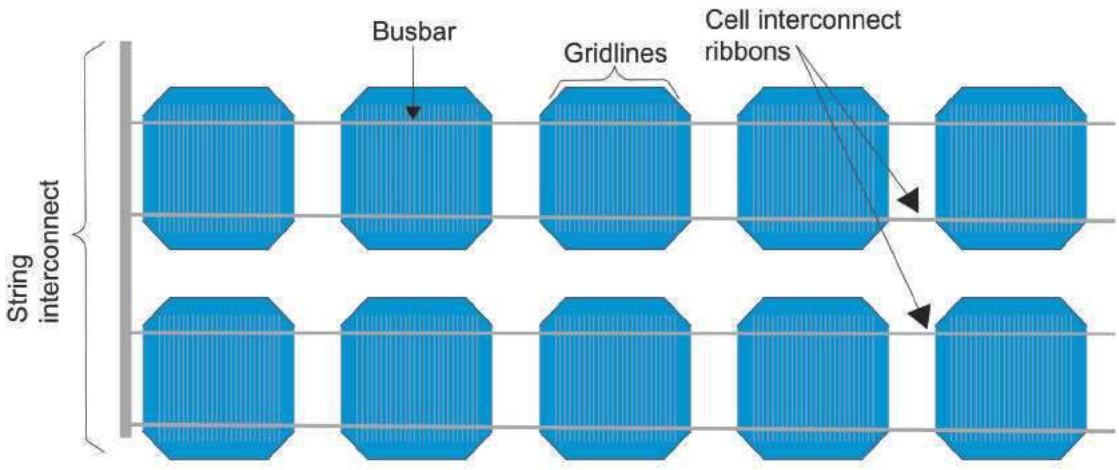


Figure 6.81: Typical structure of C-Si cell and interconnection within module.

Grid fingers are formed by using screen printed silver conductors. Multiple narrow conductors are printed on a cell's surface to get electrical contact and to reduce ohmic resistance. It was observed that this metallization undergoes hygrothermal degradation at a later stage of a module's nominal service life [50]. It has been observed that ingression of moisture and degradation of EVA polymer are the root causes of these issues. Acetic acid is produced by hydrolysis of EVA, and this acid corrodes some metal parts. It attacks the silver gridline interface with the silicon on PV cells, which is a crucial current path for photovoltaic electric current. Figure 6.82 illustrates the grid finger and busbar corrosion observed in a 5-year-old, ground-mounted power plant in a hot and humid climatic region [51]. Since the degradation of EVA polymer is accelerated by high temperature and humidity it was observed that modules in tropical and hot and humid climate are more prone to this problem.

Figure 6.82: Snail trail/grid finger corrosion and busbar corrosion

Interconnection ribbon failure accelerates the under-performance of a PV module as well causes safety issues. The soldering process of interconnecting crystalline silicon solar cells to form a photovoltaic (PV) module is a key manufacturing process. However, during the soldering process, stress is induced in the solar cell's solder joints which remain in the joints as residual stress. Furthermore, during the module's service life time, thermo-mechanical degradation of the solder joints occurs due to thermal cycling of the joints which induces stress, creep strain and strain energy. The solder joints that hold the copper (Cu) ribbon strip to the silicon wafer via silver (Ag) busbar in crystalline silicon solar cells was found to remain unaltered for 25 years of the PV module's operations. However, thermo-mechanical loads during the service operation of a PV module can result in thermal fatigue failure of the solder joint [52].

Failure of interconnection ribbon will increase the resistance at the point of failure, thereby increasing the voltage across the bypass diode causing it to get triggered. It was reported that just one disconnection among many interconnection results in 35% power loss. If the condition continues during the day time, it may lead to failure of bypass diode [6] and current will be pushed through the interconnection. This may lead to an extremely high temperature hotspot as illustrated in Figure 6.83.

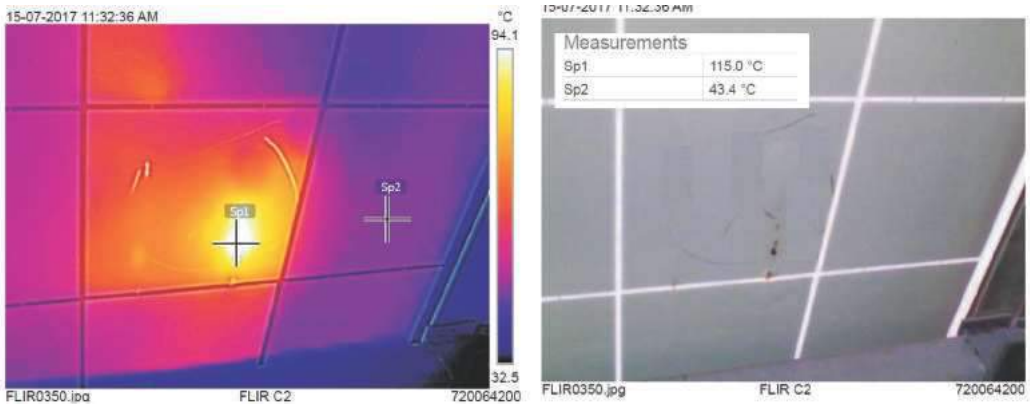


Figure 6.83: Thermal image of PV module affected by interconnection ribbon failure

The last stage of such failure is the shattering of the cover glass and burn marks on the backsheet as shown in Figure 6.84. This could lead to complete failure of the PV module and create safety issues.

Figure 6.84: Starting stage of interconnection ribbon failure and broken cover glass at the final stage

C. Discoloration effect

Discoloration observed in solar PV modules is actually discoloration of encapsulant (generally EVA) material. The most common C-Si PV module design requires a polymeric encapsulant material to embed the solar cells and the stringing tabs between the glass front sheet and the backsheet or the rear glass sheet. There are multiple roles for this embedded polymer as listed below:

- Silicon-based solar cells are themselves brittle, apart from the glass encapsulation. The encapsulant behaves as a buffer layer protecting the brittle silicon cells from shocks to the glass or the backsheet. For this, the elastic properties of the polymer are of prime importance.
- Maintain the integrity of the electric circuit which generates the required current and voltage under light exposure. The transparency of the encapsulant (at least 90% of solar light transmission) must remain throughout the lifetime of the photovoltaic module.
- Provide and maintain the physical isolation of solar cells and components and protect the circuit in the operating environment (i.e. from potentially aggressive and degrading elements).
- To show a low absorbance in the active spectrum of the photovoltaic cells in order to allow the cell to generate the highest possible photocurrent.

Encapsulant discoloration is a commonly reported defect in solar modules because it is easily noticed in a visual inspection. Solar modules operating in fields for a long time exhibit this defect which reduces the amount of sunlight approaching the PV modules. Browning and yellowing of PV cells are mainly caused by the degradation of the encapsulant material, which is usually ethylene vinyl acetate (EVA). Historically, the initial discovery of this discoloration came in the mid-1980s, and main research on discoloration started during the early 90s [53]. EVA

discoloration affects the PV module's performance directly and indirectly. Primarily, it decreases light transmission to the solar cell, which directly reduces the short-circuit current (I_{sc}) of the module and decreases the module's efficiency. Some investigations in effect of EVA discoloration reveal that it may lead to delamination, bubbling effect, and metallic contact corrosion, all of which have a direct involvement in the performance degradation of PV modules [54 - 55].

The main cause of EVA discoloration or browning is due to the overtime in service or under UV exposure, which reduces the sunlight approaching the PV modules (Figure 6.85). This effect is mostly inhomogeneous and follows spatial patterns which depend on the type of module construction. Typically, for glass/backsheet modules the browning occurs in the central region of the cell with wide clear EVA areas. Other than the issue of less light irradiance or light intensity reaching the cells, the browning of EVA is not a safety issue by itself but may reveal the presence of more worrisome failures modes. The yellowing or browning of EVA is more intense around hotspots or partially connected cells, which is due to a local elevation of temperature compared to the rest of the module.

Figure 6.85: PV module discoloration

Process of discoloration

The main reason behind discoloration is the chemical oxidation of EVA material under exposure to high temperature and UV light of wavelength >300nm. As a result of this, coloured conjugated alkene or ketone (discoloration) and acetic acid form. Further, reaction of these by-products leads to change in the mechanical properties of EVA polymer. The process is initially not attributed by EVA material since EVA polymer does not significantly absorb light in the UV-visible spectral region which is not absorbed by the glass front sheet, but is due to the degradation of stabilizer additives of the EVA compound. Residual (unconsumed) peroxide catalyst after a too rapid (short- time) lamination process leads to the UV-initiated discoloration during the lifetime of the PV module [50]. The process of discoloration formation is given in Figure 6.86.

Performance analysis of EVA discoloration

Functional effects enhancing the EVA discoloration are as follows:

- Concentration of peroxides and antioxidants in the EVA compound.
- Temperature profile and the length of the lamination process.
- Transmission of the module glass front panel in the UV range.
- Intensity of sun irradiation.
- Temperature of the module.
- Size of the cells, and permeability of the polymer backsheet or edge sealing.

Discoloration effect is observed with more intensity in PV modules installed in hot and humid climates, or in hot and dry climates, where the working temperature of the solar cells will be close to 50°C. This finally leads to loss of efficiency. Typically, a mean annual degradation rate due to yellowing is about 0.5%/yr to 1%/yr in hot and humid or moderate climates [56 - 58]. Nevertheless, power losses of up to 10%/yr have been observed for mirror enhanced

photovoltaic modules installed in desert environments [26]. Some researchers report that modules mounted on rooftops degraded ~ 0.4% per year, whereas, those on open rack mounts degraded ~0.1% per year. The difference was attributed to higher temperature of rooftop arrays resulting in more severe EVA discoloration [59]. In some sites, it is observed that the degradation rate increases with time. This increase is due to the broadening of the EVA discolouration from yellow blocking light at short wavelengths, to brown. Typically short circuit current losses of 10% were observed over the first decade of exposure for modules prone to yellowing [60]. Increased degradation of PV modules can be because of the recurring effect of mismatch losses. Hot spots formed due to the mismatch effect can be attributed to discoloration caused by high temperature which leads to further mismatch of cells.

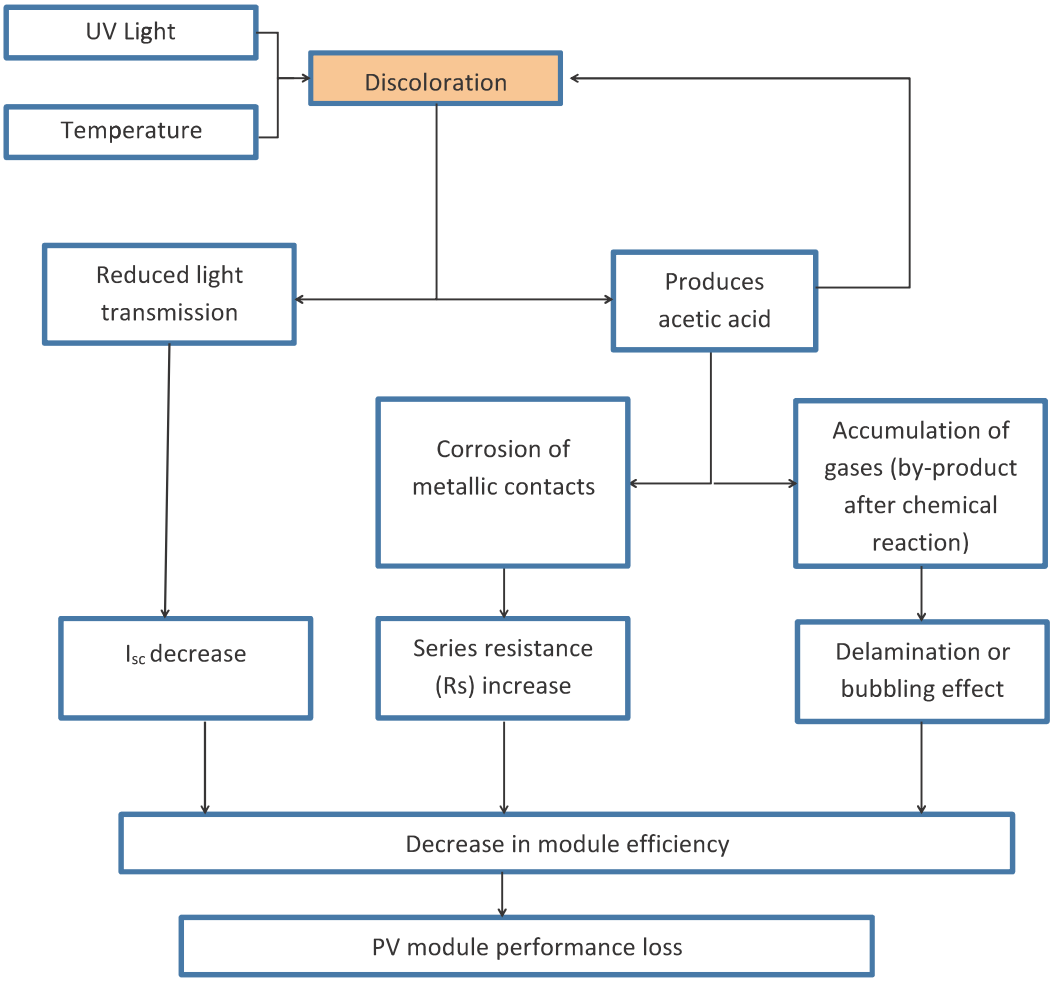


Figure 6.86: Process of EVA discoloration and its effects[56]

The most common approach for evaluating this degradation is visual inspection for the appearance of colour over the solar cells. The extent of degradation is correlated with the colour of EVA, which extends from yellow to dark brown as degradation progresses. However, it is only a qualitative way to investigate discoloration, which can be perceived differently by different people. Conventional I-V testing is generally used for quantification of degradation due to discoloration. Earlier studies have shown a wide range of I_{sc} and P_{max} losses due to EVA discoloration in the modules after long exposure, at different locations. However, the measured electrical parameters give global degradation, which could represent the combined impact of several degradation mechanisms in the module. The following methods can be used to evaluate discoloration effect:

- Visual inspection and I-V measurement.
- Differential current analysis.
- Dark lock-in thermography.
- Electroluminescence imaging.

The discoloration effect in PV modules can be treated as material issues supported by external factors like temperature and UV light exposure.

D. Delamination on PV module

As described earlier, one of the main functions of EVA is to serve as the structural adhesive in the PV module, as illustrated in Figure 6.87. The adhesion loss or separation between the different layers of the photovoltaic module is known as delamination and usually occurs at interfaces within the PV module, e.g. glass/EVA, cell/EVA, silver gridline/EVA, ribbon/EVA, inter- layer of the polymeric backsheet, etc.

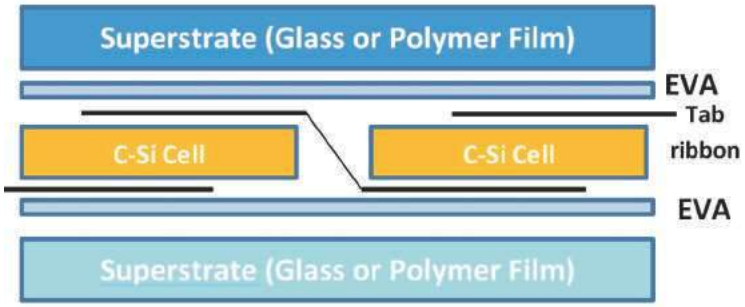


Figure 6.87: C-Si PV module structure with EVA

Delamination is one of the most common module degradation causes that occurs due to the degradation of EVA material. Field experience shows delamination occurs on the edges and in the corners of the module causing problems such as increase in reflection, greater water penetration, increase in series resistance (R_s), output power loss and electrical hazards to the modules and the installation as a whole. The following Figure 6.88 shows delamination observed in modules working on site for a long time.

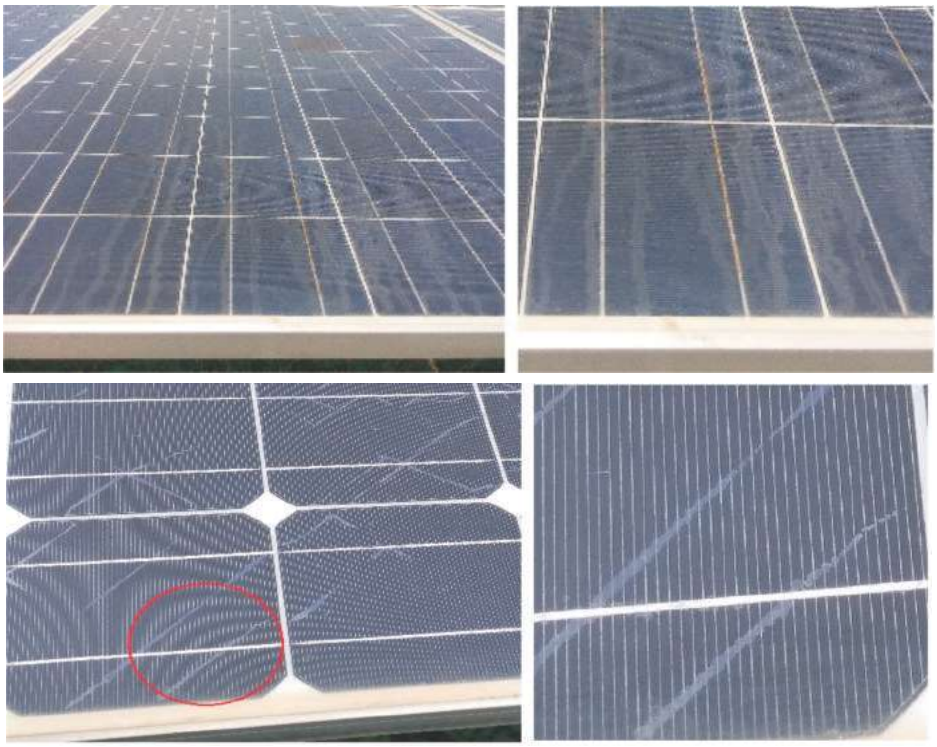


Figure 6.88: EVA delamination

Major drivers of delamination are stress exerted at the interface from residual thermal stresses or from external mechanical stress applied on the module and the deteriorated interfacial bonding as a result of the attack from heat, UV and moisture. Chromophores are formed during the crosslinking of the EVA polymer absorbing UV light, followed by the degradation of EVA and the production of acetic acid as a by-product. To avoid the absorption of UV light and to mitigate EVA degradation and the delamination process, several stabilizers including UV-absorbers (UVAbs) and phosphite are used as stebilizers [61]. Adding UV absorber initially, reduces the degradation of EVA but upon the degradation of the UV absorber leads to fast discoloration of the PV module as the material's chromophores are not protected anymore and undergo subsequent photo degradation [62]. The decomposition of UVAbs, which is confirmed by transmission measurements, leads to the formation of benzoic acid and a phenol product. The acid

catalyzes the adhesion loss at the EVA-glass interface and the phenol product is causes discoloration [61]. This raises the question of whether UV absorbers and phosphite usage as EVA stabilizers is advisable over the longterm. As per some research results the additive HALS (Hindered Amine Light Stabilizers) can delay the loss of adhesion strength and yellowing compared to the non-stabilized EVA mixture. Furthermore, it could be shown that the discoloration of EVA foils containing phosphite is reduced in the presence of HALS. Consequently, HALS seems to be the only "key" stabilizer which can enhance the stability of EVA during UV exposure at 50^0C when used as embedding material in PV modules [61].

Evaluation and effect of delamination in performance of module

Evaluation of delamination can be done by visual inspection and IR imaging. Once the delamination effect is found in a power plant, there is a chance that multiple modules will show the same failure in the nearby future.

Delamination has an adverse effect on PV module performance. Experiments have shown that for the interfaces of glass/air and EVA/air, the interfacial reflectance is about 4%. This reflection loss causes a drop in P_{max} via reduction in the short-circuit current [63]. Examination of some of newly formed delamination for long time shows propagation of the delaminated region. This is because moisture ingression in the delaminated region and condensation of moisture which accelerates the propagation of the delaminated region [64]. When delamination occurs at the cell's surface, corrosion of metallic components will take place by moisture condensation, acetic acid produced by EVA and the oxygen arriving at the interface. Increase in R_s and reduced I_{sc} due to delamination may lead to mismatch effect and power loss in the string where the delaminated PV module is connected. Further this mismatch effect results in local heating followed by burned cell. Considering the effects of delamination, it is advisable to sort the delaminated modules from the normal PV modules and monitor the output to restrict the effect of mismatching.

E. Bubbling effect

It is observed that some PV modules are found with bubbles on the rear or the front of the module. This bubble formation is a process similar to delamination, but it involves the lack of adhesion of the encapsulant EVA affecting small areas. If the module is not correctly formulated for adhesion, the cell surfaces will not be properly prepared (e.g. residual flux), the foil parts of the backsheet will not adhere well or may be sensitive to UV, or if gas forms inside the module because of too much flux from soldering or vaporization of water in the EVA, the back encapsulant sheet may not adhere well and bubbles may form on the cell surfaces . Figure 6.89 illustrates bubble formation at the back and the front of a PV module.

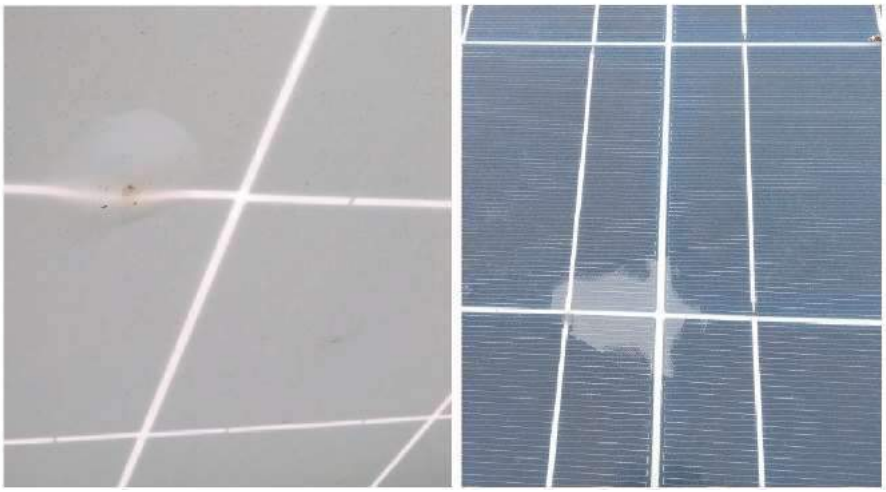


Figure 6.89: Bubble formation between (a) EVA and backsheet (b) EVA and glass

The milky formation of bubbles can lead to increased reflection and power production of the cell will reduce (Figure 6.90). This will lead to mismatch effect and result in under-performance of the string and formation of local hotspots. During the initial stage of bubble formation, the temperature of bubbles is low compared to nearby cells, but later it increases and results in overheating thus reducing the life of the PV module. The following thermal image shows bubbling and overheating of the PV module. In case of ingression of water, especially when combined with high voltage, significant and irreversible damage to cell components may occur. This type of degradation can quickly make a module unsafe and/or inoperable.

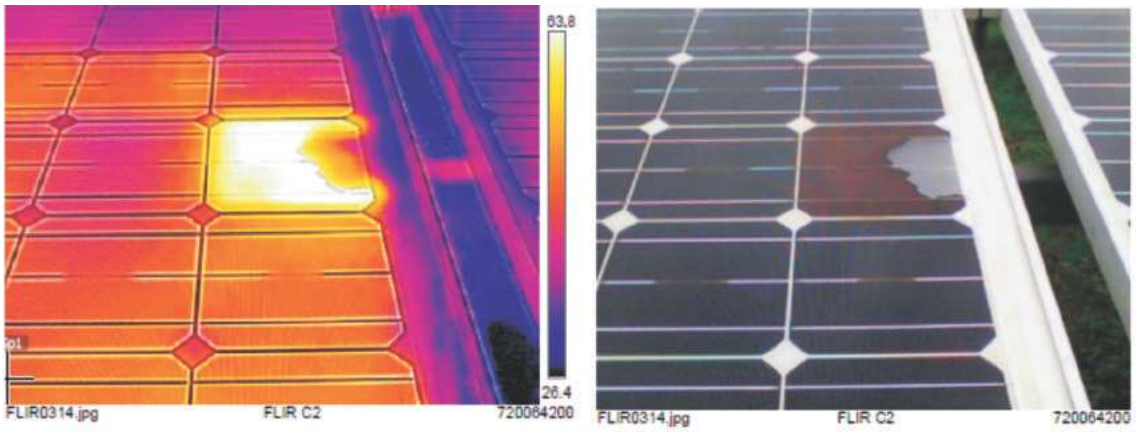


Figure 6.90: Overheating effect of bubble formation

F. Degradation of anti-reflective coating (ARC)

Solar cell efficiencies can be increased by reducing optical losses, such as reflection and absorption. One of the most apparent sources of reflection loss in any PV system is the air-glass interface at the front of the module. Reflection reduces the photon flux into the cell by ~4.3%. The application of an anti-reflective coating (ARC) addresses some of this loss of potential photocurrent. A commercial coating for solar modules is durable on a timescale compared to the industry standard for solar modules, which are normally provided with a 25-year warranty. Any solar cell technology must undergo rigorous testing to ensure that the solar modules can endure decades of outdoor exposure. Any coating applied to solar modules must have an equivalent durability. During the life of a PV module, the anti-reflective coating (ARC) receives radiation that could induce a change in the ARC colouring as illustrated in Figure 6.91.

