REVIEW OF GUIDELINES FOR PV SYSTEMS PERFORMANCE AND DEGRADATIONS MONITORING

Basant Raj Paudyal[1], Anne Gerd Imenes[1], Tor Oskar Saetre[1]
[1]University of Agder, Faculty of Engineering and Sciences, Grimstad, Norway
[1]Tel: +4737233103; e-mail: *basant.paudyal@uia.no*

ABSTRACT: The recent growth in the PV system deployment and the higher scale of their production make it necessary to pay more attention towards the performance of those systems. System monitoring will provide the status of the systems showing possible degradations and any impending system failures. It also helps with maintaining system quality and ensuring optimal performance of the system for its lifetime. COST Action PEARL PV aims to formulate such monitoring guidelines for the PV systems applicable for all types of PV technologies, depending upon the end use and duration of the monitoring need. The objective of the present paper is to quantify and provide a review of the guidelines and standards for monitoring of PV systems performance and degradation in practice, and also some results of preliminary work done regarding important information needed to be included in the monitoring guideline.
Keywords: PV Systems, Performance, Degradation, Monitoring

1 INTRODUCTION

Solar PV is one of the renewable energy technologies which converts sunlight into electricity. The PV industry and the research domain have had a remarkable global progress regarding the performance and installation volume of PV systems in the last few decades. With the laboratory efficiency crossing 40% [1] together with considerable rise in the outfield module efficiencies, PV has become an integral producer of electrical power globally. Performance monitoring of the PV systems provides a unique and adept solution to understanding the root causes of degradation while also indicating the possible measures to improve the performance of the system. In the present context, with over 400GW of global PV installation, the PV monitoring mechanisms provide a sense of security to investors, researchers and system owners alike.

Different types of PV modules are being designed based on the different materials and characteristics. The performance monitoring of such systems then becomes a necessity since they have different spectral response, sensitivity to temperature, shading, and other parameters in the outdoor environment. In this regard, monitoring can provide the essential information about the operation of such systems and could also provide insight on the necessary measures to be taken to improve their performance. Monitoring of PV systems may draw substantial costs depending upon the degree of accuracy of measured data, so the design of it must be considered carefully. For the data, appropriate performance parameters need to be chosen and their measurements should be continuously saved and updated. Depending upon the requirements, the values of different parameters could be logged every second, every minute or every hour resulting in accumulation of a huge amount of data. Standard sampling interval of measurement has been defined by the IEC61724 standard, but the monitoring frequency could be adjusted depending upon the need and budget of the user. It is better to evaluate the data that has incorporated seasonal variations as this gives a better idea of system performance along with weekly or monthly averages.

The present paper comes out as a preliminary work done within COST Action PEARL- PV, Work Group 1 PV monitoring with the objective of developing generally acceptable approaches and guidelines for the collection of data about the performance of PV modules and systems using advanced monitoring through various techniques [2]. The paper includes the literature review of the different performance parameters of PV systems and the monitoring guidelines formulated globally.

In the present paper, the authors review the monitoring guidelines formulated and implemented by various institutions. They review the current state of the art on monitoring guidelines and based on the initial feedback from the experts on the field, summarize the results on the degree of requirement of the parameters for monitoring.

2 PV PERFORMANCE AND DEGRADATION

2.1 Performance and loss factors

The performance ratio (PR) is the most important quantity to be measured for evaluating the overall behavior of a PV plant. The performance of the power plant depends on several parameters including the site location, the climate and several loss mechanisms[3]. The overall losses of a system are categorized broadly into two types of loss mechanisms, Capture Losses (LC) and System Losses (LS). Captures losses are the losses which affect the performance of PV systems with conversion of available energy into useful/output power of PV systems e.g. module and ambient temperature, obstruction or attenuation of incident radiation, module mismatches, nonoptimal MPP tracking and the parasitic resistances present in the cell and module level. System losses on the other hand are those types of losses that happen within the system and are caused by system components like DC to AC conversion losses, wiring losses and transformer conversion losses[4].

2.1.1 Capture losses

Capture losses are those types which occur at the DC side of a PV conversion chain and are attributed to operating temperature, tilt angle of modules, shading, temperature dependency of PV modules efficiency and most importantly dependence on solar irradiance level. While the PV array itself encounters some losses like MPP tracking error, module parameters dispersion (mismatch), wiring losses and aging[5]. These can be broadly classified into thermal capture losses and other miscellaneous losses[6].

2.1.1.1 Thermal capture losses

Module efficiency of crystalline modules at standard test condition (STC) is defined at 25ºC temperature. Depending on the various parameters like wind speed and the type of mounting of the PV modules, there could be a temperature rise of the modules with respect to the ambient of 20–40ºC at 1000 W/m^2. The corrected temperature DC output power, at real working irradiance and a standard temperature of 25ºC, can be obtained by the simulation model where the input are: the monitored irradiance and a fixed temperature of 25ºC[6]. The normalised capture losses can be then determined by the following expression:

$$Lct = Ya\ (G, 25^oC) - Ya\ (G,Tc) \quad (1)$$

where Lct are the thermal losses, Ya (G, 25ºC) is the normalised energy yield at real working irradiance and 25ºC of temperature, and Ya (G,Tc) is the array yield at real working irradiance and real module temperature Tc. Normalized thermal losses can give us the amount of power losses due the rise of temperature above 25ºC.

2.1.1.2 Miscellaneous capture losses

All the inherent losses such as non-uniformity of the irradiance, low irradiance, module/cell mismatch, MPPT errors, wiring, string diodes, dirt accumulation and losses caused by faulty operation at the DC side such as faulty strings, faulty modules, partial shadowing and short circuit of modules are grouped in this category[7].Since the inputs to the simulated model of the PV plant are the effective irradiance and module temperature, the simulated capture losses can be calculated by the following expression, after the calculation of the reference yield:

$$LC = Yr(G, Tc) - Ya(G, Tc) \quad (2)$$

where LC are the capture losses, Yr(G, Tc) is the measured reference yield and Ya(G, Tc) is the array yield at irradiance and temperature at the site. Finally, the reference miscellaneous capture losses are given by:

$$LCm = LC - Lct \quad (3)$$

where LC is the capture loss and Lct is the thermal capture loss of modules.