Figure 6.91: Typical anti-reflective coating degradation

Anti-reflective properties may suffer changes as well, and in this case the light that reaches the cells may be lower than expected. Nonetheless, this colour change should not cause a decrease in the wavelength radiation that the cell uses, but rather only affect a part of the visible radiation [65].

G. Galvanic corrosion in PV modules

Galvanic corrosion in PV modules is caused by an electrochemical reaction catalyzed by local environmental factors. The following are the some of the identified parts in a solar PV power plant where galvanic corrosion due to dissimilar metal can occur:

MMS parts | outdoor ACDB and AJB | outdoor inverter mounting | PV module grounding | Electric connectors with dissimilar materials

Whenever dissimilar metals are in contact, a galvanic circuit is created in which the anode loses electrons to the cathode with the assistance of the electrolyte (usually water). Consequently, the anode eventually disintegrates. Dissimilar metals in galvanic series are as follows:

CORRODED END
(Anodic or less noble)
Magnesium
Zinc
Aluminium
Steel
Lead
Nickel
Brass
Bronzes
Copper
Stainless Steel (passive)
Silver
Gold
Platinum
(Cathodic or more noble)
PROTECTED END

Figure 6.92 : Galvanic corrosion due to dissimilar metal contact

There is a strong impact of galvanic corrosion on the PV module mounting structure (MMS) grounding. For galvanic corrosion to take place, four factors must exist simultaneously: an anode, cathode, an electrolyte and a conductive path. Aluminium or galvanized, painted or stainless steel frame MMS are commonly used for PV module installations. The combination of dissimilar metals like aluminium and copper or stainless steel grounding components have been a common cause of equipment grounding system failures in PV arrays (Figure 6.92). However, corrosion can occur as a result of long-term exposure of components to cycling leakage current, which produces an electrolysis process. For a PV installation, the long-term effects of corrosion can range from unsightly finishing to racking or fastener failure followed by ground fault.

An increased rate of corrosion has been observed in highly humid areas. Atmospheric contaminants, such as chlorides (in marine environments) and sulfurdioxide and nitrous oxides (in industrial locations), are deposited on array structures. These deposited contaminants react with oxygen and water and typically increase corrosion rates by releasing electrons from the metal's surface. It is interesting to note that corrosion rates can be effectively decreased in areas of high rainfall because contaminants are regularly washed off from the structural materials.

Failures due to corrosion can be attributed to the following causes:

- Improper selection of materials for the bonded connections.
- Dissimilar metals in close proximity, which depending on the electrolyte involved, cause corrosion when exposed to water, soil, or other conductive debris elements, etc.
- Insufficient separation between dissimilar metals on undersized washers between copper and aluminium.
- Good but inadequately protected connections fail after long term exposure to leakage current, water, salty humidity and /or other corrosive agents.

Mitigating galvanic corrosion

- Avoid using multiple materials for fabrication of structures.
- If mixed-metal systems are used, then select combination of metals close in the galvanic series, or select metals that are galvanically compatible.
- Avoid the unfavorable area effect of a small anode and large cathode. Small parts or critical components such as fasteners should be made of noble metals.

A large area of 'cathode' relative to 'anode' will accelerate the anodic corrosion. Although aluminium is anodic to stainless steel, large relative surface areas of aluminium to stainless steel can be acceptable dependant on local conditions. Stainless steel fasteners in aluminium plates or sheets are normally considered safe, whereas aluminium rivets or bolts holding stainless steel parts together are an unwise combination, as there is a practical risk of corrosion.

- Insulate dissimilar metals wherever practical, such as when using a gasket. It is important to insulate completely, if possible.
- Corrosion is more often combated with coatings paints, electroplating or other coatings such as hot-dip galvanization. Keep the coatings in good condition and repair the same periodically.
- Design for the use of readily replaceable anodic parts, or make them thicker for longer life.
- Physical separation of dissimilar metals (using rubber/EPDM washers to isolate galvanized screws from painted steel sheet is a common practice in the roofing industry.)
- Select fasteners according to the manufacturer's specification. For example, some PV module manufacturers recommend the use of stainless steel fasteners to prevent galvanic corrosion but also allow for galvanized or zinc-plated fasteners.

H. Mechanical damage to PV module (broken module glass, damaged frame)

PV modules are subjected to various mechanical forces during handling, right from manufacture in the factory to installation at site and further during O&M. In order to characterize such external forces, test loboratories divide these loads into static mechanical loading, inhomogeneous mechanical loading and dynamic mechanical loading tests [66].

The international standard specifies mechanical load in terms of the magnitude and duration of applied forces, frequency and number of cycles of cyclic forces, e.g. IEC 61215 test specifies a static load test applied three times at 2400 Pa to each side of the module for 1 hour each time [67]. Also as per IEC-TS-62782 (2016), dynamic mechanical loading has been done the module which installed according to the manufacturer's recommended mounting configuration and is subjected to 1,000 cycles of alternating loading at 1,000 Pa at 3-7 cycles/min [37].

Some of the common reasons for mechanical damage during the operational phase are as follows:

- **Damage during PV module clamp installation**: One of the common reasons behind PV module breakage is improper clamping. This is more common in case of glass to glass PV module without metal frame (especially thin film). It was observed that, during the installation of PV modules workers generally use proper tools with fixed torque. However, during regular maintenance, the lack of proper tools leads to varying torque at different corners/clamps followed by uneven stress on module glass and results in glass breakage.
- **Poor workmanship**: If spacing between two adjacent PV modules is not even, thermal expansion and contraction of MMS will exert extra stress on the PV module. This may cause significant mechanical damage or cause micro cracks of PV cells followed by power loss.
- **Falling objects on module or MMS integrity issues**: If any hard objects falls on a PV module they can cause glass damage. This can happen due to the negligence of the O&M team or due to extreme events like hailstones. If MMS maintenance is not proper, it may cause increase in vibration of PV modules and may lead to mechanical damage or micro cracks. PV module mechanical damage will lead to performance degradation which is basically due to electrical circuit corrosion caused by ingression of water and oxygen into the module. Apart from electrical performance, mechanical damage will lead to electrical safety issues particularly in wet conditions. Breakage of module glass due to mechanical damage can lead to overheating of the modules and will create hotspots. Following are some photographs showing different mechanical damage to solar modules.

Figure 6.93 : Damaged PV modules due to improper clamp fixing

Figure 6.94 : Shattered glass because MMS failure

Figure 6.95: Damaged PV modules due to hailstones

Figure 6.96: Damaged PV modules due to object falling on module

I. Improper cable laying and termination

If the cable laying or routing of PV strings is not proper, it may cause accelerated degradation or aging of the cable followed by performance reduction. Some of the issues related to cable laying are as follows:

- **Improper segregation and routing of PV strings**: DC cable at PV field should be properly tied to the MMS or routed through conduits. Uneven sagging of PV cables and connection points may cause water ingression into DC connectors which may lead to safety problems.
- **Improper use of cable tie**: Over-stressed cable ties may cause the cable's outer sheet to puncture in the long run (Figure 6.97)
- **Improper conduit selection**: If the bending of cables is not proper, it may lead to cable puncture. If the conduits are not UV protected degradation of conduit will occur.
- **Cable termination**: Cable conduit ends should be sealed with proper material to avoid water ingression, and access to insects or rats. Use of improper cable glands can cause ingression of water into the AJB or may allow insects to get into the AJB causing short circuit.
- **String identification ferrules**: Harsh environmental conditions may degrade string identification ferrules or markings.

These issues should be avoided during the installation stage. If at all such issues are observed during O&M, timely corrective action is required to avoid further damage. Following are some photographs of improper cable laying and termination.

Figure 6.97: Cables are not tied or routed properly

Figure 6.98: Cable conduit ends not sealed

Figure 6.99: Cable laying without bends may damage cables

Figure 6.100: Cable conduit ends not sealed

J. MMS integrity and corrosion

It is observed that MMS corrosion is more prominent in coastal areas where atmospheric salt content may accelerate corrosion. If such corrosion is observed, timely corrective action needs to be taken to avoid further damage to the MMS. Failure of MMS will damage the modules and may lead to hazardous situations during cyclones or extreme events. Also, during visual inspection, it is necessary to check the drainage system to avoid water logging or issues like landsliding, etc. Drainage or flood control systems need to be examined to identify blockage well before the start of the monsoon period. Some photographs of MMS failures, and corrosion observed on site, are shown in Figures 6.101 to 6.104.

Figure 6.101: Corrosion on MMS

Figure 6.102: White rust on MMS observed in solar plant in coastal area

Figure 6.103: MMS integrity issue

Figure 6.104: Land sliding causes to MMS collapse

Safety note: In case of rooftop power plants, it is recommended to confirm MMS strength (walkways, rooftop structure) before proceeding with inspection. Annual torquing of MMS supports should be carried out before the start of monsoon period.

K. Light elevated-temperature-induced degradation (LeTID)

Light elevated-temperature-induced degradation (LeTID) causes multicrystalline silicon (mc-Si) solar cells to degrade in performance. It was found that this degradation is accelerated by high irradiance at higher temperatures after hundreds of hours of light exposure. This degradation has a particularly harmful impact on the efficiency of the solar cell, especially the passivated emitter and rear cells (PERCs). In some recent research papers it was found that relative conversion efficiency dropped up to 10% due to LeTID[69].

Light induced degradation (LID) is known to the solar PV industry for a long time. It is due to traces of oxygen included in the molten silicon during the Czochralski process. Under the light exposition effect, these positive-charged O_2 dimers may diffuse across the silicon lattice and create complexes with boron dopant acceptors. The B-O complexes create their own energy levels in the silicon lattice and can capture electrons and holes which are lost for the PV effect. This occurs upon first exposure to sunlight until the power level stabilizes after a short period. Other salient characteristics of LID as observed during the research study done by NREL are as follows[70]:

- There is an initial rapid decay of all cell parameters (within a few minutes), followed by a slower degradation. In general, all cell parameter experience a reduction.
- Under 1-sun at 25°C, it takes about 72 hours for complete light-induced degradation.
- The total effect of LID is about 0.5% absolute (observed maximum 0.5% degradation).
- In the initial course of light soaking, there is evidence of partial recovery of cell parameters if the cell is taken out of illumination for I-V measurement.

The LeTID is similar to LID, but is occurs during higher operating temperatures (mostly >65^0C) and higher intensities of light. From research studies it was found that LeTID can occur over a much longer period of time, i.e., between 100 and 1000 hours of operation (depending upon location and strength of irradiation), and cause up to 7% power degradation followed by generation loss[69],[71].

The most accepted explanation for LeTID is the result of interaction between the silicon nitrate (SiN_X) and aluminum oxide (Al_2O_3) passivation layers at higher temperatures during the firing process in manufacturing. It is in wafers that undergo a fast firing process, typical for industrial solar cell production, that a significantly stronger degradation is shown than in samples that were subjected to the same peak temperatures but with slower heating and cooling rates.

There are PV module manufacturers who claim that their products are LeTID resistant. This is basically by ensuring the cell processing sequence is of high quality and crystalline defects are minimized to suppress any occurrence of LeTID.

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Chapter 7

Effective Maintenance of Solar PV Power Plants

Effective Maintenance of Solar PV Power Plants

Maintenance of solar PV power plants will vary depending on the capacity, type, and class of monitoring system deployed. Energy generation from solar power plants depends on solar irradiance input and weather conditions, and hence plant maintenance will have to be strategized accordingly. The first part of this chapter describes the technical issues of solar PV plant maintenance, such as types of faults, activities in maintenance, schedule of maintenance, etc. The second part covers commercial and management issues involved in the maintenance of a SPV plant.

7.1 Types of maintenance in a solar PV power plants

Primarily, there are two types of maintenance in a SPV power plant. One is preventive maintenance (PM) and the other is corrective maintenance (CM).

Both PM and CM are interlinked. There are faults that can be avoided if the O&M team performs preventive maintenance when required. For example: If the temperature inside the inverter cabinet is rising, one of the reasons could be problems with ventilation fan(s), but this will not cause significant power loss unless and until the cabinet temperature rise makes other components fail. If this is observed during scheduled maintenance (SM), preventive maintenance needs to be performed immediately. PM and CM can be differentiated as follows:

Though monitoring and visual inspection are preventive maintenance activities, the result of visual inspection will determine whether the activity falls under preventive or corrective maintenance. Apart from this, the analysis of results from KPI and PE will help identify faults and issues which require maintenance.

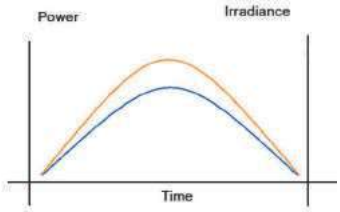
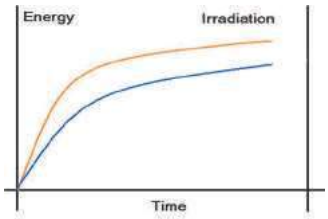
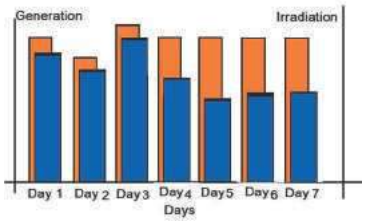
Preventive Maintenance	Monitoring	Analysis of plant performance
	Visual inspection	Inspection for faults that can be identified visually
	Scheduled maintenance	Scheduled regular maintenance activities
	Condition based maintenance	Change in regular maintenance plan due to external factors (e.g., change in PV module cleaning schedule based on weather conditions)
	Predictive maintenance	Maintenance activity to be performed before the identified fault becomes significant.
	Risk based maintenance	Maintenance activity required to be undertaken to prevent safety hazards.
Corrective Maintenance	Deferred corrective maintenance	Temporary maintenance to be performed to restore the plant's operation.
	Emergency maintenance	Maintenance urgently required when no temporary maintenance is possible.

7.2 Testing procedure for fault identification in solar PV power plants

Fault identification through preventive maintenance is dependent on the availability of fulltime staff at the site. In case of small power plants, such preventive maintenance is carried out after a specified interval, based on the plant visit by the O&M contractor. However, remote monitoring and analysis of power generation data can be carried out for all power plants that have remote monitoring and data acquisition facilities. Hence, the testing procedure for fault identification will begin with monitoring of generation data followed up with detailed analysis/testing for fault identification. Different steps/testing procedures to be followed for fault identification in a SPV plant are as follows:

Step 1A: Fault identification through plant performance monitoring (plant level, inverter level, string level)

This step involves regular monitoring of the power plant, and it will decide if a SPV power plant is under-performing and or not. Basic methodology in this step is to compare various monitored parameters and check performance degradation. Consider the following graph's preliminary performance analysis:

Y axis	Y axis	X axis	Remarks	
Daily power output (kW)	Irradiance (W/m^2)	Time (6 am to 6 pm)	Both axis should follow the same pattern	
Daily generation (kWh)	Irradiation (kWh/m^2)	Time (6 am to 6 pm)	Both axis should follow the same pattern	
Daily generation (kWh) (taken over a week or a month)	Irradiation (kWh/m^2)	Day/month	Daily generation and irradiation should follow the same pattern every day	

Note:

- The three graphs show basic monitoring parameters which indicate the power plant's performance. In case power generation does not follow the irradiance path, it should be understood that the plant is having issues.
- The bar chart shows most commonly used methods to plot the plant performance. During performance monitoring at plant level, if the generation to irradiation gap is increasing, it means that the plant is under performing. In such cases further inverter and string level analysis needs to be done.
- Power plants with higher monitoring accuracy class, temperature and string level output can be used for more in-depth analysis.

Step 1B: Monitoring during scheduled maintenance (inverter level, string level)

I. Observations made during scheduled maintenance (SM) activities like PV module cleaning, visual inspection, power plant PV string parameter check 1 and check 2 (Chapter 7.4.2), etc. is an indication of power loss.

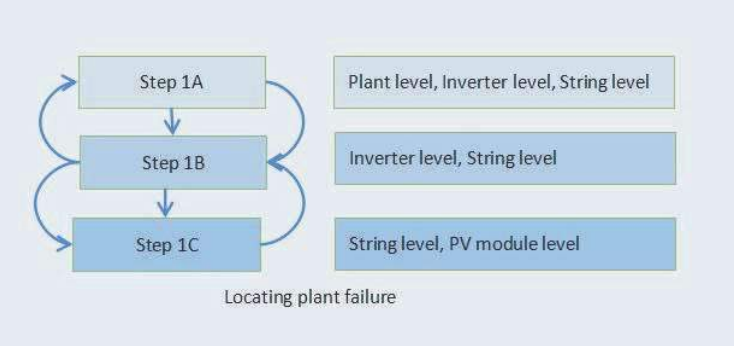
II. Once such observation is found, it is recommended to perform **step 1A** to identify the string or inverter which is causing under-performance. If the plant's monitoring system accuracy is high, resolution of output will be high and chances of identifying the root cause will also be high.

Following are the possible observation combinations from **step 1A** and **step 1B**

	Step 1A	Step 1B	Required activity
Observation	Significant power loss	Significant fault	Corrective maintenance activity.
	No significant power loss	Significant fault	Preventive maintenance activity.
	Significant power loss	No fault	More in-dept analysis on inverter, string and module level.
	No significant power loss	No fault	Continue with scheduled maintenance activities

Step 1C: Monitoring preventive maintenance or corrective maintenance (string level, PV module level)

By performing steps 1A and 1B the underperforming part(s) of the power plant can be identified. To perform preventive (PM) maintenance activity, PV module level analysis is required (power plant PV module parameter checks 1 and 2). If the PV module level performance is as expected, power degradation could be due to error in measurement.



Step 2A: Deciding on preventive or corrective maintenance

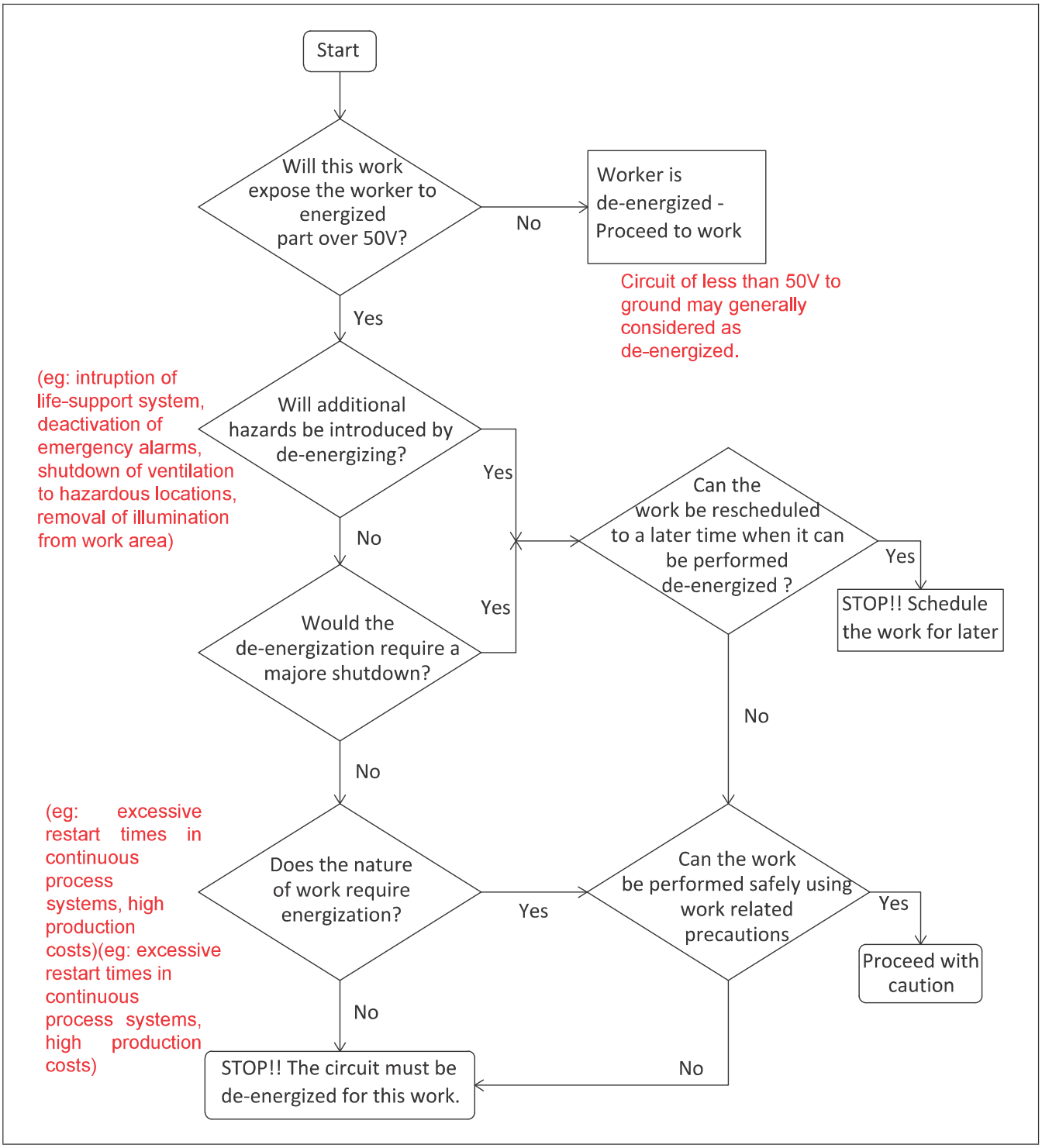
Once the plant issue has been located, the next process is to analyse it, find the root cause and resolve the issue. Isolation of the located sub part should be carried out as per the level of hazard involved with the failure. There are plant failures present with mitigated safety issues or high hazard situations.

Step 2B: Analysing safety concerns before taking action

Process the following basic hot work flow chart for the solar power plant before proceeding with PM or CM. Since the PV power plant voltage level is always more than 50V, except for individual PV modules, it is recommended to consider all safety precautions while carrying out maintenance activities (as per following flowchart[1]).

In the case of workers representing OEMs or external technicians visiting the plant, the O&M team should ensure that the worker/technician is following all safety measures.

In case the O&M team has performed temporary repair prior to permanent rectification during CM, it should prepare a separate activity chart to make sure that permanent rectification work is completed successfully.



Step 3: Rechecking the system after performing maintenance activity.

Once maintenance activities are complete, it is recommended to follow the steps below:

- Perform the tests once again to ensure the fault is repaired.
- Record the results of action taken.
- In case of any replacement of component, ensure documentation is updated.
- Prepare maintenance report for the plant O&M team's internal documentation and for the asset owner.
- Monitor the repaired plant sub-part for the next 3 to 5 days to ensure normal operations.

7.3 Faults and their rectification in solar PV power plants

Some common faults observed in a SPV power plant are tabulated in Table 7.1. The possible reasons for the fault, process of fault identification, rectification/maintenance/solution, steps to be followed after fault identification, etc., are presented in the table along with best possible solutions. However, there could also be alternate solutions based on the type of faults, local conditions, supplier specifications, etc.

Table 7.1: Faults and their rectification in a SPV power plant

Sl. No.	Fault and rectification		
A.	Soiling on PV module - Less generation recorded.	**Reason**	Soiling reduces light falling on PV module.
		Identification and solution	Visual inspection - **Clean PV modules/string.**
		Next test/step	Check electrical parameters and compare with other strings/MPPT.
		Safety	Less hazardous situation.
B.	Shadow due to vegetation on PV module -Less generation recorded.	**Reason**	Vegetation reduces light falling on PV module.
		Identification and solution	Visual inspection - **Clear vegetation.**
		Next test/step	Control nearby vegetation that is creating shadows. Perform IR imaging to make sure there is no hot spot created.
		Safety	Less hazardous situation.
C.	PV module failure: DC connector - Less generation recorded. Some of the strings shows zero value or extremely low values	**Reason**	Open circuit in DC connector, DC connector crimping issues, DC connector corrosion due to water ingression, etc.
		Identification and solution	Visual inspection. PV string and PV module parameter checks. IR imaging - loose connection or corrosion can produce hotspots. **Replace DC connector, or reconnect the DC connector properly.**
		Next test/step	Isolate the PV module or string and perform corrective maintenance.
		Safety	Potentially hazardous situation.

Sl. No.	Fault and rectification		
D.	PV module failure: PV module junction box failure - Less generation recorded. Some strings show zero value or extremely low values.	**Reason**	Continuous working of bypass diode (BD) due to shadow, uneven soiling, water ingression in junction box, corrosion of junction box components, soldering issues inside junction box, etc.
		Identification and solution	● Replace the blocking diode, and in case of de-soldering or IP67 failure of junction box, repair the junction box. ● Isolate the PV module once the fault is identified and replace the PV module with a spare one or isolate the string from the circuit.
		Next test/step	Repeat the test after fault rectification.
		Safety	Potentially hazardous situation.
E.	PV module failure: PV module component failure - Less generation recorded. Visual observation shows issues.	**Reason**	I. Snail trail on PV modules, discoloration effect, and degradation of anti-reflective coating (ARC): No immediate power loss is observed but power loss due to degradation builds up over time. Linear-shaped power loss degradation develops over time. II. Cell micro cracking: Immediate power loss can be seen and this failure is the main reason for other major failures. III. Cell interconnection failure, delamination on PV module, bubbling effect: Power loss can be observed and there is gradual degradation over time. IV. Potential induced degradation (PID), light elevated PID (LePID): Immediate power loss and gradual degradation over time.
		Identification and solution	● Visual inspection, IR imaging, EL imaging, I-V tracing. ● **PID can be recovered by using PID recovery methods. Other PV module failures are more or less permanent and so it is recommended to sort and remove these modules from healthy PV strings.** ● **It is recommended to reconnect the strings (due to failure reasons I and II above) nearer the control room for frequent observation.** ● **PV modules pertaining to failure III need to be sent for warranty claims, immediately.**
		Next test/step	Repeat the test after fault rectification.

Sl. No.	Fault and rectification		
		Safety	• Failure (I) has no effect on safety. • Failure (II) has no effect on safety but can lead to other major hazardous situations. • Failure (III) may cause fire or electrical shock if a follow-up failure and/or a second failure occurs. • Failure (IV) has no effect on safety though hot spot on PV modules may elevate other failures and cause failure III concerns.
F.	DC cable failure (PV module to string, PV string to inverter) - Less generation recorded, earth fault.	**Reason**	Cable puncture, cable interconnection or termination issues, increased voltage drop due to surrounding high temperatures.
		Identification and solution	Cable continuity check, string insulation resistance test, earth fault test, IR imaging of cable, broken cables due to animal bites, cable outer sheet degradation due to chemical reaction or natural aging. **Replace the cable in case of cable puncture or degradation, clear the cable conduit of obstacles and seal the cable conduit end to avoid water ingression, rearrange the cable to avoid overheating.**
		Next test/step	Avoid cable over heating issues. Replace cable and re-lay or rearrange cable.
		Safety	Highly hazardous situation.
G.	AJB/MJB failures - Less generation recorded, earth fault.	**Reason**	Cable termination, string disconnection due to blown fuses or SPDTs, water ingression inside the cabinet followed by earth fault, failure in IP65 property.
		Identification and solution	Visual inspection, IR imaging, electrical parameter checks from main junction box or inverter level, fuse status and continuity check. **Replacement of fuses and other degraded components, cable termination checks, ensure IP65 protection to avoid water ingression.**
		Next test/step	Cleaning of AJB cabinet, re-tightening of cable termination. Replacement of AJB, replacement of blown fuse or any other components.
		Safety	High level hazardous situation in case of earth fault or temperature build-up inside the AJB.

Sl. No.	Fault and rectification		
H.	Inverter: Fuse failure - Less generation recorded, error message in inverter.	**Reason**	Inverter fuse or SPDT failure due to surge (normally due to faults under (F, G) or lightening), strings attached to blown fuses isolated from the circuit.
		Identification and solution	If there is no failure found till string termination point at inverter level then check event logs/notification in inverter, check status and continuity. **Replace blown fuses or SPDT.**
		Next test/step	Replacement of failed component.
		Safety	Less hazardous situation.
I.	Inverter failure: Inverter shutdown - Less generation or no generation from the time of failure.	**Reason**	● High internal losses due to: High temperature in cabinet, input cable loose connection, power converter component loss of connection or malfunction. ● Inverter shutdown due to: Internal component failure, surges, input fuse failure, earth fault in any part of the inverter or strings connected to inverter. ● Short circuit inside inverter due to ingression of any external particles, soiling, or insects. ● Internal component failure due to: Natural aging of components, high internal temperature of cabinet, corrosion of components. ● Inverter software problems: Outdated software, corrupted software, failure to record the actual generation. ● Inverter settings issue: Voltage and frequency tolerance limits settings issue, country settings issue. ● Grid failure issue: Inverter tripping continuously due to low voltage and frequency tolerance window, AC output not connected properly, etc.

Sl. No.	Fault and rectification		
		Identification and solution	Check inverter event logs: for earth faults, high/low grid voltage or over/under frequency, etc. IR imaging will help indicate high temperature, component connection issues, other hot spot issues which may lead to inverter failure, etc. Visual inspection: Soiling and external particles or insect ingression issues, ventilation issues, etc. **Replacement of failed components as per warranty terms and conditions, investigating and resolving earth fault, cleaning of inverter cabinet, checking inverter software updates with OEM.**
		Next test/step	Check if the issues can be resolved by maintenance such as clearing ventilation, tightening loose connections, soiling and vegetation control, etc. Replacement of faulty components and repeating of tests.
		Safety	Earth faults can cause electrocution.
J.	Inverter failure: Inverter shutdown due to internal temperature - Less generation or no generation from the time of failure.	**Reason**	Ventilation problems inside inverter: Cooling fans not working, not enough space for exhaust hot air, hot air coming inside due to high ambient temperature, fans not working due to failure in sensing temperature inside inverter cabinet, failure of IGBT, etc. Hot spots created inside inverter due to: Corrosion or loose connection, soiling on components, low air flow near heat sinks.
		Identification and solution	Inverter event logs, IR imaging, visual inspection. **Replacement of cooling fans, cleaning inside inverter cabinet, removal of obstacles which cause poor ventilation, repair temperature sensing components, replacement of IGBT.**
		Next test/step	IR imaging can identify heating issues; replace faulty components as per OEM's directions.
		Safety	Early stage issues may be less hazardous but if the condition continues it may lead to a hazardous situation.
K.	AC cable failure: No grid connection - Less	**Reason**	Cable puncture, cable interconnection or termination issues, increased voltage drop due to surrounding high temperatures.

Sl. No.	Fault and rectification		
	generation or no generation from the time of failure, earth fault.	**Identification and solution**	Cable continuity check, earth fault test, IR imaging of cable, broken cables due to animal bites, cable outer sheet degradation due to chemical reaction or natural aging, etc. **Replace the cable in case of cable puncture or degradation, clear the cable conduit of obstacles, seal the cable conduit end to avoid water ingression, rearrange the cable to avoid overheating.**
		Next test/step	Replace faulty cable.
		Safety	Potentially hazardous situation.
L.	Solar ACDB failure: No grid connection - Less generation or no generation from the time of failure, earth fault.	**Reason**	• Blown fuses or isolation by protection devices due to surges. • Short circuit due to soiling, vegetation, ingression of external particles or insects. • Measurement component failure: CT/PT failure, CT/PT calibration issues, etc. • Cable termination loose connection, corrosion, etc.
		Identification and solution	Undertake fuse status and continuity check, relay or breaker status check, IR imaging, visual inspection, earth fault test. **Locate the earth fault and fix it. Hot spot areas need to be re-tightened or cleared; in case of ventilation issues clear the air flow resistive components; corrosive parts need to be cleared and the ACDB cabinet should be cleaned.**
		Next test/step	Clean ACDB cabinet and clear corrosion and ventilation issues. Replace blown fuses and reconnecting breakers, etc.
		Safety	Low hazardous situation unless leakage current breaker malfunctions.
M.	Monitoring issues: If the monitoring system is recording wrongly, then generation will be wrongly recorded, and malfunctioning of safety equipment possible.	**Reason**	Communication circuit failure, measuring device calibration issues, sensor malfunctioning, communication error due to external signal interference, communication line power loss due to lengthy cables, monitoring software issues, inverter data measuring errors.
		Identification and solution	Error messages on monitoring systems, compare energy meter reading and inverter reading with recorded values on monitoring system. **Once the issues are located they need to be addressed by the monitoring system OEM.**
		Next test/step	Repair/replacement of faulty part/component.
		Safety	Low hazard.

Sl. No.	Fault and rectification		
	Errors in monitoring		
N.	Monitored generation value is higher than expected.	**Reason**	Error in calculation of expected generation: Calculated expected generation is less. Error in monitoring input: If the irradiance sensor is measuring lower value than actual input to the PV modules it may indicate the power plant is over performing even if it is not. Distorted signals from sensors or other monitoring devices: Due to communication cable losses, other signal interference.
		Identification and solution	Visual inspection of sensors, compare output of multiple sensors, communication cable signal strength checks, communication cable continuity check, checking calibration requirement of sensors, evaluating the calculation methodology. **Performing maintenance activities on sensors, changing the monitoring system calculation logic in case of any error found in calculation methodology, connecting with monitoring system service provider.**
		Next test/step	Cleaning of sensors, calibration of sensors, replacing failed components, changing the calculation logic, etc.
		Safety	Low hazard
O.	PR showing abrupt high or low values.	**Reason**	• Lower PR: If the sensor is facing the south and the PV module is facing in another direction, or if the sensor is exposed to higher irradiation than the PV modules, or if temperature sensor is measuring lower module temperature than actual, etc. • Higher PR: If the irradiation sensor is soiled or placed under shadow conditions; module temperature sensor measuring higher than actual representation of whole PV arrays due to hot spot near the temperature sensor, etc. • Calculation error.
		Identification and solution	Visual inspection, document check, IR imaging. Cleaning of soiled sensors, calibration of sensors, re-positioning sensors.
		Next test/step	Cleaning of sensors, calibration and document checks, vegetation control near sensors, replacing any permanently failed components, etc.
		Safety	Low hazard.

7.4 Solar PV plant maintenance activities

Schedule of SPV plant maintenance activities are discussed here.

7.4.1 Schedule of solar PV plant preventive maintenance

All preventive maintenance activities are scheduled for specific time periods. Different schedules of maintenance activities proposed for solar PV power plants are given in Table 7.2.

Table 7.2: Schedule of SPV power plant maintenance activities

Sl. No.	Plant component-wise preventive maintenance activity	Frequency			
		Small scale	Medium	Large industrial	Utility scale
1.	**PV Module**				
	Visual inspection, plant layout check.	Regular	Regular	Daily	Daily
	PV module cleaning.	Regular	Regular	Daily	Daily
	Electrical parameter check 1, 2.	6 months	3 months	Daily	Daily
	DC connection check (IR imaging), cleaning.	6 months	3 months	1 month	1 month
	PV module tightening (as per torque mentioned by manufacturer).	Annual	Annual	Annual	Annual
2.	**Array Junction Box**				
	Integrity inspection, documents inspection, cables visual and IR inspection .	6 months	3 months	2 months	1 month
	String identification ferrule inspection, electrical parameter checks, overall IR inspection.	6 months	3 months	3 months	1 month
	Monitoring sensors functional verification, surge protection device check, fuse status check.	6 months	3 months	2 months	1 month
	Cables' terminals check, AJB cabinet cleaning.	6 months	3 months	2 months	2 months
3.	**Inverter**				

Sl. No.	Plant component-wise preventive maintenance activity	Frequency			
		Small scale	Medium	Large industrial	Utility scale
	String connection inspection, cables visual inspection, soiling and general cleaning, nearby vegetation check.	6 months	6 months	2 months	Daily
	IR imaging of inverter cabinet (string and central), internal IR imaging (central), string connection point IR imaging.	Annual	Annual	2 months	1 month
	Internal sensors functional verification, check ventilation system operation, ventilation fan functional check, ventilation cleaning.	Annual	Annual	6 months	3 months
	Electrical protections' visual inspection, electrical protection correct operations, fuse status check, display inspection.	Annual	Annual	6 months	3 months
	Labelling and identification inspection, documents inspection, parameters check.	Annual	Annual	6 months	6 months
	Inverter software updation check, warranty date check.	Annual	Annual	Annual	Annual
4.	**DC Cable**				
	Integrity inspection, cables visual inspection, labelling and identification.	Annual	Annual	Annual	Annual
	Cable conduit inspection, cable conduit opening inspection, cable trench inspection.	Annual	Annual	Annual	6 months
	IR imaging of cable terminations.	Annual	Annual	6 months	1 month
5.	**AC distribution board or solar ACDB**				
	Cabinet's general cleaning, nearby vegetation (outside IP56) check, cables visual inspection.	6 months	6 months	3 months	1 month
	Multi-function meter check, CT/PT calibration check.	Annual	Annual	6 months	6 months

Sl. No.	Plant component-wise preventive maintenance activity	Frequency			
		Small scale	Medium	Large industrial	Utility scale
	IR inspection of cable termination, ventilation check.	Annual	Annual	2 months	1 month
	Electrical protections' visual inspection, fuses and surge protection devices status check.	6 months	6 months	2 months	1 month
	Labelling and identification, documents inspection.	Annual	Annual	Annual	Annual
6.	**AC Cables**				
	Integrity inspection, cables visual inspection, labelling and identification.	Annual	Annual	Annual	Annual
	Cable conduit inspection, cable conduit opening inspection, cable trench inspection.	Annual	Annual	Annual	6 months
	IR imaging of cable terminations.	Annual	Annual	6 months	1 month
7.	**Energy meters**				
	Integrity inspection, general cleaning, labelling and identification.	Annual	Annual	Annual	6 months
	Calibration of meters.	Annual	Annual	Annual	Annual
8.	**Monitoring system**				
	Integrity inspection, general cleaning of sensors, circuit check.	Annual	Annual	6 months	3 months
	Sensor protection system's status check.	Annual	Annual	Annual	3 months
	Document check and calibration.	Annual	Annual	Annual	Annual
9.	**Control room**				
	Visual inspection, general cleaning.	Daily	Daily	Daily	Daily

Sl. No.	Plant component-wise preventive maintenance activity	Frequency			
		Small scale	Medium	Large industrial	Utility scale
	Auxiliary power supply and inverter check.	6 months	6 months	Daily	Daily
	Documentation checks, IT system checks.	Annual	Annual	6 months	6 months
10.	**Field**				
	Visual inspection, vegetation control.	Daily	Daily	Daily	Daily
	Fence or field boundary inspection, drainage inspection, approach road and internal road checks.	3 months	3 months	3 months	3 months
	Roof access check, structure integrity check.	6 months	6 months	6 months	3 months
	Plant security systems check, security log book check.	6 months	6 months	6 months	3 months

7.4.2 Preventive maintenance activities in a solar PV power plant

Following are some preventive maintenance activities described in detail. Their frequency needs to be determined by the Plant Incharge/Maintenance Incharge after considering the plant's capacity, site and weather conditions, etc.

Table 7.3: Preventive maintenance activities in a SPV power plant

Sl. No.	Preventive maintenance activity	Notes
1.	**Monitoring of plant parameters**	• SCADA/web-monitoring system should have facility to generate monitoring report, as per requirement. • Manual recording in log sheets should have minimum data such as: date, time of recording, daily/cumulative generation, main event logs, etc. • Plant generation needs to be converted into graphical representation for better understanding of the common man.
	Parameters to be monitored: As per the selected monitoring accuracy class (Chapter 4); in case of power plant having no specific monitoring facility, manual generation based monitoring and recording can be followed in log sheets.	
	Data recording Power plant having SCADA/web-based monitoring facility: Utility, industrial and commercial power plants. Power plants with no digital recording facility: Small residential power plants.	

Sl. No.	Preventive maintenance activity	Notes
2.	**PV module cleaning** **Module cleaning span**: For the initial few months of PV panel operation, cleaning span can be fixed for every 15 days at normal site conditions. In case of high soiling, the cleaning can be every 10 days. After continuous monitoring of the system's performance for the initial few months, cleaning frequency can be updated accordingly. (Chapter 6.6.4, Annexure X)	● For utility scale and large scale rooftop power plants, cleaning should be recorded separately and the supervisor should inspect the quality of cleaning after the PV module is dry. ● In case of dry areas, between two wet cleaning exercises, dry cleaning can be performed ● Ideal time for cleaning is usually in the morning from 6 am to 9 am (max.) ● Cleaning of PV modules in the evening is not preferable unless it is really necessary.
3.	**String level parameter check - 1** **Parameters to be checked:** String open circuit voltage, working voltage and current. **Testing frequency** ● Needs to be decided based on inverter level generation data analysis for utility scale, industrial, commercial power plants where data monitoring facility is available. ● String testing span can be every 3 to 4 months for residential power plants where data monitoring facility is not available.	● The parameters mentioned for checking are the minimum mandatory checks to be performed. ● Testing procedures are given in Chapter 6. ● It is recommended to schedule the testing one month prior to the monsoon or as per maintenance requirement. ● Power plant string parameter check report formats are given for ready reference in Annexure VII. ● In case of mismatch observed in measured data, PV module level analysis is required
4.	**PV module level parameter check - 1** **Purpose of testing:** This step will be initiated in case of any mismatch in measured values found in check 1. **Following basic parameters needs to be checked and recorded manually:** ● PV module open circuit voltage and short circuit current. ● Visual inspection of PV modules in string - especially soiling. ● Visual inspection of PV module junction box. ● In case of soiling on the module, after cleaning the modules check string parameters	● While performing cleaning of PV modules during testing, it is recommended to use either dry cleaning or avoid cleaning at peak generation time. Check the module temperature before cleaning. Do not pour water directly onto the module but try to use wet cloths or a brush for cleaning activities during peak generation. ● If the mismatch found in the string was a soiling issue and is cleared during the testing, before reconnecting the string make sure mismatch due to this cleaned

Sl. No.	Preventive maintenance activity	Notes
	again. ● (If any) Isolate identified PV module and proceed with **PV module parameter check-2.** **Testing frequency:** As and when required.	string to other strings is minimal.
5.	**Power plant PV string parameter check - 2** **Purpose of testing:** PV string safety status check. **The following basic parameters need to be checked and recorded manually:** Compare the measured values with standard expected values and previous recorded values. ● Ground resistance evaluation. ● PV string insulation test. **Testing frequency** ● For utility scale power plants ground resistance test and string insulation resistance tests can be done with a 6 month gap between two tests. ● For industrial large scale power plants, these tests can be carried out along with annual scheduled maintenance. ● For all medium scale power plants and small scale power plants these tests need to be done in case of any earth faults. However, the O&M team can include these tests in scheduled maintenance in a 1 year testing span. ● It is recommended to carry out tests after fault rectification.	● In case the value measured is less than desired, flag the system or sub-system as a potential hazard area and proceed to corrective maintenance. ● In case of corrective maintenance: Isolate the plant's sub-system and proceed with individual PV module parameters check.
6.	**PV module parameter check- 2** **Purpose of testing:** For detailed review of PV module parameters. **Parameters to check**: I-V curve characteristics of PV module/string, fill factor, V_{oc}, V_{mp}, I_{SC}, I_{mp} **Testing frequency** ● For utility scale and large scale industrial power plants this test can be carried out once a year and additionally can be conducted as per requirement. ● In case of commercial and small rooftop power plants, this test can be carried out if the PV module parameter check-1 is not sufficient to resolve the plant's issues.	● Generated I-V curve characteristics and other parameters need to be compared with nominal values. ● .csv or any other I-V characteristic file format generated needs to be recorded as per data management system. ● String sampling can be done based on generation i.e., select good, medium, low performance strings based on past generation records. ● I-V curve characteristics reading methodology is given in Chapter 6.6.1 and the reporting format is given in

Sl. No.	Preventive maintenance activity	Notes
		Annexure VIII.
7.	**Field visual inspection** **Purpose of activity:** General overview of the entire power plant **Points to be checked**: As per Annexure XI. **Frequency of activity**: ● In case of utility scale and large scale industrial power plants, this is a regular scheduled maintenance activity. ● For commercial and residential power plants, this activity needs to be carried out once a month.	
8.	**Thermal / IR imaging of PV plant components** **Purpose of activity:** To identify abnormal temperature rise in plant components. **Components to be checked**: PV modules, DC connectors, AJBs, inverter, other AC components (Chapter 6.6.2) **Frequency of activity**: ● For utility scale power plants, this activity can be undertaken along with visual inspection as part of scheduled maintenance. For all other power plants this will be part of the preventive maintenance activity.	● Since the loss in the power plant is mainly in terms of heat, this activity can be used to identify early stage failure in the power plant.
9.	**Documentation of plant activities** **Activity description**: Documentation of technical documents. **Parameters involved**: ● Commissioning documents, plant design and components related documents, maintenance activity documents (Annexure VIII). ● Checking and keeping records of tickets, faults, inspection results, or other events in one log book, as well as feedback and ensuing work plan for internal purposes for the asset owner and insurance, etc.	All documents should be processed based on approved document management system (Annexure VIII).
10.	**Plant generation reporting**	● Minimum parameters to be reported to the asset

Sl. No.	Preventive maintenance activity	Notes
	Activity description: Plant generation reporting to asset owner.	owner are given in Annexure VII. ● Number of KPIs can be increased as per the O&M's contractual terms.
11.	**Cleaning of monitoring systems and sensors** **Activity description**: Monitoring system and its related sensors need to be cleaned. **Parameters involved**: Monitoring system circuit integrity check, sensor cleaning. **Frequency of activity**: Sensor cleaning frequency should be less than PV module's cleaning span.	● Since plant performance calculation depends on inputs from sensors, sensor readings should be error free.

7.5 Commercial and management activities in solar PV plant maintenance

Operation and maintenance activities of solar PV power plants vary depending on installed capacity, category of consumer, plant monitoring mechanism, etc. Further, O&M activities are either executed through dedicated O&M contractor, or by O&M team of EPC, or asset owner's own team, to maintain the plant. The commercial mode and activities involved in O&M vary across different scales of power plants. Table 7.4 illustrates different commercial and management activities in a SPV power plant.