2.1.2 System losses

These losses are mainly referred to the power conditioning units, which are the DC-DC converters responsible to extract maximum available power from the PV plant, the wiring losses, transformer conversion losses as well as the DC to AC conversion losses. It can be obtained by the difference between the array yield and final yield.

$$Ls = Ya - Yf \quad (4)$$

The losses in a PV system are categorized in Figure 1.

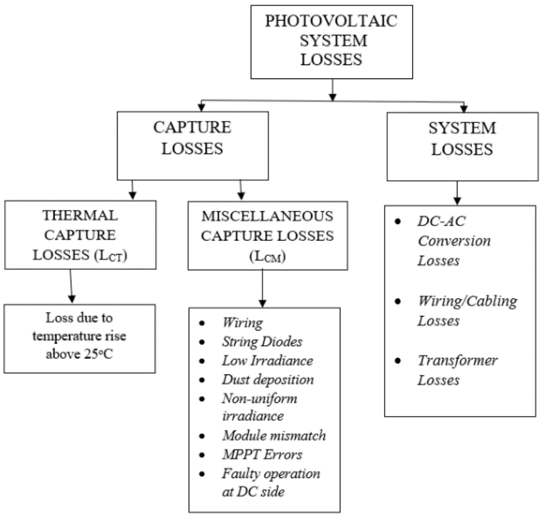

Figure 1: Categorization of losses in PV systems.

2.2 PV system performance

The reference yield is an expected yield from a system considering the energy of incoming light and modules' nominal efficiency whereas the final yield is the total yield after encountering different losses i.e. electricity delivered to the AC. The losses in plant are categorized broadly in two sections namely capture losses and system losses. Capture losses incorporate the various conversion losses in the array due to environmental parameters like irradiance, temperature, shading, soiling and design faults in DC side whereas the system losses include losses in power conditioning units, wirings and transformer conversion.

The power output of a PV system depends primarily on the latitude, outdoor operating conditions as well as the system design. Irradiance and module temperature are known to be the major operating conditions to determine the PV output, where module temperature is a function of solar irradiance, ambient temperature, other thermally related conditions such as wind speed and direction, array mounting and thermal behavior of the module [8]. Other influencing factors are the incident spectrum, angle of incidence of the irradiance and system level losses including soiling, shading and power conditioning losses. These factors in inclusion with the site-specific climate, location and the loss mechanisms are used to calculate a parameter which is the most widely used quantity for evaluation of healthiness of a PV system called Performance Ratio (PR) [4], which is defined as the ratio of final yield to reference yield.

$$PR = \frac{Y_f}{Y_r} = \frac{P_{DC}/P_o}{H/G} \quad (5)$$

Production and performance of grid connected systems are often measured in Performance Ratio (PR) and sometimes annual energy yield with both of them incorporating the degradation rates within the guarantee periods [8]. Energy yield may have some benefit of consideration in weather conditions, as the measured output can be compared with the predicted output under the similar weather. This requires constant monitoring of the parameters like solar irradiation, ambient and module temperatures while reliable simulation software should also be used.

Performance ratio in comparison is a simpler alternative as it takes the different losses in account and while the irradiation needs to be measured adjacent to the array, it gives a better output response to irradiation variation. But the seasonal change of ambient temperature will have a simultaneous impact on the module temperature. As the ambient temperature during winter gets colder this drops the temperature of the module, for the same amount of irradiance the reduced temperature will help in increased yield and hence the performance ratio. The performance characteristics used to calculate the PR is based on STC, which translates a module temperature of 25ºC. Since the modules operate at higher temperatures in normal conditions, it is possible to do a temperature correction of the power to STC. This calculation of the temperature corrected performance ratio (PR) is based on the measured back panel temperature.

$$\tau_{corr} = (T_{module} - 25^{o}C) \cdot \gamma P_{MPP} \qquad (6)$$

Here, τ_{corr} is the temperature correction coefficient, T_{module} is the temperature on the backside of the module, and γP_{MPP} is the temperature coefficient of the efficiency. Temperature coefficients for each type of module technologies can be found in corresponding data sheets provided by the manufacturer. Then using the temperature correction coefficient, it is possible to find the temperature corrected performance ratio as:

$$PR_{TC} = PR/(1+\tau_{corr}) \qquad (7)$$

2.2 Current trends in PV system performance

We already discussed how PR has been the main parameter to determine the healthiness of a solar PV system. The trend of using PR as a reference of a system performance started as far back as in the 1980's. It has continuously rose from 0.5 to 0.65 in the late 1980s to 0.7 in the 90s to more than 0.8 nowadays [4]. Early PV systems did not generate the expected energy yield due to various constraints related to poor systems design and installation coupled with inefficient devices [9].

Monitoring for one year with measurement of performance ratio and different losses of a 171.36 kWp system in Crete, Greece found that the PV system supplied 229 MWh to the grid during 2007, ranging from 335.48 to 869.68 kWh. The final yield (YF) ranged between 1.96 to 5.07 h/d, and the performance ratio (PR) varied between 58 to 73%, with an annual PR of 67.36% [10]. Meanwhile, one-year measurement and performance analysis of two real-life grid connected PV power plants in Sardinia Italy [11], which receives more than 1700kWh/m2 irradiation per year provided very encouraging results. A ground mounted system of 395.61kWp had a performance ratio of 87.3% and another building integrated system of 1042.29kWp had a performance ratio of 83.2%. Interestingly, the measured performance values were better than the expected PR simulations in the design phase. The performance analysis of a 190 kWp grid interactive solar PV system in Punjab India, the parameters like final yield, reference yield and performance ratio, were found to vary from 1.45 to 2.84 kWh/kWp-day, 2.29 to 3.53 kWh/kWp-day and 55–83% respectively. The annual average performance ratio was found to be 74% and the average measured annual energy yield was found to be 812.76 kWh/kWp, which was very close to the average annual predicted energy yield found to be 823 kWh/kWp using PVSYST. Regular monitoring of the system found the total system losses due to irradiance, temperature, module quality, array mismatch, ohmic wiring and inverter to be 31.7% [12]. In a study of crystalline silicon modules in four different climates [13], the result showed that the failure mechanisms of the modules are also location dependent along with weather. Interestingly, the same study found that the highest performance degradation rate was observed in the polar/alpine climate, which could be caused by high wind and snow loads. Regarding the performance of PV systems in higher latitudes, a study [14] of a 236kWp system in Piteå, Sweden reports a performance ratio of 0.850, specific production of 897 kWh/kWp, and an annual yield of 208 kWh. But the measured results showed inverter efficiency of 89.1% against the 96.3% as suggested by the manufacturer which was unexplained. Similarly, one of the first grid connected PV systems in Norway, installed in 2011 delivered specific yield reaching 950 kWh/kWp and PR approaching 0.8 in 2014[15]. Improvement in PR was evident with the increased operational experience and reduced system downtime.