Table 7.4: Commercial and management activities in a SPV power plant's maintenance

Points affecting maintenance	Industrial practices			
	Small scale (<10 kWp)	Medium scale (<100 kWp)	Medium scale (<10,000 kWp) Or a few hundred kWp	Large scale (>1 MWp)
Full time O&M team stationed at site.	No	If needed	If needed	Yes
Large area to be maintained - increased maintenance activity.	No	No	Yes	Yes
Spare parts management.	No	No	If needed	Yes
Non-technical activities done by:	Asset owner	Asset owner	As per O&M contract	As per O&M contract
O&M contract and methodology:	Portfolio level	Portfolio level	Plant level	Inverter level

Reporting formats to asset owner.	In case of SM, PM and CM	In case of SM, PM and CM	As per O&M contract	As per O&M contract
Detailed plant performance evaluation.	As per requirement	As per requirement	As per requirement	Minimum 2 year span
Consideration of preventive corrective maintenance.	Normally SM, PM and CM	Separate SM PM and CM are same	SM and PM performing together. CM as per requirement	SM, PM and CM treated separately
Asset owner's requirements: Points affecting maintenance				
Type and engagement of O&M contract and team	Initial 5 years by default EPC. After 5 years, by EPC or O&M contractor.	Initial 5 —years by default — EPC. After 5 years: by EPC or O&M contractor.	Initial 5 —years by default — EPC. After 5 years, by EPC, O&M contractor or asset owner.	EPC, O&M contractor or asset owner's own O&M team.
KPIs and performance evaluation	Depends on selected monitoring systems. Usually energy generation based KPI.	Depends on selected monitoring systems. Usually energy generation based KPI.	Depends on selected monitoring systems. Mix of technical and operational performance indicators.	Depends on selected monitoring systems. Mix of technical and operational performance indicators.
Plant documentation - responsibilities	Asset owner	O&M documentation by contractor, and copy of the same maintained by asset owner.	O&M documentation by contractor, and copy of the same maintained by asset owner.	All technical documentation by O&M contractor. Asset owner should have access to documents.
Type of power plant: Points affecting maintenance				
Access to the power plant for maintenance	Required			
Non-availability of safe access to plant area	Permanent safe plant access needs to be provided.			
Water access at site	Minimum 1 or 2 water points need to be provided	Multiple permanent water points need to	Permanent water point or temporary	Multiple permanent water points need to

	(permanent or temporary).	be provided.	arrangement (mobile water tank).	be provided.
Types of monitoring systems: Points affecting maintenance	**Industrial practices**			
	Accuracy class C	**Accuracy class B**	**Accuracy class A**	
String level monitoring of the system	Not necessary	Not necessary	Yes	
Selection as per capacity of the power plant	Residential, Commercial / Industrial	Commercial/ Industrial/ small utility power projects	Utility scale - commercial	
Maintenance of monitoring system	Along with SM	Along with SM	Separate SM required (maintenance span shorter than plant SM)	
Safety aspects: Points affecting maintenance	**Industrial practices**			
	Small rooftops	**Large rooftop plant**	**Ground- mounted**	
Chances of hazardous situations at plant during the operation	Medium	High	Low	
Plant accessibility requirement for maintenance	Proper walkways and handrails or plant access should provide for safe working atmosphere		Comparatively low	
Selection of O&M team	Minimum safety knowledge and need to follow PPE as per requirement.	O&M team should have knowledge of safety requirements and contractor needs to verify EHS terms as per O&M contract.		
Management of PPEs	Not required at site, however, from contractor's side it needs to be done. Asset owner is not responsible for maintenance of PPEs.	If O&M team is stationed at the site then management of PPEs is required, else it can be done by the contractor. Asset owner has to confirm the integrity or quality of PPE.	For utility scale power plants, PPE site management is required. If O&M team is stationed at the site, management of PPEs is required, else it can be done by the contractor.	
Weather parameters: Points affecting maintenance	**Industrial practices**			

	Summer	Winter	Monsoon
PV module cleaning requirements	Soiling will be high; in low humidity areas or “desert or arid” climatic zone normal soiling will not be too sticky.	Soiling will be less than in summer. Intermittent rain and wind in some climatic zones may create uneven soiling and soil spotting on PV module.	Comparatively less soiling. Uneven soiling and soil spotting after light rain will create mismatch effect.
Safety concerns	High ambient temperature effects on technician working in the field.	Intermittent rain can cause slippery conditions during roof access. On site PV module replacement during heavy wind is hazardous.	Rooftop technicians should wear proper PPEs when working at heights, considering slippery roofs. Chances of reptiles in dry areas in the field.
Unexpected maintenance	Normally less system tripping and grid failures.		Chances of unexpected maintenance are high.
Type of O&M	**Industrial practices**		
	O&M contractor	**O&M contractor and asset owner**	**Asset owner**
Plant capacity	Utility scale power plants: Asset owner giving full responsibility for O&M to O&M contractor based on KPIs.	Utility scale, commercial, industrial power plants: Asset owner will have involvement in monitoring and O&M activities along with KPIs. Residential power plants: Asset owner will have involvement in cleaning activities only; all technical activities will be done by O&M contractor.	Residential power plant: O&M technician or EPC involved only in case of corrective maintenance. Utility scale, Industrial: Internal technical team trained to maintain solar power plant.
O&M contract	Between asset owner and O&M contractor, based on KPIs. Terms and		No contract required.

	condition as per mutual agreement.		Job chart/job responsibility allotted to each O&M staff member will be followed. KPIs will be assessed to evaluate performance of plant and O&M staff.
Safety during O&M	O&M contract should contain safety requirements to be followed by the contractor at site.	O&M contract should contain safety requirements to be followed by the contractor at site.	O&M staff should consider safety. Separate set of work procedures, safety instructions, preventive measures, hazard intimation sign boards, etc., to be followed. Safety precautions given in O&M manual provided by the EPC to be followed.
Training of O&M team	Frequent training of O&M team as per HR policy, which is the O&M contractor's responsibility.	Training of O&M team is O&M contractor's responsibility and ensured by asset owner.	Frequent training of O&M team is required and is the asset owner's responsibility.

7.6 Continual improvement and review of O&M

The O&M service provider or team of the asset owner should continually review the O&M activities being undertaken at the site. This can be done by following certain quality assurance programs like undertaking internal audit, analysis of data, effective preventive maintenance activities, analysis of KPIs, etc. Internal audits are mainly undertaken to confirm compliance of work procedures, safety procedures, document management, records updation, record management of spares, internal training, compliance of earlier audit points, etc. The O&M service provider or the asset owner can undertake internal audit or take help from external solar O&M experts. The audit criteria, scope, frequency and methods shall be defined prior to the nomination of auditor. One of the main points that need to be considered is that, though it is not mandatory to conduct an audit, it is nevertheless necessary for improvement of O&M or its team. Review of O&M can be undertaken after completion of one year and thereafter, every year. The following are some points that can be reviewed under annual audit of O&M activity.

Document management :	
A.	**Record system** ● All O&M related documents shall be as per requirement of the document management system. This should cover all O&M related activities performed at the site from the date of commencement of O&M. ● The O&M team or company shall define and implement the controls needed for the identification, storage, protection, retrieval, retention and disposition of documents. ● Documents shall be legible, readily identifiable and retrievable.
B.	**Generation of records** ● All O&M activity procedures, monitoring methodology, parameters to be monitored, frequency of monitoring, frequency of reporting to asset owner, shall be clearly recorded
C.	**Validation of records** ● Documented information shall be considered valid only if it is initialled or signed, with the date, by an authorised person or electronically validated or entered by an authorised person.
Operation and maintenance methodology:	
D.	**Determination of monitoring and operational activities** ● O&M team or company should frame the optimum monitoring activities required to give maximum plant performance-related information. ● Selection of monitoring activity should take into consideration capacity of power plant, asset owner's requirements and requirement from O&M team, for extracting better performance from the power plant. ● The O&M team or company shall determine the applicable operational guidelines based on OEMs requirements and relevant standards (IEC, IS or other). ● O&M team should track the expected generation (yearly or monthly) considered at the design stage. ● If the expected generation stated in the design stage is over estimated and the plant is not technically capable of generating that power, the O&M team needs to update the expected generation as per the plant's present working condition. ● Frequency of operational activities should be decided based on technical parameters. ● O&M team or company shall devise a method to remotely and/or locally monitor the system so as to adequately identify faults or low-performance conditions and provide O&M services. ● `The system's monitoring should be capable of reporting the status of available points for all critical system equipment including network communications, protective system, metering, EHS services in time intervals to adequately provide O&M services, as decided for the size of the system.
E.	**Reporting to asset owner** ● Frequency and formats for reporting the generation to the asset owner should be predefined. ● Reporting formats for component replacement, usage of consumables, extreme events reporting, analysis of

	fault's root cause, faults reporting, time of fault event, fault rectification time, plant restoration time, etc., should be recorded and reported to the asset owner on a monthly/quarterly basis.

F.	**Evaluating the effectiveness of maintenance**
	● The O&M team or company shall analyze the points affecting maintenance and industrial practices while scheduling the plant's activities.
	● The O&M team or company shall determine the required maintenance (PM or CM) according to the SM and monitoring.
	● Effective SM, monitoring and PM together should reduce the need for CM and prevent energy losses (except manufacturing defect and component failure due to quality).
	● The effective maintenance management system should be capable of accurately recording tracking and reporting on the following:
	  ● Failures, causes, and corrective action.
	  ● Spare parts utilization and material usage and cost.
	  ● Resource utilization and cost (water, manpower, electricity, etc).
	  ● Open and closed works.
	  ● Equipment information and warranty management.
	  ● Vendor and subcontractor information.
	  ● Modification or replacement to system.

G.	**Tools, measuring and test equipment** ● Record of inventory at site is to be maintained for spares, parts, consumables, tools, measuring and testing equipment, PPE, etc. Audit of inventory, record of usage to be undertaken annually. Quality check of PPEs to be undertaken quarterly. ● All work carried-out at site should follow appropriate EHS rules already agreed to by the O&M team or company. ● Measuring and testing equipment should be initially calibrated, and then maintained at prescribed intervals. All calibration-related documents shall be documented along with main document management system. ● Whenever measuring and testing equipment is found to be out of calibration, it is recommended to perform an evaluation on already documented test results and inspections. Out of calibration devices shall be tagged or segregated and not used until they are re-calibrated. If the equipment is consistently found to be out of calibration, it needs be repaired or replaced. ● All tools, measuring and testing equipment shall be properly handled and stored to maintain accuracy
Human resource management	
H.	● Audit of attendance muster, time sheet, leave records, leave applications and other statutory documents to be carried out annually. ● Audit of outsources/contractual employees/staff/ workers time sheets, invoices, etc., shall be done. ● Audit of documents related to employment of short term contractors, workers, their educational qualification, medical tests, etc., needs to be verified. ● Workers medical fitness tests to be conducted and certificates verified annually and audited in the same interval.

I.	O&M team training programs ● The O&M company shall maintain a training program schedule that includes training identified to be critical to success, including familiarity with basic standards to be followed at site, new technical concepts, etc. ● If the O&M company is not able to provide training to all in the O&M team, selected personnel should undergo training and the company's management should make sure that the information is shared with the others. ● Documentation of such training shall be maintained and annual audits shall be carried out to check compliance.
Continuous improvement in O&M activities:	
J.	● Documentation of audit reports shall be undertaken properly. ● Audit of compliances and non-compliances of earlier audit observations, etc., to be verified. ● Audit of KPIs related to O&M shall be undertaken and compared with technical KPIs to assess he effectiveness and improvement in plant performance. ● Analysis of O&M costs, plant availability time, mean time to rectification of fault, etc., to be reviewed annually to analyze the effectiveness of O&M. ● Audit of maintenance activities, cleanliness, vegetation control, soiling control, data management and maintenance, record keeping, displays of safety instructions, documentation of test procedures, etc., to be verified. ● Soiling cleaning frequency and methodology (wet or dry) can be adjusted as per local environmental and weather conditions ● Review of performance improvement after any main activities will help the O&M team to optimize the frequency of activities ● Comparing the quality of measurement devices by using secondary set of measuring equipment will allow the O&M team to identify the malfunctioning of testing equipment, which may avoid faulty monitoring.

Reference

[1]. John Cadick, Mary Capelli-Schellpferffer, Dennis Neitzel, Electric Safety Handbook.

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Annexure

Annexure -I

Solar PV Plant Feasibility Study: Site Survey Checklist

Customer's Name & Address:	
Contact Person's Name and Designation	
Address	
Contact Details	
Email ID	
Site Latitude and Longitude	

Checklist for Rooftop Captive Plants

Electricity load details	• Collect 12 months' electricity bills for analysing consumption. • Inspect the ACDB and energy meter arrangement (check if spare MCCB or space available). • Details about type of load and daily consumption pattern over TOD slots.	
Rooftop details	Type of rooftop: Flat RCC, GI sheet, roof tiles, etc.	
	Flat RCC	Whether customer allows roof penetration or not.
	Al Sheet	Profile of roof sheet. Possibility of clip lock or penetration MMS.
	Asbestos sheet/ roof tiles	Possibility of using special structures.
	Shadow free area available:	
	Details of nearby objects creating shadow:	
	Rooftop integrity: STAAD report/roof structure strength.	
	Orientation and tilt angle for PV module installation.	
	Site drawing of rooftop with measurement.	
	Roof accessibility.	
	Availability of space for inverter mounting on rooftop or in separate control room.	
Cable routing	Cable length and routing from modules to AJB to inverter to ACDB.	
Output termination	• Get inputs from customer reading his/her requirements. • Check ACDB if spare MCCB or space available for MCCB or separate space for new ACDB available near energy meter/incomer. • Check existing cable tray/trench availability for cable routing.	
O&M requirements	• Information related to soiling at site: In case of industry, get information regarding chemical contents in soil deposition.	

	• Water availability at rooftop or length of water piping required to make arrangements on rooftop. Also check water quality, its source, availability through year, water pressure at rooftop, etc. • Walkway access for regular cleaning of PV modules.

Note:

- In case of industrial customer - interact with electrical maintenance engineer, utility incharge. Collect electrical SLD from plant incomer.
- Check availability of DG set, its rating, its connection and synchronization panel, etc.
- Get data of load shedding history, plant shut down hours, DG operation hours and frequency, etc.
- Explain working of PV plant to customer to avoid misunderstanding and get more inputs regarding plant termination.
- For captive power plants, explain local policy and regulations requirement to the customer.
- Get maximum photographs of roof and actual measurements to facilitate designing of SPV plant.
- In case of no accessibility to the site, discuss if space is available for ladder and walkways. Such basic facilities are required for easy access during installation and commissioning and during 25 years of O&M.
- Check space for material unloading prior to plant commissioning. Check space for material movement to the roof, etc.
- Check safe guards and lifeline on the roof.

Checklist for Utility Scale Ground-mounted Plants

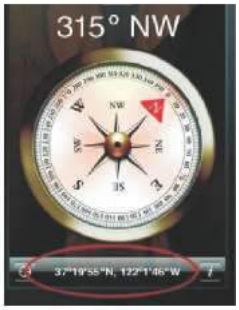
In case of ground-mounted utility scale plants, in addition to the above information the following information is also required:

Land details	Type of land	Agricultural, barren land, marshy land, _____
	Land terrain	
	Area in m^2 or acres	Collect contour drawing of land.
	Far shadows and nearby shadows	Hills, vegetation, nearby buildings, etc.
	Soil test report	
	Land ownership	
Site accessibility	Road and transportation facility to site.	
Water availability	• Water table at site or availability of water. • Quality of water.	
Infrastructure	• Nearby substation: Capacity to evacuate proposed power, interconnecting voltage, distance from proposed site, grid outage data, voltage fluctuations, etc. • Transmission line : Capacity to evacuate proposed power, interconnecting voltage, distance from proposed site.	

Other information	• Nearby village details. • Availability of manpower during the installation.

Tools required during site survey for carrying out prefeasibility to setup solar PV power plant

Compass/Latitude and Longitude Finder



- Compass required for identifying roof orientation and direction.
- Initial simulation of power plant needs weather data. This can't be done without latitude and longitude information.
- Nowadays digital instruments like GPS or mobile app-based compasses and lat. log finders are available.

Distance measuring tape or digital instruments

- If customer has provided rooftop or land drawings with all dimensions then the same needs to be verified during the visit.
- If such drawings are not provided, then a rough sketch is required to be prepared during site visit. Drawings should be appropriately marked with area under shading.
- Rooftop area suitable for installation of SPV power plant shall be clearly marked, SPV module area, cable routing and length need to be measured.

Protractor/tilt angle measurement instrument

- Roof tilt angle is required to be measured. Solar PV MMS will have same tilt. This tilt angle is required for energy estimation.
- Protector/tilt angle measurement instrument is used to measure tilt angle. Mobile applications are also available for angle measurement.

Shading analyzing tool

Solar pathfinder or SunEye are used to calculate shading at the site. A shading analysis tool determines the impact of shadows from nearby objects on the prospective area being considered for solar module installation. These tools help us to identify shadow during specific months.

Camera

Camera is required for capturing photographs of the site. Photographs are required during the design stage and for future reference.

Flashlight

For checking low light areas, e.g. control room, cable trench, etc.

Safety note:

Proper personal protective equipment should be used while visiting the site, like safety helmets, safety shoes, safety harness, etc. Also check if the roof is strong enough to withstand weight of the solar panel which is to be installed. Always keep your distance from sky lights.

Annexure II

Fire Hazards and Basic Fire Extinguishers for Solar Plant

A. Causes of fire hazard in solar PV power plants

Chapter 3 has discussed the common hazards due to fire and ways to mitigate them. This annexure elaborates the causes of fire hazard in a solar power plant and the use of a fire extinguisher.

The causes of fire in a solar power plant may be due to inferior quality material, design fault, poor workmanship, external causes, etc. Whenever such issues are observed during visual inspection, they need to be addressed during preventive maintenance. Following are the issues which can lead to fire hazard at a solar plant site:

Quality of materials

A PV power plant is intended to work under harsh environmental conditions for about 25 years. If the material quality is not as per the best practices it can lead to hazards, such as peeling of backsheet material, wire insulation failure, PV module junction box quality issues, etc.

Design fault

- Broken or damaged PV module junction boxes can lead to fire.
- Under-sized components can lead to local hot spots inside the cabinet followed by fire.
- Use of wood or inflammable materials, the use of cotton or paper left in the cubical and enclosures, will increase the chances of these catching fire.
- Lack of accessibility to the site will increase the lead time for extinguishing the fire and may increase losses. Audit needs to be taken with this in mind and appropriate approach needs to be created.
- If the electrical cables are not properly laid, or the cable conduit is damaged, it may further damage the insulation of the cable which will lead to a fire hazard.
- Use of improper or inferior quality DC connector may lead to a loose contact or water ingression inside the connection followed by earth fault, corrosion, electric arc or fire.
- If the protection class of components installed outdoor is not IP65 or above, it may lead to ingression of particles and increase the chances of short circuit followed by fire.

Poor workmanship

- If the crimping of DC connectors is not proper, it may lead to a loose connection followed by electric arcing and fire.
- Over tightening of DC cables to MMS using cable ties will lead to insulation failure in future followed by earth fault or fire hazards.
- If the O&M is not proper or regular: (a) a loose connection may occur and result in fire hazards, (b) undetected hot spot issues at various components will lead to fire hazards (e.g. failure of bypass diode due to continuous thick shadow on PV module may increase chances of melting of the junction box and shadow affected cells may get hotter leading to fire hazards).
- Use of improper tools for disconnection of DC connector may lead to failure of connection/crimping point, followed by electric arc and fire in the future.

- Over tightening of frameless (glass to glass) PV modules can lead to mechanical tensions, glass breakage, followed by electric arc and fire.

- While working on a 1000VDC or 1500VDC PV power plant during peak production time, if the DC connectors are slightly pulled or disconnected from the MC4 connector the chances of electric arc or fire increase.

External causes

- Insulation failure due to rodents and martens gnawing at cables, etc.
- Lighting strikes.
- Damage to cables/components due to third party activity on rooftop/site may lead to electric arc followed by fire.

B. Classification and rating of fire extinguisher as per Indian Standard

The standard rating of fire extinguishers recommended for Class A and Class B fires is described in the following table. The rating of different fire extinguishers is based on quantity of the extinguishing media. The table also specifies the useful life of each fire extinguisher and the recommended band colour. Details of the relevant fire extinguisher to be used are discussed in Chapter 3.

Classification and Rating of Fire Extinguisher as per Indian Standard

Sl. No.	Type of Extinguisher	Capacity	Amount of extinguishing medium and rating of an extinguisher*		Life (Years)	Band Color**
			Class A	Class B		
1	ABC dry powder (IS 4308- Classes BC; IS 14609 - Classes ABC; IS 4861 for Class D fire)	1 & 2 kg	1 A	8 B	10	Blue
		4 kg	1 A	13 B		
		6 kg	2 A	21 B		
		9 kg	3 A	34 B		
2	CO2	2 kg	-	8 B	15	Black

	(IS 15222)	3 kg	-	13 B		
		4.5 kg	-	13 B		
3	Clean Agent	2 kg		8 B	10	Green
	(IS 15493)	4 kg	1 A	13 B		
		6 kg	2 A	21 B		
4	Foam	2 litre	1 A	8 B	10	Yellow
	(IS 4989)	4litre	1 A	13 B		
		6litre	2 A	21 B		
		9litre	3 A	34 B		
5	Water IS 940 and IS 13385	2 litre	-	-	10	Red
		6 litre	2 A	-		
		9 litre	3 A	-		
* A and B rated fire extinguishers also use numbers to show how large a fire they can fight. A higher number means the extinguisher can battle a bigger blaze. A fire extinguisher with a 1 A rating is equivalent to 1.25 gallons of water. **The recommended colour for a fire extinguisher's body is usually red. A small band of distinguishing colour, of 5% of surface area, shall be painted for different types of fire extinguishers.						

Since the fire itself is a Class A or Class B hazard, the fire extinguishers shall be sized and located on the basis of the anticipated Class A or Class B hazard. Fire extinguishers with Class C ratings shall be required where energized electrical equipment can be encountered. The selection of appropriate extinguisher for electrically charged components shall be done on the basis of guidelines given in Table 3.1 of Chapter 3.

C. Location of fire extinguisher

IS 2190 specifies the desired location for a fire extinguisher. A brief guideline to selecting the location of the fire extinguisher is as follows:

- Location should be readily accessible for the immediate use of the extinguisher in all parts of the occupancy.
- Should be placed as near as possible to exits or near the ladder without hindering escape routes.
- Extinguishers should be sited in such a way that the user may not have to travel more than 15 m from the site of the fire to reach the extinguisher.
- The extinguisher should be placed either on a trolley or firmly mounted on the wall.
- There is need to provide suitable shades or covers to protect the extinguishers in the open from excessive heat and cold as well as from corrosive environment
- A framed plan showing the location of the fire extinguishers, means of access and other useful information should be displayed at suitable locations on each floor, and also be available near the entrance of the premises, preferably at the security gate, control room, reception office, etc.

D. Use of fire extinguisher

Basic components of a fire extinguisher are: carrying handle/operating lever, locking pin, pressure gauge, discharge nozzle or horn, instruction label, inspection tag, etc.

Method of Operating a Fire Extinguisher The "**PASS**" strategy provides steps to knock down a fire with an extinguisher.			
Step 1	**Step 2**	**Step 3**	**Step 4**
Pull the pin.	**A**im the extinguisher at the base of fire.	**S**queeze the handle to activate the extinguisher.	**S**weep the nozzle from side to side until the fire is extinguished.

E. Inspection and maintenance of fire extinguishers

Periodic inspection and maintenance of fire extinguishers shall include a check of at least the following items:

- Location in designated place.
- No obstruction to access or visibility.
- Operating instructions on nameplate legible and facing outward.
- Safety seals and tamper indicators should not broken or missing.
- Fullness of extinguisher to be determined by weighing or lifting.
- Examination for obvious physical damage, corrosion, leakage, or clogged nozzle.
- Pressure gauge reading or indicator should be in the operable range or position.
- Condition of tyres, wheels, carriage, hose, and nozzle to be checked (for wheeled units).

The yearly and quarterly maintenance of fire extinguishers has been explained in Indian Standards IS 3034. All fire protection systems/equipment or devices shall be inspected and maintained regularly to ensure their safe operation at all times.

Annexure III

Personal Protective Equipment

Chapter 3 discusses the hazards in a solar power plant and the requirement for different personal protective equipment. The PPE to be used during O&M activities and their usage is given in this annexure. The different makes of PPE given here are for ready reference but there could be other makes available for each PPE. The user needs to ensure compliance of IS/IEC standards while selecting the appropriate PPE.

A. Safety helmet

Safety helmets are used for protecting workers from head injury caused by falling objects, falling from heights, bumping into overhead pipes or ceilings, accidental head contact with electrical hazards, etc.

Storage: Safety helmets should be stored in a safe place away from direct sunlight or excess humidity and heat. Sunlight and high temperature can cause degradation and loss of strength of the helmet. The storage area should preferably be at the entrance where every worker can put on the helmet on entry and deposit it on exit.

Cleaning: Soap water and soft cloth should be used for regular cleaning of the safety helmet. Use of cleaning agents should be avoided as they can cause deterioration of the shell and harness. Sweatbands should be cleaned on a regular basis and should be replaced as and when necessary.

Inspection: Helmets should be inspected daily for defects before use. Shell, harness and other components should be inspected for cracks, penetration and brittleness which may reduce strength. Cleaning should be done at least once a month.

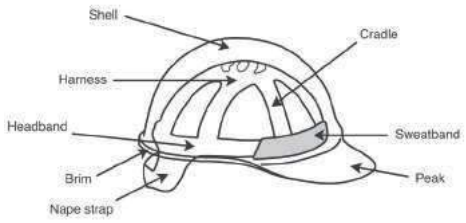
Life and replacement: The life of a safety helmet will vary depending on the manufacturer's specifications. Service life also depends on usage, quality control, care and maintenance, etc. Under normal conditions, the service life of a helmet should be 2 to 3 years but it varies according to the manufacturer. In case of any sign of damage or deterioration, the helmet should immediately be discarded from service.

Colour and marking: A lighter colour safety helmet provides better heat reflection and ready visibility. It is preferred for working in poor light conditions. As per IS 2925, each helmet shall be marked with:

a) Manufacturer's name or trade-mark. b) Range/size of helmet. c) ISI certification mark.

Relevant standards: IS 2925.

Helmet makes: Honeywell, Karam, Udyogi, Venus, 3M, Life Gear, Unicare, etc.

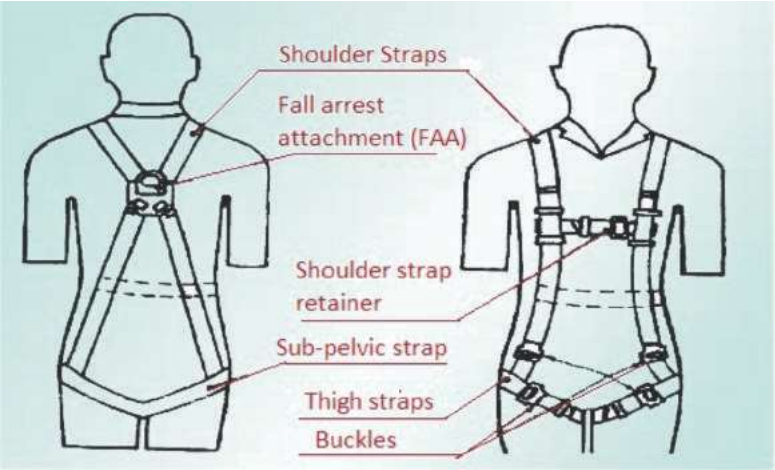


Structure of a safety helmet

Safety helmet

B. Safety harness

A safety harness is body wear used for protecting the worker from a fall impact by distributing the force of the fall over a large area of the body and ensuring the body remains suspended in an upright position after the fall has occurred. It is designed to minimize the risk of injuries caused by suspension. It also provides freedom of movement sufficient to allow the worker to effectively perform his or her job.



Safety Harness

Range of harnesses: Class A, D, E, L or P

CLASS A	CLASS D	CLASS L	CLASS P	CLASS E
Basic Fall Arrest	Controlled Descent	Tower Climbing	Work Positioning	Entry and Exit in Confined Spaces

Class and application of safety harness

Classes D, E, L, and P meet the requirements for Class A as well. Selection of harness should meet requirements of the job at the site.

Storage: Should be stored away from sunlight, in a cool and dry place.

Cleaning: Clean the dust, sweat or oil on the harness by using a dry cloth.

Inspection:

- All safety belts should be thoroughly inspected after every 12 months or after 6 months if not in use, by a competent person. Rope lanyards have to be inspected for any cuts or breaks. Cuts of 1 mm or more at the edges of webbing lanyards can lead to weakening or degradation.
- Before every use, the user must carry out a visual inspection to ensure that the harness is in serviceable condition.
- User should check for absence of any markings and evidence of defect, damage or corrosion to any part including connector hooks or D ring.

Life and replacement: The life of a safety harness may vary from manufacturer to manufacturer (refer instructions manual). In case of any sign of damage or deterioration, the harness should be immediately removed from service.

Marking: Safety harness should have the following markings:

Type of harness/belt, name, trade-mark and year of manufacture, material of construction (MOC), manufacturer's product identification information that shall include the manufacturer's batch or serial number to enable tracing of the origin of the item; warnings not to deviate from the manufacturer's instructions, etc.

Relevant standards: IS 3521: 1999.

Harness makes: Karam, Life Gear, Honeywell, Udyogi, UFS.

C. Lanyard

A "Lanyard" is a short section of webbing or cable, suitable for supporting one person. One end is fastened to a safety belt or harness and the other end is secured to a substantial object or a safety line. When working at heights, the length of the lanyard shall not exceed 3 m, subject to the condition that free fall shall not be more than 1.8 m. Belt, straps and harness should not break under a minimum tensile load of 19.6 kN (2000 kg), as per IS 3521.

Depending upon usage, lanyards are classified as follows:

Work positioning lanyards: These are used to allow workers to work hands free while remaining 100% attached to the anchored structure (with proper fall arrest in place). They should have a minimum breaking strength of 15 kN.

Picture and use of work positioning lanyards

- **Restraint lanyard:** These lanyards prevent the worker from reaching the edges and thus preventing a potential fall. They do not have shock absorption and hence should not be used for fall arrest.

Restraint Lanyard

- **Fall arrest lanyards:** Fall arrest lanyards can be divided into energy absorbing lanyards and self-retracting lanyards (SRLs). Energy absorbing lanyards are lanyards incorporated with energy absorber pack which reduces the impact of a fall from a height.

  Energy absorber pack is made of webbing which is shrink-wrapped. When the fall occurs, the special webbing inside the energy absorber pack opens up and absorbs the impact of the fall thus protecting the worker from injury. The figure below shows two types of lanyards.

Energy absorbing lanyards

Self retracting lanyards (SRLs)

Self-retractable lifelines (SRLs) are vertical lifelines that are used as a part of a complete fall arrest system. When subjected to a quick tug, an internal mechanism activates a braking system and prevents the fall. When the tension is released, the lifeline moves freely again. Compared to energy absorber packs, the fall distance is lower for SRL.
Life and replacement: All lanyards should be immediately taken out of service in case of any wear or damage.

Relevant standards: ISO/DIS 10333-2, IS 3521.
SRL makes: Karam, Udyogi, 3M, Honeywell, etc.

D. Lifeline/Safety line

A lifeline is a flexible line which may be a guide rope or rail connected to the anchorage. These serve as a platform for connecting other components like lanyards of personal fall arrest systems. These are of two types:

Horizontal lifeline: Connections are placed horizontally and anchored at both ends.

Vertical lifeline: One end is connected to the anchor and other end is usually hanging vertically or anchored and placed vertically.

Vertical Lifeline

Horizontal Lifeline

Cleaning: Remove all lifeline surface dirt using a sponge dampened in water. After squeezing the sponge dry, dip it in a mild solution of water and detergent or soap and clean the lifeline. The housing of the lifeline should be cleaned with a damp cloth and mild detergent.

Inspection: Visual inspection of the equipment should be undertaken before use to ensure that the equipment is in serviceable condition and operating correctly.

- Examine and make sure that the right type of rope (material) is used for the lifeline.
- Inspect the rope for any wear, cuts or shape variation or decreased elasticity. It should only be used if there is no damage.
- Ensure that the vertical lifeline is used by one person at a time.
- Ensure that the lifeline is protected from sharp or abrasive objects.

Life and replacement: The lifetime of a lifeline may vary as per the manufacturer. Service life also depends on usage, quality control, care and maintenance. In case of any sign of damage, cuts or deterioration, the lifeline should immediately be taken out of service.

Some manufacturers provide colour tracer strands. These strands on exposure to ultra-violet fade indicating possible damage and weakening of the rope lanyard. Thus the user knows that the lanyard is no longer fit for further use.

The lifeline should be replaced in the following cases:

- Tears or cut.
- Unequal strand size or shape variations.
- Discolouration.
- Broken or loose strands inside the rope (untwist the rope and check inside).
- Accumulated powder or dirt inside the rope (untwist the rope and check inside).
- Loose thimbles (ensure that thimble splices are in good condition).

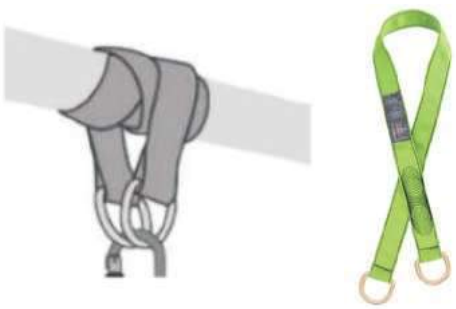
Relevant standards: IS 3521: 1999.

Makes: Karam, Life Gear, Miller, Honeywell etc.

E. Anchorage, Hooks and Connectors

An anchorage point is a secure tie-off point where the worker anchors himself so that he can move around that point, which will also act as protection in case of a fall. The worker should make sure that the anchorage used (scaffolding bar, ladder or anchorage connector) is strong enough to hold his/her weight in case of a fall. The worker should

anchor themselves to a point which is at his/her shoulder level or higher because if the anchorage is below this point, the fall distance increases.



Anchorage Webbing Slings

Fixed Anchorage

Range of connectors: D rings, hooks, clamps, snap hooks and other fastening and holding devices.

Storage: Store in a cool and dry place.

Cleaning: Should be properly cleaned with a wet cloth and dried before use.

Inspection and replacement: Inspect closely for any distortion, cracks, pitted surface or corrosion. If damage of latch is observed, the hook should not be used.

Relevant standards: IS 3521: 1999.

Makes: Karam, Life Gear, Miller, Honeywell etc.

Hooks

D Rings

F. Reflective jacket

A reflective jacket is clothing that has highly reflective properties or a colour that can be easily seen against any background. Retro-reflective materials alert others to the worker's presence.

Storage: Reflective jackets should be stored in a cool and dry place.

Cleaning: Avoid washing along with jeans or garments with a rough finish. The microscopic glass beads on the reflective tape could wear off with rough treatment. Avoid use of softeners or bleach to protect the reflective tape of the safety jacket. Just one wash with fabric softener may significantly damage the reflective ability of the tape. Follow the cleaning instructions provided by the manufacturer.

Inspection: Reflective safety jackets should be inspected each time before use.

Life and replacement: Reflective safety jackets can be rendered unacceptable for use due to poor colour contrast, low or no reflectivity, and deteriorating reflective strips. Reflective jackets should be replaced when they fade, are torn, dirty, soiled, worn, or defaced, or if they are not visible from a distance of 1,000 feet during day or night. Generally, safety jackets have a service life expectancy of approximately 6 months when worn on a daily basis, and may have a useful service life of up to 3 years if used less frequently, depending on the manufacturer.

Marking: Each piece of clothing should be marked on the product itself or in the labels attached to the products, with the following information:

a) Name, trade-mark or other means of identification of the manufacturer or authorized representative.

b) Size designation.

c) Fabric content.

d) Garment class and level of performance of the retro-reflective material.

e) Standard BIS mark.

Relevant standards: IS 15809.

Makes: Aktion, Hammer, etc.

G. Safety shoes

Safety shoes should be mandatorily used at solar power plants for protecting feet from injuries caused by the fall of heavy objects, obstructions, slips, etc. They also help in electric shock protection, protection from bite of reptiles like snakes, scorpion etc,. Safety shoes should be slip and abrasion resistant, with shock absorption properties, lightweight and flexible. Safety shoes should be provided with toe caps (IS 15298-2).

Material and range of safety shoes:

Class I- Leather and other materials, excluding all-rubber or all-polymeric footwear.

Class II - All-rubber (i.e. entirely vulcanized) or all-polymeric (i.e. entirely moulded) footwear. Class II safety shoes are antistatic and hence commonly used in solar power plants.

Storage: Safety shoes should be stored in a cool, dry place, away from direct sunlight. They should preferably be stored in a proper box.

Cleaning: Regular cleaning of safety shoes should be done. They should not be cleaned with solvents or force dried, i.e. drying under a heater. The soles of the shoes should be brushed and washed in order to remove contaminants. Remove excess water with a dry cloth and allow the shoes to dry in a ventilated area away from direct sunlight before reuse. Antistatic shoes should be free from soil or dirt as it affects the property.

Inspection: Walk in new safety shoes to ensure they are comfortable. Try on your new boots with socks that you usually wear at work to ensure they allow you free movement. Safety shoes should be inspected regularly for damage (e.g. sole cracks, exposed toe-caps, breaks in leather).

Life and replacement: Defective safety shoes should be repaired or should be replaced or repaired. If the steel toe of safety shoes can be seen or there is any penetration of the sole, the shoes should be replaced immediately.

Marking: Each safety shoe should have markings by embossing or branding and should provide information like size, manufacturer's identification mark, year and quarter/month of manufacture, number and year of standard, symbols marking categories of safety footwear, etc.

Relevant standards: IS 15298-2.

Makes: Bata, Liberty, Pro-safe, Aktion, Novelty, Armour, Acme, Yezdi, Tango, Karam, etc.

There are 3 types of safety shoes available in the market: Anti-static shoes, conductive or ESD shoes, and insulating shoes.

Reflective Jacket

Safety Shoes

H. Safety goggles and spectacles

Safety goggles and spectacles should be used while working at the site for protection against dust particles, welding, UV rays, etc. Adequate protection should be afforded by the goggles as per the type of hazard.

Storage: Safety goggles and spectacles should be stored in a glass covered, dust proof cabinet in order to prevent scratches, and permit easy inspection and maintenance, if possible. If dust proof cabinets are not used, it is desirable to provide small boxes or compartments for each employee to store his goggles or spectacles between shifts. Group storage of either type permits periodic inspection, cleaning and sterilization while the employee is off shift.

Cleaning:

1. Keep goggles and spectacles clean and daily wipe lenses carefully with a clean, soft cloth.

2. Clean the oil, grease, acids or solvents from the eyecups, rubber or metal parts by thoroughly rubbing with warm soap water solution, followed by rinsing in lukewarm water and thorough drying.

3. Lenses should be wiped with a clean, soft cloth.

4. Oil, grease, acids, or solvents should be removed from eyecups, leather, rubber or metal parts of the goggles. Oil and grease deteriorate rubber parts and reduce the life of headbands. Headbands should be occasionally washed with warm soap solution followed by thorough rinsing.

Inspection:

1. Inspect the safety goggles and spectacles frequently, while in service. If any pitted lenses or damaged parts are observed, they should not be used.

2. Train personnel to make minor repairs within the plant but discourage employees from doing makeshift repairs which might shorten the life of the goggles.

Life and replacement: If frequent replacement of the lenses is necessary, select goggles with frames or eyecups that will permit easy replacement on the job.

Relevant standards: IS 8940: 1978.

Makes: Honeywell, Uvex, Venus, Millenia, etc.

Safety Goggles

I. Rubber gloves (electric safety)

Rubber gloves are used for protection against electric hazards.

Material:

Type 1 - Good quality natural rubber.

Type 2, 3, 4- Made of good quality natural or synthetic rubber or from a mixture thereof.

Range of rubber gloves: Type 1, Type 2, Type 3, Type 4.

The gloves are colour coded for use at different working voltages as follows:

	Type 1	Type 2	Type 3	Type 4
Max Working Voltage(AC RMS)	650	1100	7500	17000
Minimum Breakdown Voltage (V)	6000	12000	20000	30000

Storage: Should be stored in a dark, dry and cool place where the temperature is preferably between 27°C ± 2°C. Gloves which have been issued for service but are not actually in use should be kept in their containers. These should not be used for any other purpose, and should be kept in such a place where they will not be easily subjected to mechanical or chemical damage.

Cleaning: Gloves shall be cleaned with water and soap. For removing materials like paint, insulating compounds, etc., solvents like acetone should be used for cleaning. Wet gloves should be dried thoroughly. If heated air is used, temperature should not exceed 65 °C.

Inspection: Before issuing the gloves for use, a visual inspection should be made inside and out for every glove. Gloves issued for frequent use should be retested after intervals of not more than 6 months. Gloves which are issued for occasional use and kept in store shall be retested at intervals of not more than 12 months.

Life and replacement: The gloves should be replaced when torn or when they cannot be used.

Marking: Marking on the glove shall contain information like size and type of glove, month, year, and source of manufacturing, maximum “working potential” in volts, etc.

Relevant standards: IS 4770

Makes: Honeywell, Hammer, Jayco, Karam, Udyogi, 3M, etc.

J. Leather gloves (cut protection hand)

Leather gloves are used for protection against mechanical hazards like cuts.

Material: Leather

Storage: Store the gloves in a cool, dry, well ventilated place.

Inspection and replacement: The gloves should be replaced when torn or when they cannot be used.

Marking: The gloves shall have the following markings:

a) The manufacturer's name or recognized trade-mark; b) The type and nominal size of the gloves;

c) Year of manufacture; d) Where applicable, the words 'light mass', 'medium mass', or 'heavy mass';

e) Standard BIS mark, etc.

Relevant standards: IS 6994

Makes: Honeywell, Hammer, Jayco, Karam, Udyogi, 3M, etc.

K. Hand gloves (cut resistant with PVC dotting)

Hand gloves provide excellent cut resistance and the PVC dotting gives stronger grip.

Material: Cotton with PVC dotting.

Storage: After cleaning, store the gloves in a cool, dry, well ventilated place.
Life and replacement: The gloves should be replaced when torn or when they cannot be used.

Makes: Honeywell, Hammer, Jayco, Karam, Udyogi, 3M, etc.

Leather Gloves

Hand gloves with PVC dotting

Annexure IV

Safety Work Permits

A. Working at heights

Permit No.	Date:
Project Name:	Location:
Contractor/Sub-contractor/Supervisor:	Location/Area of work:
Job description:	

Check points	**YES**	**NO**	**N/A**
Overhead Clearance: Required clearance available from all overhead electrical lines?			
Medical conditions including vertigo (certificate needs to be attached).			
Ladders: Well-maintained ladders with adequate strength. Ladder is fastened to prevent falls or slips. Work area under the ladder is barricaded to prevent persons from walking beneath.			
Wall Opening All open sides or openings through which a person can fall are covered. All barriers that are placed to prevent falls, like guard rails, safety nets, etc., are inspected and in good condition.			
Personal Protective Equipment: All PPE has been inspected and is in good condition. Safety harness provided. Proper lifelines, lanyards, connectors, anchors are placed at the site. Safety Helmets. Safety Shoes.			
Workers' Safety: Are all the workers trained for working at heights and the proper use of PPE and fall arrest systems? Are all workers aware of hazards involved in working at heights? Is the supervisor adequately qualified and trained to ensure that safe work practices are followed at the site?			

A. Permissions

Permission granted from _____ to _____ hrs on .....(Date)

Time and date:

Name and signature of approving authority

B. Receipt I hereby declare that I accept responsibility for carrying out the work as detailed on this permit and no attempt will be made by me or the personnel under my control to carry out any other work. Time and date: Name and signature of permit receiver
C. Clearance certificate Work completed by taking all precautionary steps as approved by the permit issuing authority. Time and date: Name and signature of permit receiver
D. Cancellation This permit to work is hereby cancelled. Time and date: Name and signature of approving authority

B. Hot work permit

Permit No.	Date:
Project Name:	Location:
Contractor/Sub-contractor/Supervisor:	Location/Area of work:
Job description:	

Check points	**Yes**	**No**	**N.R.**
The work area is clear of oil, grease and waste cotton.			
In case of gas welding, are proper hose pipes and pressure gauges used?			
Are regulators, hoses, gauges, torches, cylinders, lighters and other equipment in good working condition?			
Flashback arrestors provided for oxy-acetylene cylinders?			
In electrical welding is proper earthing provided?			
Personal Protective Equipment: All PPE are available, inspected and are in good condition. Safety helmets with vice. Safety shoes. Safety gloves. Safety goggles. Other PPE _____			
Workers' Safety Fire Extinguishers are available at site. Fire sand buckets are kept handy at site. Tin sheet/wet gunny bag/fire retardant cloth (to prevent sparks from causing fire) available. Safety Signs in place.			

A. Permissions

Permission granted from _____ to _____hrs on .....(Date)

Time and date:

Name and signature of approving authority

B. Receipt

I hereby declare that I accept responsibility for carrying out the work as detailed on this permit and no attempt will be made by me or the personnel under my control to carry out any other work.

Time and date:

Name and signature of permit receiver

C. Clearance certificate Work completed by taking all precautionary steps as approved by the permit issuing authority. Time and date: Name and signature of permit receiver
D. Cancellation This permit to work is hereby cancelled. Time and date: Name and signature of approving authority

C. Excavation permit

Permit No.	Date:
Project Name:	Location:
Contractor/Sub-contractor/Supervisor:	Location/Area of work:
Job description:	

Check points	**Yes**	**No**	**N.R.**
Open area of trench is barricaded and safety signs are placed.			
Risk of excavation on surrounding structures & underground cables.			
Risk of excavation on water hydrant, sprinkler pipes; telephone & sewer lines.			
Personal Protective Equipment: **All PPE are available, inspected and are in good condition.** Safety Helmets. Safety Shoes. Safety Gloves. Eye and Ear Protection. Nose Mask.			
Presence of experienced supervisor during the work.			
Use certified machinery and inspect their condition			
No person working in trench during excavation.			

Note: This Permit shall lapse after a rain/storm in the work area. A fresh application is required.

A. Permissions

Permission granted from_____to_____hrs on.....(Date)

Time and date:

Name and signature of approving authority

B. Receipt

I hereby declare that I accept responsibility for carrying out the work as detailed on this permit and no attempt will be made by me or personnel under my control to carry out any other work.

Time and date:

Name and signature of permit receiver

C. Clearance certificate

Work completed by taking all precautionary steps as approved by the permit issuing authority.

Time and date:

Name and signature of permit receiver

D. Cancellation

This permit to work is hereby cancelled.

Time and date:

Name and signature of approving authority

D. Night work permit form

Permit No.	Date:
Project Name:	Location:
Contractor/Sub-contractor/Supervisor:	Location/Area of work:
Job description:	

Check Points	Yes	No	N.R.
Responsible engineer available on site with the authority of decision making for night activity.			
Night shift risk assessment done and all hazards identified and mitigation measures taken.			
Emergency response plan and procedures for night activities available at site.			
Work area provided with sufficient lighting and backup power.			
Emergency vehicle available at site.			
Intimation given to client for the night shift activity.			
Workers are trained for safe working at night and aware of all night hazards and mitigation measures.			

A. Permissions

Permission granted from ____ to _____hrs on .....(Date)

Time and date:

Name and signature of approving authority

B. Receipt

I hereby declare that I accept responsibility for carrying out the work as detailed on this permit and no attempt will be made by me or personnel under my control to carry out any other work.

Time and date:

Name and signature of permit receiver

C. Clearance certificate

Work completed by taking all precautionary steps as approved by the permit issuing authority.

Time and date:

Name and signature of permit receiver

D. Cancellation

This permit to work is hereby cancelled.

Time and date:

Name and signature of approving authority

E. Restricted area work permit

This is for working on AHU/control panels/inverters/server/battery rooms/junction boxes

Permit No.	Date:
Project Name:	Location:
Contractor/Sub-contractor/supervisor:	Location/Area of work:
Job description:	

LOTO required or not _____

Hot work/Height work permit required _____

Any other precautions, if required _____

A. Permissions Permission is granted from _____to _____hrs on .....(Date) Time and date: Name and signature of approving authority
B. Receipt I hereby declare that I accept responsibility for carrying out the work as detailed on this permit and no attempt will be made by me or personnel under my control to carry out any other work. Time and date: Name and signature of permit receiver
C. Clearance certificate Work completed by taking all precautionary steps as approved by the permit issuing authority. Time and date: Name and signature of permit receiver
D. Cancellation This permit to work is hereby cancelled. Time and date: Name and signature of approving authority

F. Disposal permit

Permit No.	Date:
Project Name:	Location:
Contractor/Sub-contractor/Supervisor:	Location/Area of work:
Job description:	

Sl. No	Date	Waste Stream (Source or process in which waste generated)	Quantity	Nature of waste	Method of disposal	Remarks
1						
2						
3						
4						

The procedures posted at the burning ground and disposal area must be followed in detail during these operations.

Time and date:

Name and signature of approving authority

G. PPE checklist

Sl. No	Particulars	AV/NA/NR
1	Safety Helmets for workers.	
2	Safety gloves (rubber gloves for electrical protection/leather gloves for cut protection).	
3	Safety Shoes.	
4	Safety Harness.	
5	Lifeline Lanyards Anchors Connectors	
6	Ear Protection	
7	Safety glasses/Safety screens/Safety goggles	
8	Anchorage Hooks Connectors	
9	Reflective Jacket.	
10	Respirator/protection from inhalation hazards.	