2.3 System degradation

Degradation of PV modules in a system is known by the gradual deterioration of the initial characteristics which may hamper its operation within the acceptable limits and which is caused by the operating and environmental conditions. Production of a degraded module may not completely stop as it may still produce electricity from sunlight, although with the significant reduction from the initially labelled value [16]. But when the degradation rate exceeds some predefined threshold level, it could be problematic [17]. From a study of around 2000 degradation rates, derived from the measurements of individual modules or entire systems, a median of 0.5% degradation per year was found [18]. When a module's output power reduces below 80% of the initial power during the service period, the module is said to be degraded but the degraded module may not last the entire lifetime and to wait for the module to be tested for degradation after life time may be unacceptable for the PV power plant. Most of the modules go through the wear out scenario, which is the basis of best case yield analysis and determines the cost efficiency of well operating modules [3]. So, the degradation of modules can be classified in short term, medium term and long-term categories. The PV module performance can be degraded due to several factors such as: temperature, humidity, irradiation, and mechanical shock [19, 20]. Each one of these various factors may induce one or more types of module degradation such as corrosion, discoloration, delamination and cell cracks.

The IEA-PVPS task 13 report [3] gives an outline presented in Figure 2 of the major identified degradations of the crystalline silicon modules. There are different failure modes in the lifetime of a PV module. The early life failures appearing at the beginning of the working period are called the infant failures, the one occurring at the mid-years are called the mid-life and the failures occurring at the end of working period are called wear out failures[3].

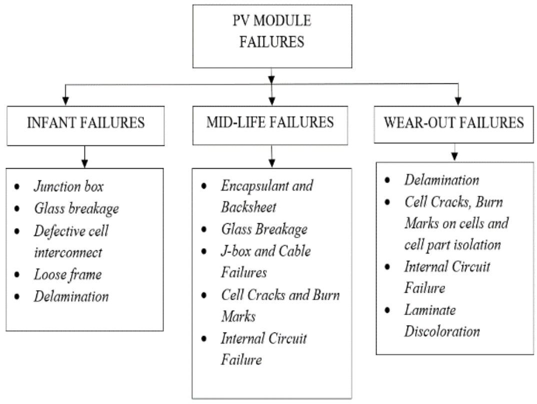

Figure 2: Major identified degradation modes of Crystalline PV modules [3]

2.4 Failures in PV systems

The PV array is the main component of a PV power system which will be affected by the degradation and failures. The PV modules undergo different modes of failures which is discussed in brief below.

2.4.1 Backsheet adhesion loss

The backsheet of a PV module provides protection of the electronic components from external factors as well as shielding from high DC voltages. This failure can be caused by delamination leading to the exposure of active electrical components which would result in insulation faults presenting safety concerns[21]. The backsheet may be constructed with various materials like glass, polymer and metal foils, and each material is susceptible to their own failures. Glass breakage can cause a failure and this could produce an electric arc. When this happens in conjunction with bypass diode failure, there's a possibility of a fire. Metal foils provide more robust electrical insulation layers in order to prevent modules from being charged at the system voltage. Multiple layer polymer laminates have multiple interfaces behaving differently in response to heat, thermal cycling, mechanical stress, humidity, UV light and others. There's a chance of bubble formation which is a more serious issue when it is formed around junction box and module edges compared to other parts[3].

2.4.2 Bubbles

Degradation caused by bubbles formation is much similar to delamination but in this case, the loss of EVA adhesion only affects a small area and the surface gets swelled after loosing the adhesion. The bubbles at the backside of modules are formed as a result of backsheet adhesion loss, which is generally due to chemical reactions that emit gases trapped in the PV module. When this happens on the back side of a module it causes difficulty for heat dissipation in cells, increasing their overheating and reducing then their lifetime[3]. Bubbles appearing in the center are not as harmful as those which are formed in the area around the junction box which may cause the box to become loose, thus adding stress on components and potentially breaking them. Bubbles on the module edges on the other hand may provide a pathway to liquid penetration during rain or dew formation, thus providing a direct electrical pathway to ground, which may be a serious safety concern. Their formation can be due to poor adhesion of the cell caused by the high temperature [20]. Bubbles located on the module front side can produce a reduction of the radiation reaching the module since they can cause a decoupling of the light and increase reflection[20].

2.4.3 Burn marks

These are one of the most common failures observed in Silicon modules. This failure is associated with some module parts becoming very hot because of localized heating caused by reverse current flow. This happens due to some cells operating in reverse bias by partial shading or cell cracks[3], solder bond or ribbon breakage failures caused by thermal fatigue. These marks can be seen through visual inspection but infrared imaging under illuminated or partially shaded conditions can be used to identify if the module needs to be changed or not[3].

2.4.4. Cell cracks and breakage

Cell cracks are failure modes which can be encountered at every lifetime level of the PV module. Silicon cells are prone to breakage during the manufacturing process due to its brittle nature and can avoid inspection from human eye. The stringing process of solar cells is known to have high risk of creating cell cracks[3]. These faults can be generated during packaging or transportation due to mishandling and vibrations. Small cracks or microcracks in cells due to thermo-mechanical stresses, always pose a risk of developing into longer and wider ones during the operation[22, 23].

2.4.5 Corrosion

Moisture penetration through lamination edges in PV modules is known to cause corrosion resulting in increment of electrical conductivity of the material [24]. Corrosion is known to degrade the adhesion between cells and metallic frame and attack the metallic connections of PV cells causing a loss of performance by increasing leakage currents[16]. In [25], the impact of humidity and temperature on PV module degradation is studied thoroughly. A accelerated testing named 85/85 ($T = 85\ ^0C/RH = 85\%$) was carried out according to the IEC 61215 standard. It was found out that corrosion appeared after 1000 hours of exposure of PV module under 85 ^{0}C and 85% relative humidity.