AV- Available

NA- Not Available

NR- Not Required

Verified and checked the condition for use by

EHS Manager/Site Safety Officer

Contractor's Site Incharge/Safety Incharge

H. Incident/near miss

Permit No.	Date:
Project Name:	Location:
Contractor/Sub-contractor/Supervisor:	Location/Area of work:
Job description:	

Injuries:

Treated by: _____ Treated at: _____

Type of Incident (First-aid/Recordable/Lost Workday/Fatal/Near Miss): _____

Task assigned to person at the time of incident	
Description of the Incident	
Primary root cause of the Incident	
Contributory factors	
Safety training provided to employee	Yes/No
Were the checklists & safe work procedures followed	Yes/No
Preventive measures proposed to avoid recurrence in future	

Contractor / Site Incharge Contractor

Safety Incharge

Annexure V

General Electrical Parameters

Parameter	Symbol or equation	Unit	Description
Plane of array irradiance	G_i	$W.m^{-2}$	Solar resource falls at an angle equivalent to the array tilt angle.
Plane of array irradiation	H_i	$Wh.m^{-2}$	Solar energy falls at an angle equivalent to the array tilt angle.
Nominal PV module power (STC)	P_{module}	W	Power rating at STC.
PV module open circuit voltage (STC)	V_{oc}	V	Open circuit voltage of PV module measured at STC.
PV module maximum voltage (STC)	V_{max}	V	Live voltage of PV module connected to load or inverter measured at STC conditions.
PV module short circuit current (STC)	I_{sc}	A	Short circuit current of PV module measured at STC.
PV module blocking diode voltage	$V_{oc.diode}$	V	Measured between blocking diode terminals.
PV module maximum current (STC)	I_{max}	A	Maximum current of PV module connected to load or inverter measured at STC conditions.
Fill Factor	$FF = (V_{max} . I_{max}) . (V_{oc} . I_{sc})^{-1}$	-	The Fill Factor (FF) is essentially a measure of quality of the solar module. It is the ratio of the maximum power to the theoretical power (that would be: output at both the open circuit voltage and short circuit current together).
Nominal PV plant power (STC)	$P_{plant} = P_{module} \times$ Total number of modules.	kW	Maximum power output of solar power plant at STC.
PV plant area	A_{PV}= Area of one module × Total number of modules.	m^2	Total surface area of all the PV modules.
Maximum string voltage	$V_{max.string} = V_{max}$. number of PV modules connected in series.	V	
String open circuit voltage	$V_{oc.string} = V_{oc}$. number of PV modules connected in series.	V	
Maximum array current	$I_{max.array} = I_{max}$. number of strings connected in	A	

	parallel.		
Solar energy generated	E_{Solar}	kWh	Energy generated from solar power plant. Measured after solar inverter or energy meter installed before evacuation point.
Auxiliary energy consumption	E_{auxi}	kWh	Energy consumed by power plant. In case of net metering system or captive system the parameter will be high.
Net energy import	$E_{net} = E_{Solar} - E_{auxi}$	kWh	In case of captive power plants, $E_{net} < E_{auxi}$ In case of utility scale power plants, $E_{net} > E_{auxi}$
Soiling ratio (SR)	SR using power = $P_{max, measured} / P_{max, expected}$ SR using short circuit current = $I_{sc, measured} / I_{sc,expected}$		It's the measure of soil deposition on PV module.
Bypass diode forward voltage	$V_2 - \sum_{i=1}^{n} V_i \geq V_D \quad , \ i \neq 2$	V	V_D – forward drop voltage of the diode.
Average power	$P_{avg} = E_{Solar} . t^{-1}$	kW	t - total runtime of power plant or inverter (only uptime).
Installed power load factor	$K_u = P_{avg} . P_{plant}^{-1}$	-	
PV array energy yield	$Y_{array} = E_{DC} / P_{plant}$	kWh. kW^{-1}	E_{DC} - PV array DC energy , kWh
Final system yield	$Y_{final} = E_{Solar} / P_{plant}$	kWh. kW^{-1}	
Reference yield	$Y_{ref} = H_i / G_{i.ref}$	kWh. kW^{-1}	$G_{i.ref}$ - irradiance at which DC rated capacity of array is determined (normally it is 1000 W/m^2).
Expected yield	$Y_{exp,final} = PR_{exp} \times Y_{ref}$	kWh. kW^{-1}	PR_{exp} - average expected performance ratio (PR_ power plant based on simulation with actual meteorological parameters).
Array capture yield loss	$L_C = Y_{ref} - Y_{array}$	kWh. kW^{-1}	
Balance of system yield losses	$L_{BOM} = Y_{array} - Y_{final}$	kWh. kW^{-1}	
PV system DC efficiency	$\eta_{DC} = E_{DC} / (H_i . A_{PV})$		
Balance of system efficiency	$\eta_{AC} = E_{solar} / E_{DC}$		

Performance ratio	$PR = Y_{final} / Y_{ref}$ $\left(\sum_{k} P_{solar,k} \times T_k \Big/ P_{plant}\right) \Big/ \left(\sum_{k} G_{i,k} . T_k \Big/ G_{i,ref}\right)$		K - recording interval. $P_{solar,k}$ - power generated at k^{th} interval. T_k - time span between two intervals. $G_{i,k}$ - solar in-plane irradiance on k^{th} interval.
Temperature corrected performance ratio	$\left(\sum_{k} P_{solar,k} \times T_k\right) \Big/ \left(\sum_{k} (P_{plant} \times C_k).G_{i,k}.T_k \Big/ G_{i,ref}\right)$ $C_k = 1 + \gamma \cdot (T_{mod,k} - 25^0 C)$		Ɣ - relative maximum power temperature coefficient ($^0C^{-1}$). $T_{mod,k}$- module temperature (^0C).
Power Performance Index	$PPI = P_{actual} / P_{expected}$		
Energy Performance Index	$EPI = E_{solarI} / E_{expected} = Y_{final}/Y_{exp}$= Temperature corrected PR.		
Uptime	$U_{time} = (T_{useful} - T_{down})/T_{useful}$		T_{useful} - indicates the total time period in which useful irradiance is available; it can vary as per inverter rating, number of PV modules in series, DC to AC ratio, PV module technology, climatic conditions, etc. T_{down}- time period inside T_{useful} where the power plant is down or not producing power.
Availability	$A = (T_{useful} - T_{down} + T_{excluded})/T_{useful}$		It is the measure of plant availability for energy generation.
Energy based availability	$A_{energy,i} = E_i / (E_i + E_{loss(i)})$		$A_{energy,i}$- Energy based availability for period I E_i- Energy produced in the time period I $E_{loss(i)}$ - Estimated energy loss during the time period i

Annexure VI

Quality Assurance Plan

A model quality assurance plan to be followed at the time of a solar power plant's commissioning and before its handing over to the operations team is given for ready reference. The solar PV plant owner can modify the content suitably, based on the solar PV plant's capacity and site conditions. Quality checks are required to ensure quality of material and workmanship during installation and commissioning. The considerations and documents verified in QAP plan will be the reference during O&M period.

QAP Document Revision: _____

Project name and capacity	_____MW/kW solar PV power plant.
Address of power plant	
Type of power plant	Captive/Utility scale.
Type of installation	Flat rooftop/tilted rooftop/ground-mounted/_____.
Work order details	
Customer details	
EPC contractor	
Project team	EPC
	Asset owner
	Third party or consultant

	Standards (Standards applicable as per site and plant design)	Document name/parameter (Parameters or documents to be checked to ensure the quality of material)	Acceptance methodology (Method to be followed by the EPC/asset owner/consultant to confirm the expected quality)	Involvement of stakeholders			Record or documents (Documents to be submitted by EPC during the plant handing over process)
				Customer	EPC	Consultant	
Supply stage							
PV module	All applicable standards. e.g. IEC 61215, IEC 61730, IEC 61701, IEC 62804, etc.	PV module datasheet. PV module manual. Module BoM. PAN file. Module rating or specification. Module quality. Warranty certificate. Earthing requirement. Protection class. PV module after service plan. Packaging and transportation plan.	Visual inspection. Flash test reports. EL imaging test reports. PID test reports (on request). PV module I-V curve. Comparison with module datasheet and test reports.				Datasheet. BoM details. IEC test certificate of selected model. PAN file (for PV syst). Warranty certificate. Factory test certificates. Installation manual. Specific maintenance instruction from OEM (if any).
Solar Inverters	All applicable standards. e.g. IEC 62093, IEC 62116, IEC 60529, IEC 61683, IEC 60068, etc.	Inverter datasheet. Internal drawing. Inverter manual. Power quality. Installation manual. Unpacking procedure. Inverter protections.	Visual inspection. Factory test reports. Type test reports. Functional test reports. Comparison with datasheet and test reports.				Datasheet. IEC test certificate of selected model. OND file (for PV syst). Warranty certificate. Factory test certificates. Installation manual.

	Standards (Standards applicable as per site and plant design)	Document name/parameter (Parameters or documents to be checked to ensure the quality of material)	Acceptance methodology (Method to be followed by the EPC/asset owner/consultant to confirm the expected quality)	Involvement of stakeholders			Record or documents (Documents to be submitted by EPC during the plant handing over process)
				Customer	EPC	Consultant	
		Maintenance requirements. Earthing requirement. Warranty certificates. Services centres and response time offered.					Specific maintenance instructions from OEM.
Module mounting structure	All applicable IS and IEC standards	General arrangement drawing. MMS BoM. Material test certificates. Design specification and calculations. Installation manual (if any). Earthing provision. STADD report. Surface coating parameters. Plant accessibility and O&M considerations.	Visual inspection. Factory test reports. Type test reports. BoM verification.				As built general arrangement drawing (including changes after installation). Editable digital copy of all drawings (e.g. .dwg). Factory test certificates. Material certifications. STAAD report. Surface coating reports. Physical test report.
ACDB	All applicable IS and IEC standards.e.g. IEC 60947, IS 694, IS 1248, IS 2551, IS 2705, IS 3156,	General arrangement drawing. BoM. Electrical SLD. Datasheet. Design document.	Visual inspection. Factory test reports. Type test reports. BoM verification.				General arrangement drawing. Electrical SLD with design considerations. Factory test reports. Material certifications.

	Standards (Standards applicable as per site and plant design)	Document name/parameter (Parameters or documents to be checked to ensure the quality of material)	Acceptance methodology (Method to be followed by the EPC/asset owner/consultant to confirm the expected quality)	Involvement of stakeholders			Record or documents (Documents to be submitted by EPC during the plant handing over process)
				Customer	EPC	Consultant	
	IS 3072, IS 3202.	Protection class. Foundation or mounting arrangement requirements. Surface coating parameters. Warranty certificate. Installation and commissioning checklists.					Surface coating reports. Installation and operation manual. BoM.
AC & DC cables	All applicable IS and IEC standards. e.g. IEC 60227, IS 694, IS 1554,IS 7098, IEC 60332, IEC 60754.	Datasheet. Design document. Earthing requirement. BoM. Installation manual. UV Protection. Quantity received at site. Warranty certificate.	Visual inspection. Factory test reports. Type test reports. Planned design length.				Factory inspection reports. Routine test reports. Relevant certifications. Type test reports. Warranty Certificate.
Earthing system	All applicable IS and IEC standards. e.g. IEEE 80, IS 2309, IEC 62305, IEC 62561, IS 3043.	Earthing system design and requirement. Earthing layout. Test certificates. SLD showing earthing points. BoM.	Visual inspection. Factory test reports. Type test reports.				Factory inspection reports (if applicable.) Design documents. Relevant certifications. Type test reports.

	Standards (Standards applicable as per site and plant design)	Document name/parameter (Parameters or documents to be checked to ensure the quality of material)	Acceptance methodology (Method to be followed by the EPC/asset owner/consultant to confirm the expected quality)	Involvement of stakeholders			Record or documents (Documents to be submitted by EPC during the plant handing over process)
				Customer	EPC	Consultant	
Other miscellaneous: MC4 connectors, monitoring system and sensors, etc.	All applicable IS and IEC standards.	Design considerations. Installation procedure. Rating. Calibration requirements.	Visual inspection. Datasheet. Test certificates. Warranty certificates. Product manual. Installation manual.				Datasheet. Warranty certificates. Test certificates.
Monitoring system	All applicable IS and IEC standards e.g. IEC 61724.	Monitoring class. Sensor position and quantity. Monitoring methods. Warranty certificate. Calibration requirements.	Datasheet. General arrangement drawing. Feasibility report/DPR.				Datasheet. General arrangement drawing. Warranty certificate.
Installation stage							
Project timeline	Design finalization and acceptance. Material supply. Installation stages. Pre commissioning testing. Commissioning schedule.	Gantt chart or any other methods to represent the timeline.	As per the agreement.				Project timeline Gantt chart.

	Standards (Standards applicable as per site and plant design)	Document name/parameter (Parameters or documents to be checked to ensure the quality of material)	Acceptance methodology (Method to be followed by the EPC/asset owner/consultant to confirm the expected quality)	Involvement of stakeholders			Record or documents (Documents to be submitted by EPC during the plant handing over process)
				Customer	EPC	Consultant	
	Post commissioning testing. Handing over.						
EHS	General EHS rules of the EPC company - for installation and operation. General EHS rules of the asset owner - for installation and operation (if any). Material shifting plan - machinery planning to use PPEs using at site. Selection of sub contractors and EHS requirement.	Safety rules of EPC company. Safety rules of asset owners (if any). EHS plan for installation. Risk assessment plan. Safety checklists and permits.	Visual inspection. As per the agreement.				Risk assessment report. EHS requirement for plant operation.
Electrical Installation	All applicable IS and IEC standards. e.g. IEC 62124, IEC 60364	Design of PV strings. Inverter overloading. PV string distribution among inverter MPPT.	Visual inspection Verification with approved SLD. Site installation testing.				Electrical SLD. Site test reports.

	Standards (Standards applicable as per site and plant design)	Document name/parameter (Parameters or documents to be checked to ensure the quality of material)	Acceptance methodology (Method to be followed by the EPC/asset owner/consultant to confirm the expected quality)	Involvement of stakeholders			Record or documents (Documents to be submitted by EPC during the plant handing over process)
				Customer	EPC	Consultant	
		Considered cable length in design and actual cable length. Earthing requirement. Details in SLD. Power evacuation. Quality of workmanship.	Feasibility report/DPR.				
Civil works	All applicable IS and IEC standards.	General arrangement drawings. Installation manual. Cube test reports.	Visual inspection. Supplier reports. Feasibility report/DPR.				Site test reports. General arrangement drawing.
Mechanical Installation	All applicable IS and IEC standards. Design as per site condition and RFQ.	O&M provisions. Roof access provisions. Direction, tilt angle, shadow. MMS strength. Torque of connection points.	General arrangement drawing. Visual inspection. STAAD report. Feasibility report/DPR.				General arrangement drawing.
Testing and Commissioning							
Testing and commissioning	All applicable IS and IEC standards. e.g. IEC 62446, IEC 63049.	Connection testing. Documentation. Plant performance. Commissioning tests.	Standard commissioning procedures. Inverter manual. Key Performance Indicators.				Pre- commissioning test report. Post- commissioning test reports. Commissioning checklist.

	Standards (Standards applicable as per site and plant design)	Document name/parameter (Parameters or documents to be checked to ensure the quality of material)	Acceptance methodology (Method to be followed by the EPC/asset owner/consultant to confirm the expected quality)	Involvement of stakeholders			Record or documents (Documents to be submitted by EPC during the plant handing over process)
				Customer	EPC	Consultant	
Operations and Maintenance							
Operations and Maintenance	All applicable IS and IEC standards. e.g. IEC 63049, IEC 61724.	Monitoring methods and procedures. Scheduled maintenance procedures. Asset management. Warranty management. KPI evaluation.	O&M manual.				O&M manual.

Annexure VII

Power Plant Monitoring Report Formats

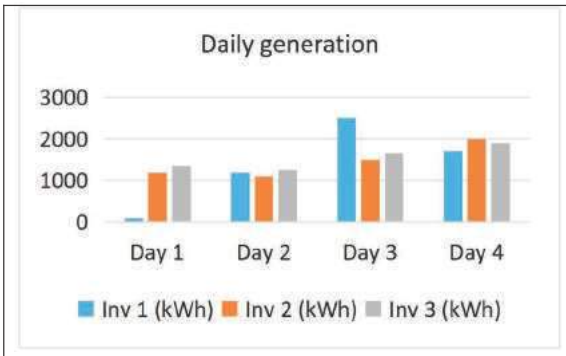
A. Daily monitoring report format

This annexure gives sample formats for the daily plant monitoring report. Tabulated and graphical representation of data will give a clear understanding of plant functioning.

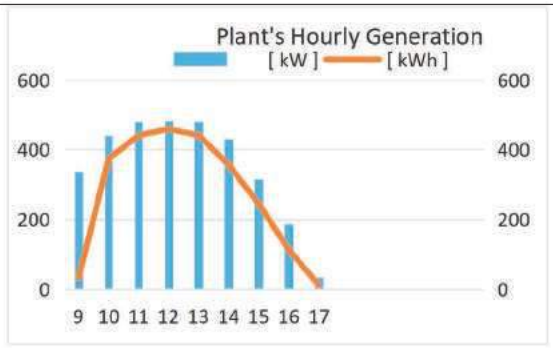
Project name/Customer's name	
Location details	
Date of Commissioning	
Report prepared by/On Duty Plant Incharge	
Plant capacity (kW)	
System configuration	
Yesterday's key observations	

All inverter level data is to be acquired in the following proposed format on a daily basis.

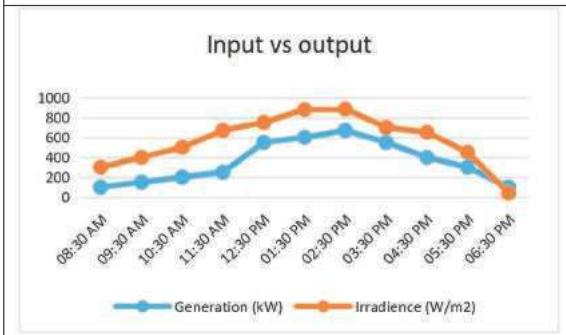
		Solar PV power plant daily generation data				
Inverter	Inverter rating (kW)	Peak Irradiance [W/m²]	Total Irradiation [kWh/m²]	Peak Power [kW]	Total Energy [MWh]	PR [%]
Inverter 1						
Inverter 2						
Inverter 3						
Total for plant						



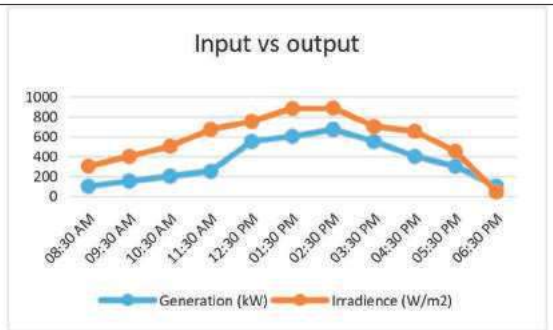
Daily inverter-wise generation



Plant's hourly power and energy generation



Hourly energy generation vs. irradiance (Inverter 1)



Hourly energy generation vs. irradiance (Inverter 2)

Observations and action to be taken:

Name and Designation of Engineer

Name and Designation of Supervisor

Note:

- Plant monitoring report is generated under scheduled O&M activity.
- Inverter level and plant level generation monitoring is required for performance analysis and to identify fault/issue.
- In-depth analysis of PV plant at inverter level needs to be performed if the gap between irradiance and generation is increasing in the graphical representation.
- If such increase in gap is observed, then undertake string level analysis.

B. Inverter level analysis report format

String level analysis is undertaken after observing deviation in daily monitoring report. All the strings connected to the inverter where deviation was observed are proposed for analysis. Here, the voltages and currents of all the strings connected to the inverter will be checked to identify the faulty string.

Project name/Customer's name	
Location details	
Date of Commissioning	
Type of testing	String parameter check
Testing done by (name and company)	
Date and time of testing	
Work assigned by	

System information	
Plant capacity (kW)	
System configuration/No. of strings per inverter	
Last string parameter check date for the inverter	
Significant observation found during last check	
AJBs or strings checked during last testing	

All the strings connected to the shortlisted inverter shall be tested to identify the faulted string causing drop in power generation. Following parameters shall be tested:

AJB No. _____, Time:_____, Day: sunny/cloudy				
String no.	Vmp (VDC)	Imp (A)	Voc (VDC)	Observation
1				
2				
3				
4				

Observations and action to be taken:

Name and Designation of Engineer

Name and Designation of Supervisor

Note:

- All safety precautions need to be taken by the workers.
- Workers should have a clear overview of the plant's technical details.
- Before testing the strings, the inverter should be switched off.
- DC connector should be opened by using appropriate disconnection tools.

C. String/Module level analysis report format

Once the faulty string is identified during the inverter level analysis, detailed analysis of identified string should be carried out.

Project name/Customer's name	
Location details	
Date of Commissioning	
Type of testing	
Testing done by (name and company)	
Date and time of testing	
Work assigned by	

System information	
Plant capacity (kW)	
System configuration/No. of modules per string	
Last string parameter check date	
Significant observation found during last check	
AJBs or strings checked during last testing	

Shortlisted string is tested to identify the fault. As per requirement, the modules connected to the string shall be tested. Following parameters shall be tested:

String No.	PV string/module insulation resistance	Comments	String No.	PV string/module ground fault	Comments

Observations and action to be taken:

Name and Designation of Engineer

Name and Designation of Supervisor

Note:

- All safety precautions need to be taken by the workers.
- Workers should have a clear overview of the plant's technical details.
- DC connector should be opened by using appropriate disconnection tools.

D. PV module/string parameter analysis report format

The faulty module/string identified will be further analysed to determine the root cause of the fault. The indicative tests to be carried out for this are proposed in this check.

Project name/Customer's name	
Location details	
Date of Commissioning	
Type of testing	
Testing done by (name and company)	
Date and time of testing	
Work assigned by	

System information	
Plant capacity (kW)	
System configuration/No. of modules per string	

Faulty module will be further tested to undertake root cause analysis. The steps to be followed or the tests to be undertaken will vary based on the type of fault. Indicative parameters of the faulty module to be tested are as follows:

String or module No.	V_{oc}	V_{mp}	I_{SC}	I_{mp}	I-V Characteristics type (distorted or not)	Time of check	Irradiance (W/m^2)	Module temp. (^0C)	Remarks

Observations and action to be taken:

Name and Designation of Engineer

Name and Designation of Supervisor

Note:

- All safety precautions need to be taken by the workers.
- Workers should have a clear overview of the plant's technical details.
- DC connector should be opened by using appropriate disconnection tools.

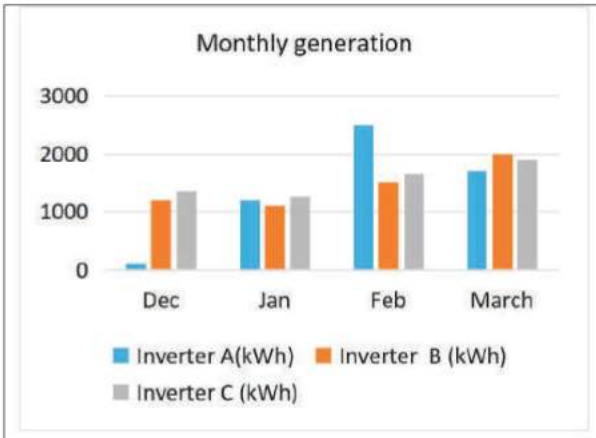
E. Plant monitoring report format

This format can be used to monitor the periodic performance of a solar PV power plant. Report can be generated on monthly/quarterly or yearly basis, based on the requirement. Indicative list of parameters and KPIs to be monitored is given for ready reference and this can vary based on plant capacity and plant owner's requirement.