Authors in study [26] argue that corrosion and discoloration are the generally prevalent modes of photovoltaic modules degradation. Sodium contained in the glass which is reactive with moisture is a major factor of the corrosion of PV modules' edges. Sodium contained in the glass which is reactive with moisture is a major factor of the corrosion of PV module edges[27] while faster silicon PV module degradations are caused by oxygen which is the main factor of the corrosion of silicon junctions[28].

2.4.6 Defective bypass diode

Bypass diodes are integrated into the PV module in parallel to certain number of cells. The main role is to reduce the power loss and avoid reverse bias caused by partial shading on PV modules. Bypass diodes avoid reverse biasing of single solar cells higher than the allowed cell reverse bias voltage of the solar cell[3]. If a cell is reversed with a higher voltage than it is designed for, the cell may evolve hotspots[29] that may cause browning, burn marks or even fire. Bypass diodes are Schottky diodes which are very susceptible to static high voltage discharges and mechanical stress and this demands a careful handling[3].

2.4.7 Delamination

Delamination is also a type of adhesion loss which occurs between the encapsulating polymer and the cells or between cells and the front glass. Delamination is easily visible but if it cannot be identified visually, pulse and lock-in thermography methods may be used while X-ray tomography and ultrasonic scanner can also be used[3]. Different factors like UV, moisture and temperature affect the durability of lamination interfaces in a PV module. Study [3] points out that new pathways and subsequent corrosions following delamination reduce module performance but do not pose a safety threat, study [20] argues delamination can be major problem in the long term because it increases the light reflection and water penetration inside the module structure. Delamination is known to be most severe when it occurs on the edges of the module because, in addition to the degradation of power, it causes electrical risks for the module and the entire installation. Delamination is more frequent in hot and humid climates causing moisture penetration in the module and therefore resulting in various chemical and physical degradations such as metal corrosion of the module structure[16]. Delamination may also be caused by salt accumulation and moisture penetration into the PV module.

2.4.8 Disconnected cells and string ribbons

Poor soldering between string interconnect and cell interconnect ribbon is the main reason for the disconnections. Hot spots by partial shading, stresses during transportation, thermal cycle or repeated mechanical stress during long term operations, force weak ribbon interconnects to break[21]. Short distance between cells develops this kind of failure resulting in short circuited or open circuited cells and resistance increment[30]. These failures can be identified by electroluminescence, infra-red imaging, ultraviolet imaging or the signal transmission methods[3].

2.4.9 EVA discoloration (yellowing and browning)

Discoloration is a widely reported defect in solar modules which usually results in a degradation of the encapsulant module, EVA (Ethylene Vinyl Acetate) or adhesive material between the glass and the PV cells. Module discoloration is a change in color of material which turns yellow and sometimes brown. This is noticeable during visual inspection[16, 31]. It modifies transmittance of light reaching PV cells and therefore the power generated by the module is reduced. Main causes of discoloration are encapsulant quality and UV rays combined with water under temperatures higher than 50ºC[32]. Sometimes insufficient adhesion between the cells and glass materials is also known to contribute[33]. Discoloration may appear at different and not necessarily neighboring zones of a PV module, meaning it is more dependent encapsulating polymers. Since the discoloration doesn't lead to any fatal failures, it can be termed as degradation rather than failure. When very high incident UV radiation of 4000 W/m^2 was applied, there was an increase in photosensitivity after 400 h exposure and an increase in transmissivity between 280 nm and 380 nm[34]. This is mainly due to the depression of the UV absorber which must protect PV cells of photodegradation. Besides, there appears a weak yellowing at the EVA films that causes a loss of the photovoltaic module power[34]. However, for a 1000 Wm^2 radiation, no change occurred in the wavelengths range between 280 nm and 380 nm after 500 h exposure. In UV tests on PV modules carried out under a 60 ^{0}C temperature, it was found that the discoloration of the encapsulant only appears when global UV irradiation reaches 15 $kWhm^{-2}$ in a wavelength range included between 280 nm and 385 nm without exceeding a 250 Wm^{-2} exposure[25]. Research shows that the slow module degradations in the long term are linearly correlated to the exposure of PV modules under UV radiation[28]. From various experiments, it was found that the discoloration degrades the short-circuit current (Isc) of the PV module; this degradation of Isc may vary from 6% to 8% below the nominal value for a partial discoloration of the PV module surface and from 10% to 13% for complete discoloration[16]. The module discoloration degrades maximum power (Pmax) of the PV module as shown in Figure 3.

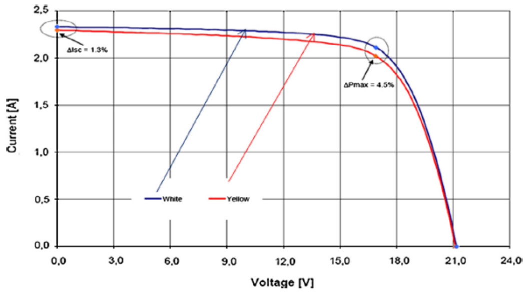

Figure 3: I-V Characteristics of normal and discolored PV modules [35].

2.4.10 Hot-spots:

A hot spot is an area of a PV module that has a very high temperature that could damage a cell or any other element of the module[16]. Hot spots result from the generation of less current in a cell than string current in modules, possibly due to reasons like cell failures, including partial shadowing, cells mismatch or failures in the interconnection between cells [36, 37]. In short circuit conditions, when a PV cell is defective, its voltage is reversed. This defective cell becomes both a load for other cells and a place of a relatively high thermal dissipation constituting thus a hot spot[16]. The risk of hotspots can be reduced by using shorter solar cell strings and by using advanced in-line quality control tools for cell testing[38]. Bypass diodes normally protect against this failure mode.

2.4.11 Junction box failure

Junction box failure is a failure mode generally seen in every type of solar module. Junction box is basically a box attached at the back side of PV modules which also houses a bypass diode to protect cells in the strings during partial shadowing and which protects the connection of cell strings of modules to outer terminals. Generally, poorly manufactured, junction box fixed with poor adhesion to backsheet, and moisture penetration in the modules leading to corrosion of connections are the failures observed in junction boxes[3]. Improper soldering and bad wirings can cause arcing in the box which may lead to fire.