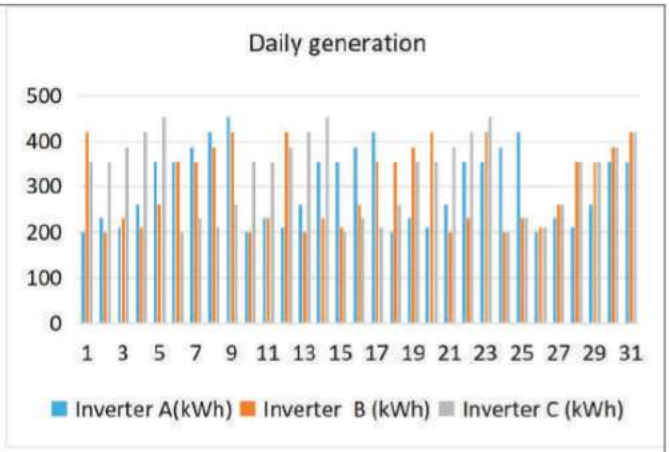
Project name/Customer's name	
Location details	
Date of Commissioning	
Type of testing	
Testing done by (name and company)	
Date and time of testing	
Work assigned by	

Sample parameters and KPIs to be monitored are as follows:

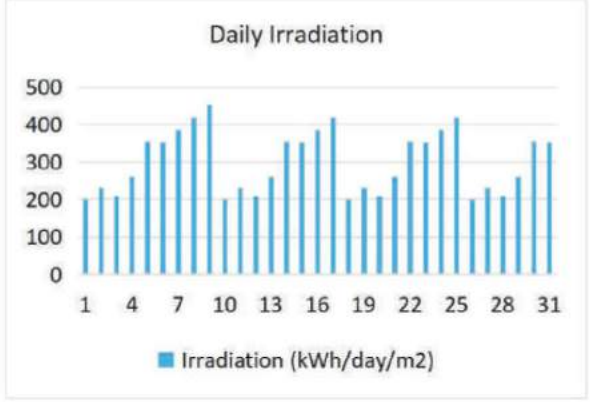
Reporting period	Cumulative plant generation (kWh)	Plant generation for reporting period (kWh)
DD/MM/YYYY to DD/MM/YYYY		



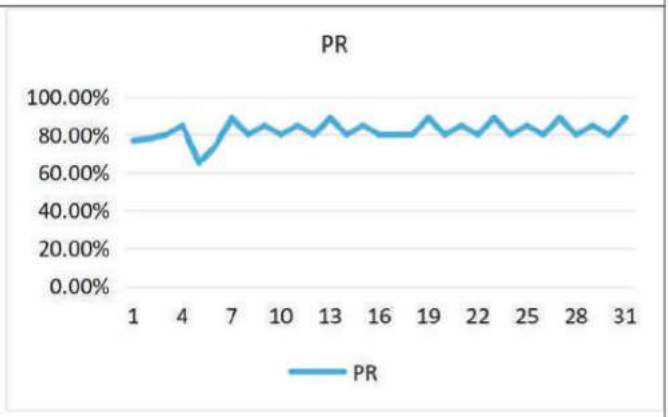
Monthly generation of power plant



Daily power and energy generation



Daily Irradiation



Performance Ratio

Maximum generation (kW)	Date and time at maximum generation	Irradiance at maximum generation	Ambient temp. at maximum generation

Total generation (kWh) at reporting period	Irradiation for reporting period (kWh/m2)	Performance ratio	Working hours (hrs)	Total down time (hrs)

Observations and action to be taken:

Name and Designation of Engineer

Name and Designation of Supervisor

Note:

- Major plant events need to be described separately.

Annexure VIII

Solar PV Power Plant Documentation

Project name	_____MW/kW solar PV power plant.
Address of power plant	
Type of power plant	Captive/Utility scale
Type of installation	Flat rooftop/tilted rooftop/ground-mounted/_____

Documents to be recorded	Remarks
PV power plant installation records	
All documents as per Annexure VI (QAP) ● Components' records including factory test certificates. ● As built system layout record. ● Commissioning test reports. ● O&M manual. ● Reporting formats. ● Documentation of health and safety issues and rules.	This is the core of the documentation process. All operational activities of the power plant will be based on these documents. It is recommended to display physical copies of plant layout and EHS rules at the power plant.
PV Plant Operations Records	
● General power plant monitoring details including generation. ● Plant operational tests. ● KPI evaluation and reporting. ● Performance audit reports. ● O&M schedules and activities. ● Spare parts/Tools/Instruments inventory at site: stock count and location; names and part numbers; date purchased. ● Contact details of major component manufacturer's service centres. ● Re-commissioning and inspections reports. ● EHS permits and technician's details. ● Visitors' details and log book. ● Past and current contracts with all service providers and suppliers' names, start and end dates, scope of work, contract value and pricing, performance indicators and guarantees, contract clauses.	Performance analysis and O&M records mainly used for comparing present generation patterns with the past. Ongoing activities' records to be maintained. Internal audit of documents should be carried out to ensure that the O&M team is following the set procedures and processes.
Plant Component's Warranty and Calibration Records	
● PV module, inverter and BoS warranty documents. ● Monitoring system warranty. ● Warranty claim details, communication with OEM.	All warranty related documents need to be recorded at the site for reference of the terms of warranty and its validity, in case required.

• Energy meters and weather sensors' calibration details. • O&M tool's calibration and warranty. • PPE's warranty/useful life related documents.	
Contract Documents and Records	

• O&M contracts including scope of O&M contractor.
• HR documents:
  ○ Training details of O&M team.
  ○ Medical fitness of O&M team.
• All commercial documents required for the audit.
	O&M contract, HR and financial documents' records are required for ready reference at the site and for compliance of govt. rules and regulations.

Annexure IX

Brief Contents of a Solar PV Plant's O&M Contract

The brief contents of a solar PV power plant's O&M contract are presented here for ready reference. The conditions of the contracts will differ based on the capacity, scope of work, size of team to be deployed at the site for O&M and mutual negotiations between the plant owner and the O&M contractor.

Sections	Remarks	
Definitions	Definition of all technical terms is required at the start of the agreement, i.e. before the main contents, since there are many technical parameters in the operations of a solar PV plant. KPI terms need to be defined with equation and calculation methodology or in the appendix.	
Scope of services/O&M Services	Scope of activities generally covers visual inspection, cleaning and maintenance, reporting, schedule of activities, etc. The activity list depends on the type of O&M services required by the asset owner.	
	Residential, Small scale (<10 kWp)	Frequency of site visits, performance evaluation and remote monitoring (if any), PV module cleaning scope, etc.
	Commercial, Medium scale (<100 kWp)	Frequency of site visits (scheduled maintenance), performance evaluation and remote monitoring (if any), PV module cleaning scope, etc.
	Industrial, Medium scale (<10,000 kWp) Or a few hundred kWp	Site O&M activities (if O&M team stationed at site) and regular performance monitoring activities. Intermittent performance auditing of power plant (scope under asset owner or O&M contractor). Following this schedule, it is intended to outline responsibilities and sometimes exclusions.
	Utility scale - Commercial, Large scale (>1 MWp)	Site O&M activities, site maintenance, regular monitoring activities of performance, reporting frequency, grid compliances, etc. Intermittent performance auditing of the power plant (scope under asset owner or O&M contractor). Following this schedule, it is intended to outline responsibilities and sometimes exclusions.
Repair/services outside contract	Terms for repair and replacement of failed components which are outside the warranty period need to be specified. Repair due to unforeseeable circumstances need to be clearly mentioned, i.e. how repairs will be made, and the payment mechanism. Non-availability of the plant for generation due to events outside the operator's contractual liability is to be excluded from the contractual availability calculation.	

Sections	Remarks
	In case the O&M team is not stationed at the site, maximum response time can be included in this section.
Commercial terms	Lump sum charges per annum for different activities, rate/charges of manpower, rate of consumables, etc. Mention the terms for payment of taxes and duties. Time period for payment from the date of receipt of invoice and penalty clauses for delay in payment. Clauses for payment of disputed invoices, etc.
Monitoring equipment	Available monitoring provisions at the site need to be mentioned in the agreement separately, including monitoring accuracy class, number of sensors, sensor location, etc. If the O&M contractor plans to install or modify the existing monitoring system using his own dedicated systems, the following points need to be considered by the asset owner: • Degradation of monitoring accuracy class of the power plant is not acceptable. • At the end of contract period - ownership of additional monitoring components. • At the end of contract period- either O&M contractor has to replace the previous monitoring system or allow the asset owner to use the existing system.
Uptime, response time and resolution time	Outline of methodology for calculating uptime, response time and resolution time need to be included either in the main contract content section or along with KPIs. Exclusions in calculation need to be clearly mentioned in this part. Any event that serves to exclude downtime in an availability guarantee calculation such as grid events, force majeure, vandalism, certain preventative and corrective maintenance, etc., that fall outside of the contract between the owner and O&M service provider and the liability of the O&M service provider. Some force majeure clauses include all the 'excluded' events and go beyond just defining what could be considered traditional force majeure items, e.g. earthquake, hurricane, tornado, acts of war or civil unrest, etc.
Force majeure	This typically refers to low probability/high consequence events that are outside the O&M service provider's control and are not assigned to the operator for repair within the O&M service contract. The lost energy in these situations may mean loss of revenue if the event was not covered by insurance. The O&M service provider may be asked to offer services outside the main O&M contract after a force majeure event occurs. These events do not count against the O&M service provider when making the contractual availability calculation.

Sections	Remarks
Key performance indicators	Selection of KPIs should be optimum and should consider points like monitoring accuracy class, type and capacity of power plant, asset owner's requirements, etc. Over-engineering in selection of KPIs will not deliver expected outcomes. All selected KPIs should be defined clearly along with the calculation methodology. Threshold values against each KPI and penalty clauses can be included as per mutual agreement between all stakeholders.
Warranty management	In case of a newly commissioned power plant (most plant components are under a warranty period), the contract should clearly describe the proposed warranty management system by the O&M contractor. Some O&M contractors think that when components are no longer under warranty, they fall under repair services outside the contract. In such cases, the repair time for that component will not be counted against the contractual availability. It provides an opportunity for the O&M provider to conduct activities outside the anticipated and agreed-upon O&M agreement's scope.
Insurance	Apart from normal plant and asset insurance, special insurance related to O&M activity may cover the following: • Insurance for covering business interruptions. • Insurance for covering third party liability, employee insurance of O&M contractor. • Equipment breakdown insurance, etc. The contract document should specify the party responsible for taking insurance, its renewal, raising the claims, etc. It should also mention who the receiver of the insurance claims will be and mode of payment for restoring the fault till the insurance claim is received, etc.
Third party audit and dispute resolution	Contracts should have the option for third-party review of technical disputes. Further, the contract should specify the mode of dispute resolution, whether it will be through an arbitrator or through the courts. The mode of appointment of an arbitrator or the location/place of the court for filing such cases should be mutually decided upon and appropriate provisions should be made in the document.
Preventative maintenance	O&M manuals given by EPC contractor/OEM describing all preventative maintenance activities need to be handed over to the contractor at the start of the contract and need to be mentioned in the agreement. By following the agreed schedule, the O&M service provider can minimize his risks in underperformances and penalties linked to KPIs. The premise is that by following a PM schedule that respects the manufacturer's warranties and industry's best practices, the PV system would have greater uptime and high availability than a project with no preventative/predictive maintenance. This is also required for complying with warranty and insurance claims. Failure of compliance with preventive maintenance as suggested by the OEM, may lead to rejection of warranty claims for failed components because it cannot be proved that preventive maintenance has taken place based on the manufacturer's recommended schedule. Hence, proper documentation of preventive maintenance is required from this perspective and such activity and its compliance should be documented in the agreement.

Sections	Remarks
Corrective maintenance	Corrective maintenance is of two types: • Work without involving extra component cost. • Work involving extra component cost which falls outside the O&M services agreement and is sometimes referred to as "additional work." When corrective maintenance is performed after warranty expiration, some contracts are explicit about how repairs are to be handled. This type of activity is not generally counted against the O&M service provider's contractual availability guarantee calculation if performed outside the contract's scope.
Performance guarantee	The performance guarantee can be linked either with KPI or can be defined outside KPI as separate monitoring parameters. Underperformance can result in liquidated damages, and in some contracts, over performance can result in performance bonuses. The targeted value of a KPI or another parameter which is to be used for calculation of liquidated damages needs to be specified in the agreement.
Spare parts	Being able to keep a spare parts inventory during the contractual time period is beneficial in reducing the amount of downtime associated with outages requiring the replacement of parts. However, over-inventory will add to the cost. Hence, the contract should provide detailed instructions and delegate responsibility for maintaining the suggested list and quantity of spares and consumables, their procurement and replacement, record keeping, etc.
Liquidated damages	This applies to when the measured availability (and/or performance) is below the threshold stated in the contractual availability (or performance guarantee). Amounts paid are typically tied to the performance of the PV system, based on the amount of revenue lost and other considerations, and usually capped at the total O&M contract amount.
Reporting plant data	As per applicability, the contract should mention reporting responsibilities and the frequency for submission of information to the asset owner. It may include information related to generation data, faults data, extreme events data, utility billing data, KPI related data, etc.

Annexure X

Cleaning of Solar PV Module and Cleaning Cycle Optimisation

Soiling on solar PV modules and its impact on generation is discussed in Chapter 6.6.4. The chapter also discussed the methods to analyse the soil ratio (SR) apart from the observations made in a visual inspection. This annexure gives more information on the solar PV module cleaning activity and its optimisation.

A. Factors affecting cleaning cycle

The PV module cleaning activity is linked with the rate of soil deposition, which depends on the power plant's site and weather conditions. It is observed that a PV module's SR is comparatively less in the monsoon than in winter and summer. During the rainy season, the area near the power plant will be wet and therefore less dust will be carried by the wind. Also the rain plays an important role in naturally cleaning the PV modules. Ideally, the soiling will be less than in summer. Also, the amount of soil carried by the wind will be less in winter compared to summer and soiling will also get reduced due to the presence of vegetation (promoted by the monsoon rain) near the plant area. But due to the presence of high humidity in winter, dust is likely to stick to the PV modules. In summer, due to less moisture in the soil, there is high soil deposition on the modules. The soil deposition also varies with nearby activities (e.g. construction, mining, etc.). Hence, having a fixed cleaning frequency or cycle is not a good plan. Apart from the factors which affect soiling on a PV module, there are other factors which decide the cleaning cycle, such as:

- Cost of cleaning.
- The rate at which soil accumulates on the array; expressed as a power loss in %/day.
- Capacity factor for the location: The better the solar resource, the higher the reward for cleaning.
- Value of the delivered power (INR/kWh): The higher the value of the power, the higher the reward for cleaning.
- PV module efficiency: Lower the efficiency, more area (m^2) of the arrays needs to be cleaned for equivalent benefits.

Actual measurement of soiling on PV modules can be assessed analytically or with the help of instruments (Chapter 6.6.4). The measurement of SR or soiling will trigger the cleaning requirement. In case of large scale power plants, decision on cleaning requirement can be taken by studying the rainfall predictions. For example: an instrument may indicate that the array is soiled, which would trigger a cleaning requirement, but if the weather forecast shows heavy rain the next day, the cleaning of the array would be for free. Hence, soiling situations need to be assessed along with weather forecasts to evaluate the cleaning requirement. Further, in case of uniform soiling, a site-specific, cost-benefit, analysis should be performed to determine whether routine cleaning of the array is warranted.

B. Effect of climate on soiling

Studying the climatological influence on soiling is critical since it enhances understanding of the soiling process. Different weather parameters have great influence in increasing or decreasing the soiling level. Some of the factors affecting soiling levels are as follows:

Rainfall: Heavy rains are helpful for cleaning soiled solar modules. In case of light rain, the rain droplets can collect airborne dust particles and deposit them with high concentrations of residue which stick to the surface of a collector. If the rains do not persist to help wash off this residue, then after the module dries, large soiling dirt spots will smudge the surface. Effects of these deposits are partial soiling as illustrated in the following figures. Dry periods with the absence of rainfall are usually times when losses due to soiling peak during the year.

Figure : Partial soiling due to light rain conditions

Wind speed: Several research studies have concluded that high wind velocities result in high dust depositions. However, high winds can also remove dust from the surface of solar modules.But, high winds during dust storms, speed up the soiling process since they carry a lot of dust during these episodes.

Humidity: Humidity is another factor that may worsen the soiling problem. At high humidity, water soluble dust particles on the surface form microscopic droplets of salt solutions that also retain any insoluble particles. When dried, the precipitated salt acts as a cement to anchor insoluble particles to the surface, as shown in the following figure.

Figure :Rooftop Soiling level (picture taken from coastal area)

Apart from the above climatic conditions affecting soiling, the following three factors which depend on the above mentioned climatic parameters, are also key contributors to soiling and PV performance deterioration.

1. Principal dust material (chemical composition).
2. Size distribution of dust particles, which may be represented by mean diameter and standard deviation.
3. Dust deposited layer density on the module surface (which depends on 1 and 2 above).

C. PV module cleaning strategies

There are several methods for cleaning solar modules, such as: 1) water cleaning, 2) dry cleaning, 3) pressurised air cleaning and 4) robotic cleaning. A most common and simple method of cleaning PV modules is with normal demineralised water with mild detergent, as per recommendations of the manufacturer. Further, depending on the local climatic conditions, the cleaning method will vary. Some factors which affect PV module cleaning and common strategies are:

- Type and capacity of power plant
- Environmental conditions
- Water availability and quality
- Rainfall forecasts/availability
- Manpower availability, etc.

Some common strategies for preventing power loss as follows:

Strategies to avoid power loss due to soiling	
Preventative	**Restorative**
Deterrent: - Keep dirt from settling and adhering to the surfaces. Surface modification: - Modify the surface (treatments, coatings, films) so that strong bonding will not develop.	Washing: Wash off the dirt with water or low surface energy detergent type solutions before strong chemical or mechanical bonding can develop. Cleaning: Use chemicals or mechanically active cleaning techniques capable of breaking the chemical and mechanical bonds.

The first and most logical strategy is to mechanically remove the soiling by washing or wiping (restorative). This involves using a cloth or other medium to wipe the surface, or to employ water or low surface energy, detergent-based solutions to remove soiling before any strong chemical or mechanical bonds develop. These techniques, of course, can be extremely labour-intensive and require frequent and repeated procedures. If chemical agents are used, the chosen detergent solutions should be environmentally friendly. Furthermore, the solution-based processes can use significant amounts of water depending on the method used. The processes are potentially capable of some degree of automation (e.g. use of vehicles, robots, or mechanically integrated mechanisms, etc.). All these techniques, however, add concerns about damage to the surfaces being cleaned.

Consider the following tables in which cleaning strategies for solar power plants of different capacity have been explained based on climatic parameters and water availability.

Ground water and rainfall for different climatic regions in India

India's Climatic regions *	Tropical wet	Tropical wet and dry	Semi-arid steppe	Humid sub-tropical (warm summer)	Alpine (mountain climate)	Desert or arid
(A) Ground water potential (Yield Litres/sec) **	>40 (mostly near coastal areas). 1-5 (average, except in hilly areas).	>40 (mostly near coastal areas). 25-45 (for some parts near coastal areas). 1-5 (average except in hilly areas).	1-5 (average, except in hilly areas).	>40 (average). 25-40 (average NE except in hilly areas).	1-5 (average, except in hilly areas).	10-25 (average, except in hilly areas).
(B) Annual average rainfall (in centimetres)*	150-250 and >250 (average)	50-100 (average). 40-50 (some parts of MH, KA, TS). 100-150 (some parts of OD, WB). 150-250 (some parts of OD, WB).	50-100 (average) 20-40 (few near PB).	50-100 (average, except NE). 150-250 and >250 (average NE).	50-100 (average).	<20, 20-40 (maximum in parts), 40-50 (in few parts).

MH- Maharashtra, KA- Karnataka, TS- Telangana, WB- West Bengal, OD- Odisha, PB- Punjab, NE- North East

*India Climatic regions, Mapsofindia.com , accessed on 14/05/2018.
**Hydrological map of India, Central Ground Water Board; Online available: http://cgwb.gov.in/AQM/Pilot-AQM.html, accessed on 14/05/2018.
***India annual rainfall, Mapsofindia.com, accessed on 14/05/2018

Rooftop solar PV power plant	
<100 kW	• SPV power plants commissioned by residential, small commercial (warehouses, factory, commercial buildings, etc.) owners connected under net-metering. • Mainly no dedicated workers for O&M. • O&M team needs to analyze the power restorative method that may be preferred. • Cleaning cycle can be decided as per power production (it can be fixed as per power generation and seasons). • In case power plant maintenance is done by a separate O&M team, the owner needs to undertake visual inspection twice in a week. • Areas where **(A) Ground water potential is >40 Litres/sec and (B) Annual average rainfall is >250 centimetres** getting good rain (for at least 3 months), cleaning can be decided as per power production. It is required to conduct physical inspection after each rain event. Since these climatic regions have a good vegetation growth rate, falling leaves from nearby trees or other obstacles may land on the PV module after the rain. • In **coastal areas**, responsible persons need to check the PV module once in two weeks, due to high rate of salt cementing and bird droppings. • For power plants installed on factory premises where there may be polluting industries in the vicinity, construction work going on, or the plant is located close to the road side and affected by dust carried by vehicles, there should be regular checks on soil deposition, and condition and characteristics of corrosive components in the atmosphere etc., need to be verified. • **Tropical wet and dry** areas with less humid conditions can increase the cleaning span in summer and reduce the cleaning span in winter. • In case of RCC roof installations in **desert or arid** regions, the cleaning span can be set for more than 20 days on average, throughout the year, according to environmental conditions and power generation. Since humidity is low, the chances of high dust accumulation on a fixed tilt solar module are less. • Cleaning schedule should be fixed in such a way that all the modules connected to one MPPT are cleaned in one cycle.
>100 kW	• Commercial (warehouses, factories, commercial buildings, etc.) solar PV projects connected under net-metering policy or established for captive use without net metering. • In most cases there will be dedicated staff (not specifically in charge of power plant monitoring) who take care of power plant activities. • Preventative and Restorative strategies can be adopted. • Mainly string inverters are used, due to distributed rooftops and to avoid DC losses. • There are space constraints in allotting control rooms. • String level or MPPT level generation monitoring is done as per electrical component specifications. In case of distributed rooftop installations, it is not practical to visit the power plant for physical verification. • Soiling will not be even across all strings (because of cleaning schedule or due to environmental factors). • Cleaning span and area of modules should be selected in such a way that all strings connected to one inverter/MPPT are completely cleaned in a cleaning cycle. • In most cases, irrespective of latitude and climatic region, tilt angle of the power plant would be as per tilt angle of the roof sheet. This is to avoid increase in MMS and installation charges. So in **desert or arid climatic** regions it is suggested to carry out one cycle of dry cleaning between wet cleaning cycles. Dry cleaning can also be undertaken after a dust storm. • SPV power plants located in **tropical wet and dry climatic** regions with low humidity can increase the cleaning span in summer and reduce it in winter. • Areas where **(A) Ground water potential is >40 Litres/sec and (B) Annual average rainfall is >250 centimetres** getting good rain (for at least 3 months), cleaning can be decided as per power production. It is necessary to conduct physical inspection after each rain event. Since this climatic region has a good vegetation growth rate this may lead to falling leaves from nearby trees or other obstacles on the PV module after rain. • In **coastal areas**, the Plant Incharge needs to check the PV module once in two weeks, due to high rate of salt cementing and bird droppings. • Apart from the above discussed climatic regions, SPV power plants installed in high humidity areas

	may have high soiling and the cleaning span should be less than 20 days apart (need to consider the cost for cleaning and power gain after cleaning).
Ground-mounted solar PV power plant	
<1 MW	• Commercial (warehouses, factories, commercial buildings, etc.) owners connected under net-metering or captive user established for captive use without net metering. • In most cases there will be a dedicated staff to take care of power plant activities. • If the power plant is near an industry, warehouse, factory, or commercial building, the soil accumulation will be high. Hence, continuous visual inspection along with performance verification is required. • Cleaning span can be decided as per above points. • Area where the **(A) Ground water potential is >40 Litres/sec and (B) Annual average Rain availability is >250 centimetres, in tropical wet and dry, or humid sub tropical (warm summer) climate,** ground vegetation control and backsheet soiling due to heavy rain need to be considered. • Proper cleaning schedule should be undertaken in this category of power plant using string or central inverter cleaning scheduling as per MPPT or AJB respectively. • In high humidity regions, water-soluble dust particles on the surface form microscopic droplets of salt solutions that also retain insoluble particles.
>1 MW	• Utility scale projects established for sale of power to a utility, or utility scale solar projects established for wheeling power under open access for captive use or third party sale. • Dedicated O&M team will be available at the site. • There may be a maximum number of power plants located in isolated areas with no nearby industries. • Power plants placed in **urban/industrial areas** may have more soiling issues due to nearby activities (e.g. airborne ash particles from coal-fired utility power plants, vehicle emissions, particulates from construction, etc.). Likewise, projects located near agricultural farms or poultry farms may have deposits of species from fertilizers, windblown soil, or plant matter, flies and insects, etc. • Areas where **(A) Ground water potential is >40 Litres/sec and (B) Annual average Rainfall is >250 centimetres, in tropical wet and dry, or humid sub-tropical (warm summer),** ground vegetation control and backsheet soiling due to heavy rain need to be considered. • **For desert or arid climatic** regions, the cleaning span can be set for more than 20 days average, throughout the year, according to environmental conditions and power generation. • Proper cleaning schedule should be undertaken. In this category, maximum power plants use central inverters and hence cleaning should be scheduled so as to cover all the modules/strings connected to one AJB. • Robots or mechanically integrated module mechanisms can be used for large scale power plants based on technical feasibility and financial viability. • Average water requirement is around 2 litres/module/cleaning; in **tropical wet and dry** areas with high humidity conditions, soiling is high during the winter season. One best practice is to reduce the span of wet cleaning cycle during winter season and increase it during the summer by having one dry cleaning cycle between wet cleaning cycles. • Power plant cleaning span can be optimized by analysing soil ratio.