2.4.12 Light induced degradation

Light induced degradation is a natural degradation phenomenon when crystalline silicon modules are initially exposed to light. It is caused by physical reactions causing permanent reduction in output power. It is reflected as a loss in the silicon solar cell efficiency, and seen as a reduction of the short circuit current and open circuit voltage of the solar cell[39]. Boron doped silicon solar cells are found to degrade in efficiency as much as 10% when exposed to light or when minority charge carriers are injected in the dark until a stable level of performance is reached, and this effect is related to the presence of boron and oxygen in different concentrations in the material. More recently it has been related to the presence of copper as well[39, 40]. On average, LID for crystalline silicon modules ranges from 0.5% to 3%, with some modules exhibiting a loss of up to 5%. LID is an unavoidable failure type and manufacturers take this into account by factoring in a 3% power loss (typically) during the first year of the module warranty as the rated module power is printed on PV modules after adjusting the expected standardized saturated power loss[3, 41]. To ensure that LID does not jeopardize the conclusions of the chamber testing, all PV modules in the PV Module Reliability Scorecard are light soaked for at least 40 kWh/m2 before entering the testing chambers[41].

2.4.13 Module/frame breakage

Glass breakage is a typical degradation mode of PV modules generally occurring during transportation, installation and maintenance at sites, and are easily detected by visual inspection [25]. Modules broken or with cracks may keep functioning correctly, however, the risk of an electrical shock and of a moisture infiltration increases[16]. Sometimes the cracks may be present from the manufacturing process due to thermochemical and mechanical stresses. These cracks, if not inspected and treated in time, are usually followed by other severe degradation types such as corrosion, discoloration and delamination. For saving silicon and reducing production costs, the thickness of silicon PV cells has been reduced from 300µm to less than 200µm and sometimes to less than 100µm, whereas the cell surface has been increased to 210mm x 210mm[42]. This makes PV cells more fragile and more susceptible to breakage during handling (rolling and storage). Since it is often impossible to detect cracks on the already operational PV module to the naked eye, various optical methods, in particular electroluminescence can be employed to detect the cracks [43].

2.4.14 Potential induced degradation

Individual modules in PV systems are often connected in series to increase the voltage of the system. The potential difference of such a connection may sometimes reach several hundred volts[44]. In order to protect people against electrical shocks, all metallic structures of modules are often grounded. Because of this electrical voltage between PV modules and their structure, it is possible that electrons in materials used for PV modules escape via the grounded framework when the insulation between structure and active layers is not perfect, thus creating leakage currents[44, 45]. From this phenomenon subsists a reversible polarization that may degrade the electrical characteristics of the photovoltaic cells. This phenomenon known as PID (Potential Induced Degradation) is characterized by the progressive performance deterioration of crystalline silicon photovoltaic modules, due to the presence of an electrical current induced in the module[46]. If some cells in a module remain at the original short-circuit value, the module's short circuit value is almost unchanged. A study showed that PID is more likely to happen in humid climates than in hot and dry ones[45]. In early stages, power degradation due to PID at high irradiation conditions is small and it is only pronounced in low irradiation conditions, making it difficult to detect within the power plant's monitoring data. Even a high degree of PID may not be seen through visual inspection[46, 47]. The electrochemical degradation was descried as the migration of ions from front glass through the encapsulant to the anti-reflective coating (SiN_x) at the cell surface driven by the leakage current in the cell to ground circuit[48]. This leakage current is typically in order of µA and its value strongly relies on material properties, surface conditions, applied voltage and environmental conditions dependent parameters like module temperature and applied voltage[45].

2.4.15 Shadowing

Two types of shading exist, (i)hard shading; which occurs if PV panels are shaded by a solid material, e.g. buildings or dust and (ii) soft shading; which can be caused by smog in the air[49]. The first one results in a voltage decrease whereas the second one affects current only, hence both are known to affect the performance of PV modules[21]. Shaded cells behave as a resistance to generated current within a module and as a result the heat builds up creating a hot spot which may lead to permanent module damage.

2.4.16 Snail tracks

PV modules exposed to outdoor environment for a few months can develop a degradation effect known as snail tracks, which effectively is a grey/black discoloration of the silver paste of the front metallization of screen printed solar cells. The discoloration usually starts at edges of cells and along usually invisible cell cracks and take up irregular dark stripe shapes in cells[37]. Choice of EVA and back sheet material is important for snail track to show up as the modules affected by it show a tendency of high leakage currents[3]. General IEC61215 testing is not competent enough to generate snail tracks as the module under investigation should have preexisting cell cracks existing in the module itself. Combined mechanical load, UV and humidity freeze tests could be applied in conjunction to each other for testing of snail tracks[50].

2.4.17 Soiling

Soiling is an important degradation mode which affects the performance of PV modules or systems by obscuring the irradiation through the layer of dust present at the face of the module. If proper cleaning mechanisms are not applied, soiling can starkly reduce the power production of PV systems. Various articles from around the world have suggested significant efficiency reduction from the dust accumulation as a function of exposure time[51]. Power output and efficiency are drastically reduced due to soiling in various locations as some regions like Kuwait and Nepal experienced power reductions up to 17% and 29.76% respectively [52, 53]. The corresponding reduction of output efficiency varied from 0% to 26% when dust deposition density increased from 0 to 22 g/m^2

[49]. PV modules require frequent cleaning and sometimes the orientation and tilt angle of modules also play a crucial role in soiling[54].

3 MONITORING OF PV SYSTEMS

Solar PV fortunately is a simple technology with no moving parts and requires very low maintenance. However, there is a high chance of hidden problems being overlooked during operation [8]. The power consumer may not know the difference between what is being achieved and what it was supposed to be. Hence, there should be available valid and regular data of electric outputs with other desired or required parameters at suitable intervals. To be applicable, a monitoring report should include information on relevant aspects of operations in such a way that a third party could understand[55].

The main purpose of monitoring a PV system is to determine and validate the required level of agreement between system performance and expectation. For this it is mandatory to have measurement systems with sufficient accuracy, a standard method to convert or compare the output to the output at standard test conditions and finally an expected value which should be maintained [56]. So, it is desired to have some monitoring guidelines to provide instruction on how to make measurements, how to analyze those measurements and how to determine whether the system is performing as expected. If the user wishes to ensure that the optimum output is obtained, then this process must be carried out regularly over the operating period with any shortfalls in output investigated and rectified. Monitoring guidelines are thus expected to provide guidance on the frequency of both measurement and analysis and some diagnostic capability in terms of loss mechanisms. A robust and dynamic Operation and Maintenance Program enables PV system production to reach and maintain the desired efficiency levels [21].