D. Solar PV panel cleaning requirements and precautions

Generally, wet cleaning of solar modules is preferred. However, in some cases where there is water scarcity, dry cleaning of modules is carried out. The detailed procedure and precautions to be followed during cleaning are as follows:

Wet Cleaning

Water is a very effective medium for surface cleaning of solar PV modules. Periodic rain helps in cleaning the soiling in solar power plants. However, in many regions and for climate seasons, other than the monsoon, human intervention is required for cleaning of modules. It is recommended to follow the PV module manufacturer's instructions while selecting or designing a module cleaning system. Following, is an example of some of the points projected by a PV module manufacturer, 'First Solar', for performing wet cleaning:

- Fresh water with TDS < 1500 mg/L may be used for cleaning the modules.
- If required, a mild, non-abrasive, non-caustic detergent is mixed with fresh water. A detergent solution with a pH of 6.5 to 8.5 at <25°C may be used.
- Water must be free from floating oil or other immiscible liquids, floating debris, excessive turbidity, and objectionable odours, etc.
- When using water, RO water provides the best results. When RO water is not available, tap water with low mineral content (total hardness <75 mg/L) or deionized water may be used. Calcium should not exceed 75 mg/ml.
- When using hard water (75 mg/L < total hardness < 180 mg/L), the water must be squeegeed off to prevent scale build-up.
- Chlorides should not exceed 250 mg/ml and water conductivity should be < 250 mS/cm.
- Do not use abrasive cleaners or de-greasers on the module. Do not use cleaning solutions containing hydrochloric acid, D-limonene, ammonia, or sodium hydroxide.
- Water pressure must not exceed 35 bar (500 psi) at the nozzle. Do not apply water that is more than 20°C warmer or colder than the module's surface temperature.

Dry cleaning

The simplest procedure for dry cleaning of solar PV modules is to mechanically remove the dust by wiping the module surface with a cloth or some other soft medium. If proper material is not used for cleaning, damage of the module surface, by way of scratches, may be caused. Repeated wiping of abrasive sand on a reflective mirror or transmissive glass cover can destroy the surface completely. Dry cleaning is preferred in locations where water availability is poor. It was observed that during the summer, dry cleaning can be performed between wet cleaning cycles so as to increase the span of wet cleaning and thereby reducing water usage.

Solar module cleaning tools: Some manual cleaning tools for cleaning solar PV modules are as follows:

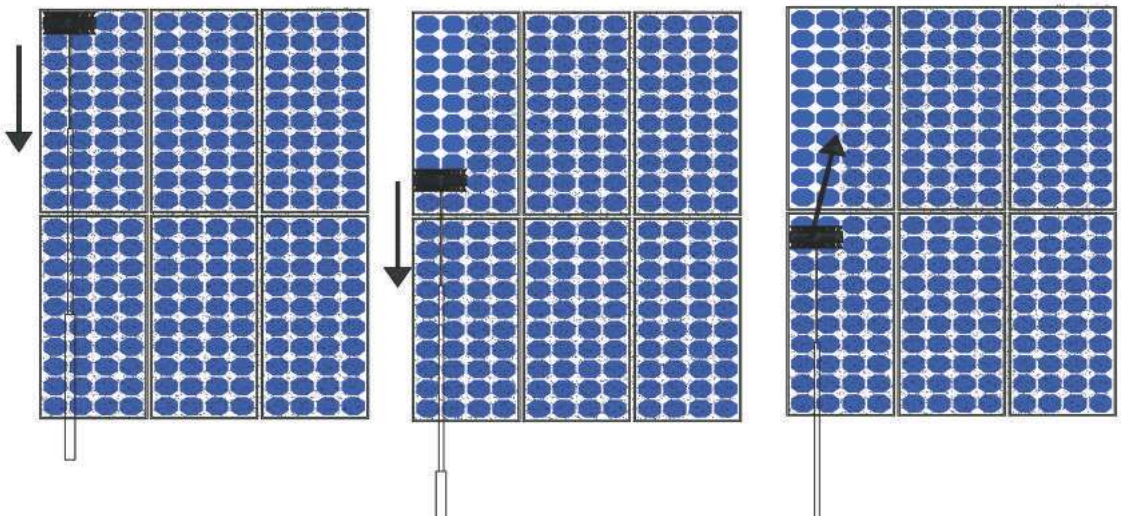
Material - Nylon strands or other equivalent material.
Support rod and extender: Should be of aluminium or plastic with arrangement to attach multiple extenders to achieve desired length. Lightweight is preferred.
Type of length adjustment – Part-by-part type or telescopic adjustable extender rods can be used.
Application - Used for wet cleaning of solar modules (rooftop and ground-mounted installations).
Other features - Some brushes are connected with rubber wipes on the end to wipe the water from the modules and to avoid scaling at the module's bottom edge.

Material - Squeegee rubber or other proper materials.
Support rod and extender: Should be of aluminium or plastic with arrangement to attach multiple extenders to achieve desired length. Lightweight is preferred.
Type of length adjustment – Part-by-part type or telescopic adjustable extender rods can be used.
Application - Used for wet cleaning of solar modules (rooftop and ground-mounted installations).
Other features - Direct cleaning and wiping; it will avoid scaling at the bottom of the module.

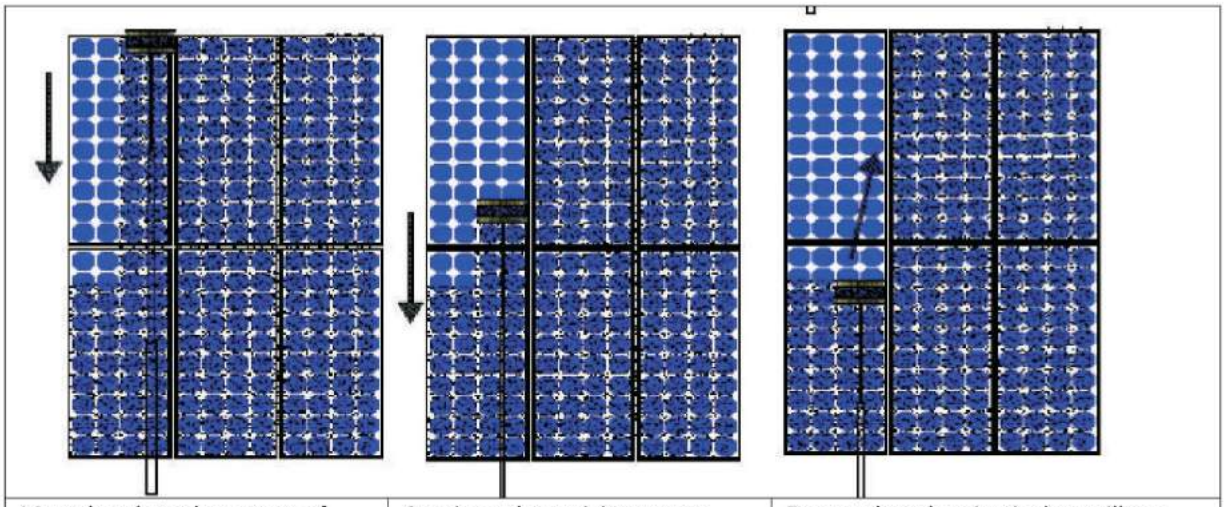
Material - Soft cloths or mops.
Support rod and extender: Should be of aluminium or plastic with arrangement to attach multiple extenders to achieve the desired length. Lightweight is preferred.
Type of length adjustment – Part-by-part type or telescopic adjustable extender rods can be used.
Application - Dry cleaning. Suited to both rooftop and ground-mounted systems.

PV module cleaning is an important activity and directly affects energy yield and longevity of a solar plant. Following factors need to be considered before performing cleaning activity:	Accessibility to solar modules (rooftop). Safety of worker. Source of water availability and quality. Number of modules that can be cleaned in one cycle. Cleaning scheduling, number of modules per MPPT/inverter. Knowledge of worker. Time of cleaning.

Pictorial representation of proper module cleaning procedure:



Moving the brush from top to bottom.	Continue the activity two to three times till the dust is removed completely.	Ensure that cleaning is done till top end of next row. This is to avoid water and dust logging at the bottom edge of first module.



Move brush to the corner of first module and start cleaning the module to the bottom.	Continue the activity two to three times till the dust is removed completely.	Ensure that cleaning is done till top end of the next row so that the complete module is cleaned and there is no water or dust logged at the bottom of first module.

When robots or mechanically integrated module cleaning mechanisms are used, ensure that the process covers the cleaning of the module completely and there is no water and dust logging at the bottom edge of the PV module.

Safety note:

- Workers cleaning the solar modules need to take care of safety precautions during cleaning and should follow proper EHS guidelines. In case of rooftop SPV plant, safety procedures for working at heights should be followed.
- Cracked or broken modules may lead to leakage of current and hence the risk of an electric shock while performing wet cleaning. Visual inspection of panels for cracks, damage, and loose connections is required before starting any wet cleaning.
- Follow instructions and requirements specified by OEM for cleaning solar modules.
- Cleaning of solar PV modules should be undertaken in the morning.

E. Optimizing PV module cleaning cycle

It is important to optimize the cost-effective cleaning periodicity of the cleaning process. Excessive cleaning will increase cost due to increased labour and water usage. Sometimes, excessive cleaning will lead to negative generation effect rather than positive generation pattern. Insufficient cleaning or increase in time span between two cleaning cycles will lead to generation loss. Typically, the cleaning is conducted during times when the system is disconnected from the load and/or during times that the balances of systems' components are not operating (e.g. early morning low light conditions, night time, etc.). Applying cool, cold or lukewarm water to hot modules can cause components (e.g. glass) to shrink rapidly, potentially causing cracks and breakages. If a fluid is used, it is best to have its temperature (within 10–15^{0}C is the rule of thumb) close to that of the surface module's to prevent excessive thermal shock. Abrasives and fluids that act as degreasing agents are to be avoided. If the surfaces are to be cleaned under dry conditions, non-conductive materials (brushes, clothes, etc.) should be used. In all circumstances, it is best to consult the manufacturer to ensure that the process is compatible with either the module itself or any coating that has been applied to it.

Factors affecting cleaning optimization are given below:

Factors affecting cleaning optimization	Dust accumulation rate.
	Climatic conditions.
	Power generation.
	Water availability.
	Cost of cleaning.
	Accessibility to rooftop and overall safety.

Solar PV module cleaning cycle optimization is a site specific activity. The following points are for reference and can be customized/improvized as per system configuration and actual site conditions.

<100 kW (Rooftop)

- Generation-based cleaning optimization is applicable.
- Monthly review of daily generation is required.
- Generally no monitoring system is used for systems below 10 kWp.
- Difficultly in analysing generation since there is no irradiance sensor.
- Accessibility to the rooftop is an important factor in determining the cleaning of PV modules by the owner.
- Cleaning cycle optimization can be done based on visual inspection and by analysing generation data.

>100 kW (Rooftop)

- Generation and Performance Ratio (PR) based cleaning optimization is applicable.
- Most string inverters have web-monitoring or SCADA-local monitoring with weather sensors. This will make the comparison of power generation easier.
- Scheduling of cleaning is important because of multiple rooftops and inverters.
- It is important to keep proper documentation of the cleaning cycle.
- Cleaning cycle span needs to be reviewed as per climatic conditions.
- Power generation review can be performed once in a week.
- It is important to keep generation gain in terms of 'cost for cleaning'.
- If power plant capacity is more than 1 MW, cleaning cycle can be optimized by using soiling ratio, information of DC generation (DC output measurement done at string or at MPPT level or at inverter level).
- Most power plants are designed with rooftop accessibility which will enhance the safety aspects of the cleaning process.

< 1 MW (Ground-mounted)

- Generation and Performance Ratio (PR) based cleaning optimization is applicable.
- Most of the string inverters have web-monitoring or SCADA-local monitoring with weather sensors. This will make the comparison of power generation easier.
- Scheduling of cleaning is important, because of multiple inverters.
- It is important to keep proper documentation of cleaning cycle.
- Cleaning cycle span needs to be reviewed as per climatic conditions.
- Site Incharge can perform visual inspection to monitor the soiling.
- It is important to keep generation gain in terms of 'cost for cleaning'.
- If possible, soiling ratio based string level or MPPT level DC optimization can be adopted.

> 1 MW (Ground-mounted)

- Generation and Performance Ratio (PR) based cleaning optimization is applicable.
- Plant will have web-monitoring or SCADA-local monitoring with weather sensors. This will make the comparison of generation easier.
- Scheduling of cleaning is important because of multiple inverters, AJBs, and widespread area.
- It is important to keep proper documentation of the cleaning cycle.
- Cleaning cycle span needs to be reviewed as per climatic conditions.
- It is important to keep generation gain in terms of 'cost for cleaning'.
- DC input or AC output based cleaning optimization can be performed.

F. Dos and Don'ts in solar PV module cleaning

<100 kW (Rooftop)	**Dos** ● O&M contractor or power plant owner needs to ensure accessibility to the PV module (Safety is first). ● Water connection with proper pressure on rooftop <35 bar. ● 1 + 1 number of workers or helpers at the site, every time. ● Ensure proper drainage of waste water. ● Cleaning activity to be undertaken preferably in the morning. ● Try to complete cleaning of the inverter wise or MPPT wise in a single attempt. ● Wipe excess water from the bottom of the PV module. **Don't** ● Clean without proper safety equipment. ● Walk over PV module. ● Partially clean the PV module. ● Partially clean the MPPT strings (string inverter), AJB (central inverter).
>100 kW (Rooftop)	**Dos** ● O&M contractor or power plant authority need to ensure accessibility to the PV module (Safety is first). ● Water connection with proper pressure on rooftop <35 bar. ● Ensure proper drainage of waste water. ● Cleaning activity to be undertaken preferably in the morning and finished before power production starts. ● Schedule cleaning as per inverter, MPPT, or AJB. ● Wipe excess water from the bottom of the PV module. ● Keep proper documentation of cleaning schedule. ● Select number of workers as per cleaning schedule. ● Clean the irradiance sensor and other sensors regularly. **Don't** ● Clean without proper safety equipment. ● Walk over PV module. ● Partially clean the PV module. ● Partially clean the MPPT strings (string inverter), AJB (central inverter).
<1 MW (Ground-mounted)	**Dos** ● Water connection with proper pressure <35 bar. ● Ensure proper drainage of waste water. ● Cleaning activity to be undertaken preferably in the morning and finished before power production starts. ● Schedule cleaning as per inverter, MPPT, or AJB. ● Wipe excess water from the bottom of the PV module. ● Keep proper documentation of cleaning schedule. ● Select number of workers as per cleaning schedule. ● Clean the irradiance sensor and other sensors regularly. **Don't** ● Clean without proper safety equipment. ● Place ladders on the edges of PV module instead of using proper ladder clamps. ● Partially clean the PV module. ● Partially clean the MPPT strings (string inverter), AJB (central inverter).
>1 MW (Ground-mounted)	**Dos** ● Water connection with proper pressure <35 bar. ● Ensure proper drainage of waste water. ● Preferably select the morning for cleaning and finish before power production starts. ● Schedule cleaning as per inverter or AJB. ● Wipe excess water from the bottom of the PV module. ● Keep proper documentation of cleaning schedule including power production of recently cleaned PV strings/MPPT/inverter. ● Standard check list before and after cleaning. ● Select number of workers as per cleaning schedule and season. ● Clean the irradiance sensor and other sensors regularly.

- Visual inspection by plant supervisors after cleaning.
- Discuss plant condition with workers after cleaning. This is to know the plant's physical condition; in case of larger power plants it is not practical for supervisors or engineer to go for plant visits every day. Interaction with workers will give a brief idea about certain issues like bird's nests, vegetation, land sliding, MMS issues, etc

Don't

- Clean without proper safety equipment.
- Walk over PV module.
- Partially clean the PV module.
- Partially clean the MPPT strings (string inverter), AJB (central inverter).
- Place ladder on the edges of PV modules instead of using proper ladder clamps.

Annexure XI

Visual Inspection Report

Preparing and scheduling the visit

Power plant name, address, contact no.	
Date of inspection	
Last visual inspection date	
Type of power plant	Ground-mounted/flat rooftop/slanted rooftop/other
Power plant capacity (kW)	
Type of system	On grid Captive/Utility scale
Details of power plant area inspected *(for large utility scale power plants visual inspection will be done along with other activities).*	If possible attach layout with inspected plant area demarcation.
Tools to be carried	- Plant layout - Camera
Inspection done by (Name and designation)	1. __ 2. __
Safety Note: Ensure all safety measures are followed before proceeding with the inspection. Avoid plant visit during rainy weather. Always keep in touch with control room engineers and try to give updates at regular intervals (in case of large scale ground or rooftop power plants with site monitoring).	

PV field inspection and recording

	Major points to be noted down (Location, Pictures, Comments)
PV module	Overall status. In case of any significant issues found, note down the PV module details (Chapter 6.6.10). Check frame earthing integrity and points, take IR image (if possible) if significant issue observed, note vegetation and nearby shadow issues, soiling on PV modules, etc.
PV module connectors/DC connectors	Connector integrity, IR image (if possible).
Array Junction Box (AJB)	AJB cap or box integrity, cable connection points, AJB area and vegetation, earthing points, fuse status.
Inverter (string inverters)	Overall status, nearby vegetation, earthing points, mounting integrity, connector integrity, IR image (if possible). Check if exhaust fan is working or not (all fans will operate only during the peak production time), note down any unusual sounds.
Module mounting structure (MMS)	MMS integrity, corrosion, vegetation, MMS foundation, earthing connection points.
Plant area	Water logging, approach road cleanliness, vegetation, drainage and water flow issues, roof walkways and connector integrity, water tank and piping, safety marks and sign boards.
Weather monitoring station	Check soiling on irradiation sensor, functioning of wind vane and anemometer, integrity of module temperature measurement sensor, etc.

Control room and other BoS inspection and recording

	Major points to be noted down (Location, Pictures, Comments)
Control room	Overall cleanliness, internal temperature, control room's ventilation, water logging, nearby vegetation, inventory systems or spare part's room, UPS status, status of battery charging, gravity, water level, etc.
Inverter	Overall status, nearby vegetation (outdoor), earthing points, mounting integrity, connector integrity, IR image (if possible). Check if exhaust fan is working or not (all fans will operate only during the peak production time), note down any unusual sounds.
Switch yard (for utility scale)	Water logging, nearby vegetation, earthing point integrity, corrosion on structures and transformer.
Solar ACDB or termination point (for captive generation)	Overall status, nearby vegetation (outdoor), earthing points, mounting integrity, connector integrity, IR image (if possible).
PPE, fire extinguishers and display sign boards	Check display sign boards for their integrity, proper visibility and condition. Check expiry date on fire extinguisher and its availability at desired location. Check PPE inventory, condition, tools and instruments, etc.

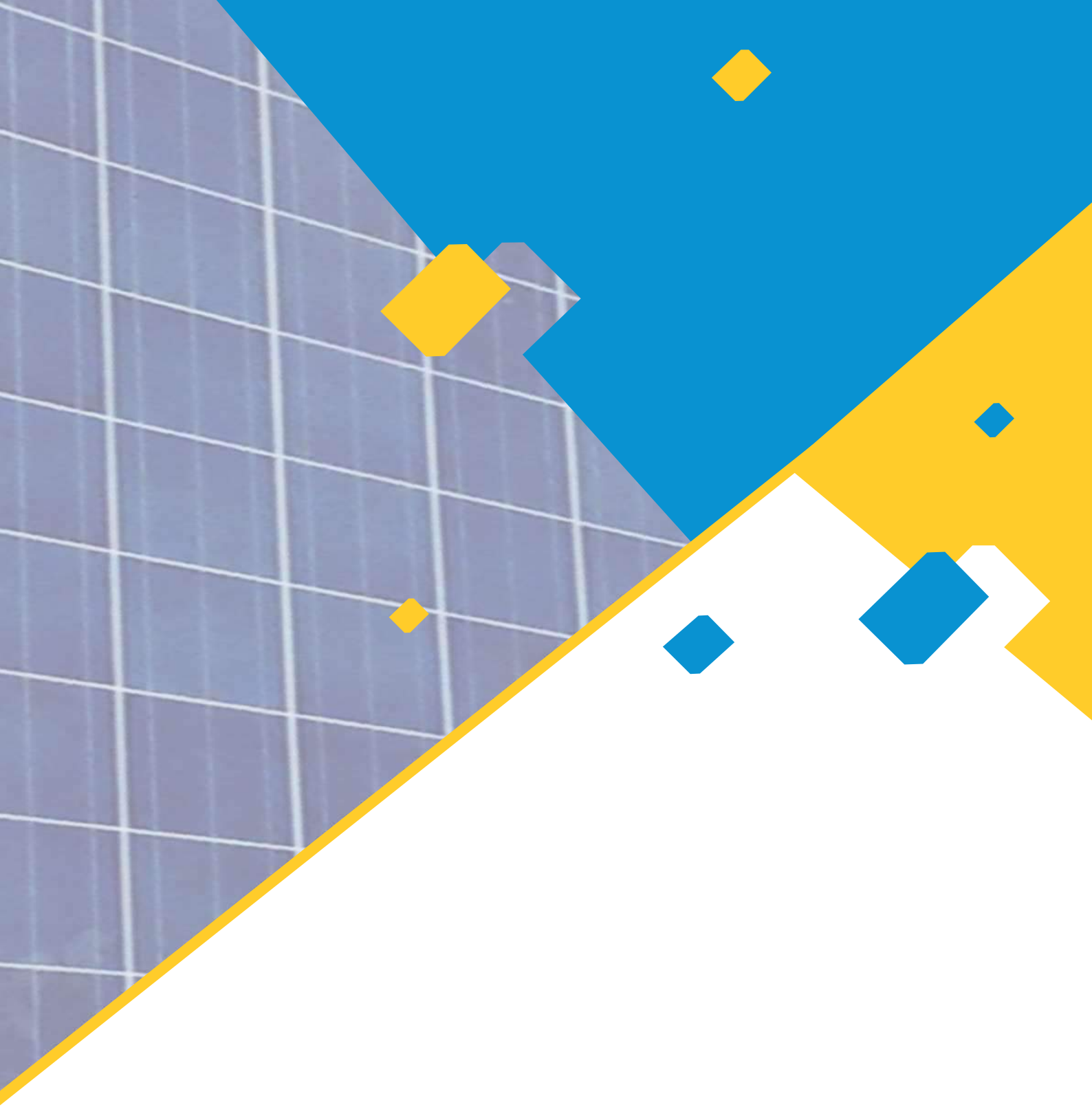
Summary/analysis of observations during visual inspection

This section needs to be filled after analyzing the issues or observations listed in the previous visual inspection report. It should contain the following points:

- Explanation of failure modes – type of fault, faulty component and probable reason for failure.
- Location of failure (note down sufficient information so as to identify the exact fault location);. in case of PV modules (note string, PV module number, demarcation in plant layout), etc.
- Action to be taken – preventive maintenance, differed corrective maintenance or corrective maintenance.
- Required resource and cost of rectification.

NOTES

NOTES



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