It is difficult to regularly judge the PV systems' performance with the expected production. A more scientific way is to measure and inspect the electrical as well as other parameters at regular intervals [8]. The main reason for monitoring a PV system is to constantly measure the energy yield, verify the performance of the system to required standards and sometimes identify if there is a problem in the system. Monitoring of the PV system generally includes certain number of parameters to be measured and stored in a data acquisition system.

Presently, the most accredited reference document for the monitoring of PV systems is the IEC61724-1 standard, but the older IEC 61724 standard, guidelines of DERlab, and other guidelines being implemented in the different countries are also reference literatures for the PV system monitoring which will be discussed later. These standards and guidelines provide the instructions for measurement and analysis of the measured data and determine the performance of the system.

3.1 Monitoring procedures and parameters

The required level of monitoring in terms of parameters to be measured, duration of the measurement and precision vary according to the size and complexity of the PV system along with the timely need to identify faults [8]. The faster the system faults are identified; the lower the system downtime, which boosts the overall output of the system and eventually the revenue. Monitoring the system performance is often a balance between the costs of instrumentation with the loss of revenue due to output loss.

Monitoring of the PV system can be done in two different ways in general, known as global and analytical monitoring[8]. The global monitoring includes measurement of limited set of parameters, sometimes just the output energy of the system through inverters to ensure the operational status of the system is at a reasonable level. This is usually implemented in systems where the monitoring costs need to be low. However, this approach usually requires additional information to determine the cause of any losses observed. Analytical monitoring on the other hand provides a more comprehensive dataset of operating parameters and allows investigation of performance trends and problems. Table 1 shows the list of parameters that need to be monitored in a PV system.

Table 1: Basic parameters required for monitoring [57, 58]

PV System Type	Parameters		
	Metrological	Electrical	
Grid Connected	i) Total irradiance, in plane of Array ii) Ambient Temperature iii) Module Temperature iv) Wind Speed v) Wind direction vi) Humidity vii) Barometric pressure	*PV Array*: i) Output Voltage ii) Output current iii) Output Power iv) Output energy	*Utility Grid* i) Grid Voltage ii) Current to utility grid iii) Current from utility grid iv) Power to utility grid v) Power from utility grid vi) Utility grid impedance
Stand Alone			*Load:* i) Output Voltage ii) Output current iii) Output power

3.2 Basic parameters for measurement

For the grid connected utility scale PV systems, monitoring provides the comparison between performance and expected energy yield. So, for the performance assessment purpose, the monitoring should include electrical energy generated as well as the incident irradiation. Electrical parameters include current, voltage and power. These parameters are sometimes available in the inverters, but these inverter integrated measurements lack required precision, so dedicated energy meters are prescribed.

3.2.1 Irradiance

Irradiance is the major parameter to be monitored. Irradiance simply is defined as the solar power received in a unit area denoted by W/m^2. There are two possible measurement instruments for solar radiation, pyranometers and reference cells, with their own differences. Pyranometers being thermopile devices, have a slow response time and are affected by the angle of incidence, tilt angle as well as ambient and dome temperature. Reference cells on the other hand, suffer from stability as only crystalline silicon sensors provide the required stability [4]. It is also a general norm to use the same type of reference cell as the modules in PV array. Pyranometers have a slow response time compared to the reference cells and hence cannot detect the sudden change in irradiation values due to a passing cloud or a partial shade.

For the standard measurement of irradiance, the reference device or pyranometer should be calibrated and aligned on the same plane as the photovoltaic array. The accuracy of the irradiance sensors, including signal condition should be better than 5%. Choice of irradiation sensors is based on how the measured data would be used. Despite the thermopile pyranometers having a slower response time, [59] propose them for the long-term monitoring, while the reference devices would be preferred to measure irradiance when investigating the variability effect of PV. For the highest level of accuracy on irradiance, the data should be measured on site, ensuring appropriate calibration, installation and maintenance of sensors. The sensors should be co-planar with the modules with maximum deviation not more than 20 degrees. Regardless of shadowing effects on PV-arrays, the sensors should be placed in such a way that they remain unshaded as well as remain accessible for frequent cleaning. For the small-scale systems with relatively low budget on performance monitoring, low standard sensors or various data sources provide another option.

3.2.2 Ambient temperature

Ambient temperature values represented by ^{0}C are measured at location exactly supplying the photovoltaic array conditions. As the ambient temperature influences module temperature, it is monitored to estimate the losses compared to the STC conditions. The sensors need to be housed in radiation shields, ensuring temperature sensor measures the air temperature only and is not heated by direct irradiance from the sun or even cooled by the wind effects. These sensors should not be placed near any kind of heat sources, being 1m above the ground as prescribed by IEC 61724 while DERlab TG 100-01 guidelines recommend ground clearance of 2m [60].

3.2.3 Wind speed

Wind speed is known to affect the performance of PV systems by triggering convective heat losses thus reducing the module temperatures. As recommended by IEC 61724, for the high standard measurement, wind speed should be measured at the same conditions as the arrays. Anemometers position as defined by IEC 61215 should be 1.2m on the east or west side of the system and 0.7m high above the upper edge of the system.

3.2.4 Module temperature

Similar to the ambient temperature, module temperature is also represented by ^{o}C and is measured at locations exactly depicting the photovoltaic array conditions by the help of temperature sensors attached on the back of one or more modules in such way that the temperature of cell in front of sensor is not altered. It is recommended for the large systems to measure module temperatures from various parts within the array as temperature fluctuations can occur within the array [60]. Such measurements can be averaged to provide better understanding of temperature effects on the entire PV system.

3.2.5 Current, voltage and power

Measurement of AC and DC voltage, current and power are the most important parameters for the PV system performance monitoring. These parameters can be used, in combination with the irradiance measurements, to directly determine when a PV system is underperforming [60]. The DC parameters help in diagnosing system faults at system level as reduction in DC quantities means problem in array and its yield, which is a fundamental quantity for degradation analysis.

Voltage and current values may be measured either on DC or AC side. Sensors should be selected to ensure they have a measurement range that is compatible with the output of the PV array (i.e. upper voltage limit > $1.3*V_{OC}$ and upper current limit > $1.5*I_{SC}$) and selected to have minimal impact on the electrical operation of the array. Accuracy of these sensors, including signal conditioning, should be higher than 1% of the reading [57]. For large PV systems containing huge number of arrays and sub-arrays, it is recommended to individually measure both the AC and DC parameters of each sub-array which thus simplifies the location and isolation of faults.

Power data can also be available on DC or AC side or both sides. It can be measured directly by means of power sensors or calculated in real time as the product of sampled voltage and current values. The general recommendation is to measure power directly, but if the direct measurement of power is not available it can be derived from the product of current and voltage. The current and voltage quantities must be the simultaneously sampled ones rather than the averaged quantities. Power sensors accuracy, including signal conditioning, should be greater than 2% of the reading.

3.3 Monitoring standards and guidelines

With the growing deployment of the PV systems, there arose a need to properly measure and verify the degree of production from the PV systems. Some research institutes and some joint projects have worked together in different parts of the world to develop a general norm to guide through the monitoring of those systems. Some of those guidelines are discussed here.

3.3.1 IEC61724 standard

The IEC 61724 standard is a set of international standards for the parameters for PV systems measurements and monitoring presenting guidelines for analysis and monitoring of PV systems performances. Although this standard has been replaced by the IEC61724-1, it still remains one of the influential standards as the many monitoring systems and instruments in practice today are based on this standard. Figure 4 presents an example for basic monitoring parameters required and illustrates the electrical and environmental data to be measured. These data are listed in Table 1. Other parameters can be calculated from these measurements in real time, using data acquisition systems. Monitored parameters are classified under two groups: environmental or meteorological parameters, and electrical parameters.

This standard has requirements to measure total irradiance, module and ambient temperature, wind speed and electrical parameters (current, voltage and power).

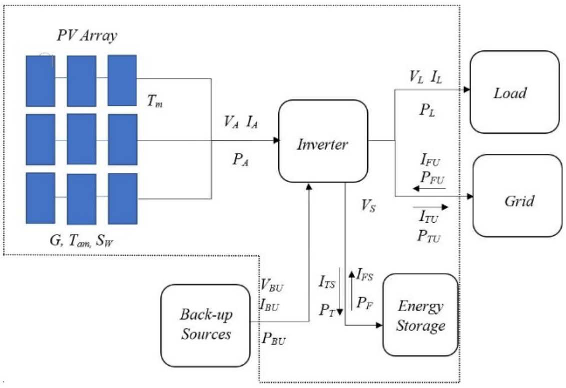

Figure 4: Diagram of basic real time parameters to be measured[57]

The irradiance should be measured in the plane of the array with an uncertainty including the instrumentation to be less than 5%. This should be done either by use of a pyranometer or a reference cell. The irradiance sensors installed according to this standard have to be calibrated every second year. The ambient temperature should be representative of the array location, but the module temperature should be measured on the center of the back of the module or more modules, or the center of arrays while uncertainty including the instrumentation should be less than 1%. Wind speed should be measured at the height and location representative of the array conditions with an uncertainty including the instrumentation less than $0.5 ms^{-1}$ for speeds less than $5 ms^{-1}$ and less than 10% of the reading for speeds greater than $5\ ms^{-1}$. For current and voltage both AC and DC parameters have to be measured with the level of uncertainty including the instrumentation to be less than 1% of the reading. For power, the DC power is to be calculated based upon instantaneous measurements but not the averaged reading or directly measured with a wattmeter. AC power meanwhile accounts for the power factor and harmonic distortions and the uncertainty including the instrumentation has to be less than 2%.

3.3.2 Australian guidelines

The Australian guideline is a national technical guideline developed for the Australian PV Institute (APVI) by various research institutions with the support of the Australian government. This guideline offers a guidance on need to measure parameters, measurement mechanisms of those parameters and the frequency of those measurements based on the seven different uses of PV performance and reliability data [60]. This guideline is primarily based on the IEC61724 standard but with a more detailed approach to the use of measured data. The potential use of the data has been categorized in seven different uses which are briefly presented in Table 2.

This guideline has defined conditions for the need or demand of the monitoring on the different uses along with the instrumentation and financial requirement of sensors. The general flow of the guideline is based on the pre-determination of the end use of the measured data. When the end use has been finalized, it then requires selecting the parameters as not all parameters defined in Table 2 are required in each of the seven end uses, but if the end use is not known, all the parameters are suggested to be measured.

Table 2: Categorization of recording interval according to the uses[60]

Use	Use of measured data	Recording interval (τ_r)	Monitoring period
1	Performance assessment under outdoor conditions	Max 15min	Min 1 year
2	Performance diagnostics	Hourly	System Lifetime
3	Degradation & uncertainty analysis with time	Hourly	Min 3-5 years
4	Understanding system losses via comparison to modelled data	Hourly	Min 1 year
5	PV Performance forecasting	5min, 30min or hourly	Min 1 year
6	Grid interaction of PV systems	1 to 15min	Min 1 week
7	Grid integration of distributed generation and load control	1 to 15 min	Min 1 week

Next is the confirmation of required level of accuracy, as the instrumentation requirements are already stated in the IEC61724. To follow those requirements is a best option but for limited budget, monitoring instruments with less accuracy and less costs can also be used. Finally, the recording and monitoring intervals as mentioned in Table 2 can be applied based on again the end use. The whole process is shown in Figure 5.

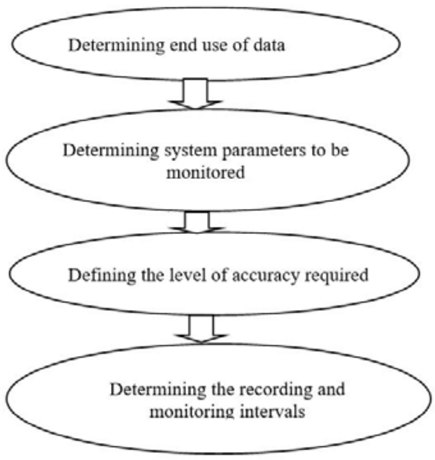

Figure 5: Flow diagram of monitoring decision making from Australian Guideline[60].

3.3.3 DERlab guidelines

This guideline was developed to harmonize the outdoor testing procedures that would be useful for energy yield measurement of different PV technologies. It is meant to provide basic guidelines and procedures regarding testing locations, placement of sensors and accuracy of the whole measurement equipment. Developed as a complimentary to the international standards, this guideline discusses only the measurements on the DC side and it does not include data analysis and evaluations. The DERlab guideline mentions that a maintenance plan consisting of visual inspection and cleaning of the measuring instruments should be well documented along with the proper calibration of the used sensors on a regular basis.

The parameters suggested by this guideline to be measured are the basic ones also prescribed by the IEC61724. Current and voltage are to be taken at the maximum power point (MPP), but the recording time interval is set 15 seconds. The secondary class pyranometer is prescribed for the irradiance measurement while comparing different technologies, owing to its sensitivity over the wide range of spectrum. But for the single technology modules, a reference cell of same technology is preferred. The installation plan of this standard suggests the modules to be placed 1m above the ground and the meteorological sensors to be placed 2m from the ground while being at least 1.2m from the PV array and with such location that it would not shade the modules. For the module temperature measurement, the sensor is suggested to be installed at the middle of the modules rear side. Also, for the long-term PV yield measurement this guideline proposes that an IV curve is retrieved once each month, on a clear day with light wind and corrected for STC, to analyze PV module degradation over time. The matter of operativity of the sensors and subsequent data logging is also quite important as this guideline proposes the availability of 98-99% of data from its potential operation per year necessary to avoid uncertainties in forecasting of the annual energy yield.

3.3.4 IEC 61724-1 standard

The IEC 61724 standard[61] is now replaced with the IEC 61724 series consisting of three separate parts, each part with specific purpose as opposed to the former one. The first part IEC61724-1 is named as monitoring, IEC61724-2 as capacity evaluation method and IEC 61724-3 as energy evaluation method. IEC 61724-1 standard categorizes the monitoring of PV systems on three different scales with the specific emphasis on accuracy and frequency of sensors and measurements, recommending number of measurements based on the scale of a project and requirements for servicing and maintaining the instruments [62].

With the new standard, each monitoring system classification provides a guideline of what measurements can be done. The monitoring classes are divided in three parts with A being the one with highest accuracy and class C being the most basic one and a medium accuracy level of class B. Solar Irradiance and ambient temperature are the parameters commonly required for all level of measurements. Table 3 presents the outline of monitoring system classifications as per the required applications.

The standard has requirements not only for the accuracy and parameters, but these are also related to the number of sensors. This is based on the different classification from the system less than 5 MW to the system greater than 750MW. The cleaning and recalibration of sensors is also an important issue. The irradiance sensor needs to be calibrated annually for high class accuracy and in every two year for other accuracies. It also lays requirements to at least have an annual inspection every year for sensors in class A and B monitoring systems. The power consumed by the tracking and monitoring systems installed in the site are now categorized as the power loss of PV plants as opposed to the loads of the plant. The sampling and recording intervals are different for each of the classes as class A require 3 seconds sampling and 1 min recording interval of the basic parameters whereas class B and C have 1 min sampling for basic parameters and while the class B has 15 min of recording interval, an hourly recording interval is enough for the system with basic accuracy. The newly introduced parameters like soiling, rain, snow and humidity are required to have a sampling rate of 1 min for all classes in ground based measurements and also satellite based for the class A systems.

Table 3: Monitoring system classifications as per the required applications

Typical Applications	Class A High Accuracy	Class B Medium Accuracy	Class C Basic Accuracy
Basic System performance assessment	×	×	×
Documentation of a performance guarantee	×	×	
System loss analysis	×	×	
Electricity network interaction assessment	×		
Fault localization	×		
PV technology assessment	×		
Precise PV system degradation measurement	×		

This standard has the recommendations for all the sensors to be used according to their accuracy including uncertainty levels. Thermopile pyranometers, reference cells and photodiode sensors are prescribed along with the locations and angular alignments based on the accuracy required for irradiance measurements. For both the ambient and module temperatures, the measurements should represent the array conditions and recalibration of sensors should be done every two years for high accuracy systems. The module temperature sensors require the uncertainty of ≤ 2ºC while for the ambient temperature this should be ± 1ºC. Wind sensors require to measure the wind speed and direction from position representing the array conditions but the recalibrations is dependent on the manufacturers recommendations. Soiling ratio(SR) is a new parameter introduced in this standard which is the ratio of actual power output of PV array under soiling conditions to the expected power when the array had no soiling effects. The prescribed method to find SR is to calculate maximum power loss reduction due to soiling among other alternative methods. Rainfall, shading effect of snow and effects on incident spectrum through humidity are also the parameters that need to be measured in the high accuracy monitoring system. The electrical measurements are also defined according to the accuracy requirements where the uncertainty levels are stated as

±2% for the class A systems, ±3% for the class B systems and the basic systems have no such requirements on inverter level measurements.

The data processing should not include the night hours and should strictly include the hours between sunrise and sunset with irradiance being $\geq$ 20 W/m^2. The measured data requires to be filtered and checked to ensure there are no missing or invalid data points. The missing or invalid data can be processed in various ways which are discussed in detail in the part 2 and 3 of the now IEC 61724 series.

4 DISCUSSION AND CONCLUSIONS

Regular measurements and analysis of the performance ratio (PR) over the life span of a PV system allows the detection of the serious malfunctions or the degradation and through prompt operation and maintenance action, facilitates the reliable power production. Normally the bigger scale PV systems are equipped with the sophisticated monitoring devices whereas the small scale residential and commercial systems are not given the same level of attention. This could be due to financial constraints. The performance of PV systems mainly depends on the solar irradiation, ambient temperatures and local weather conditions as well as the power conditioning units employed. These are the fundamental components of any PV system. The various monitoring guidelines discussed are based on the IEC61724 standards and with the revision of this standard it can be concluded that with growing investments and grid injections, the monitoring needed to be more precise. IEC61724-1 standard fills the void in many such conditions with defined level of precision for sensors and monitoring mechanisms.

The IEC61724 standard created an understanding of the basic relation of different variables such as irradiance, temperature with power output as well as their combined effects on one another, but the understanding was limited on the variation in the performance and of the instruments/sensors as well as the data those sensors reported. Performance monitoring is significantly dependent on the accuracy of the measuring instruments and the installation procedures. Regular calibration is the best way to ensure the greater significance of the monitored data and subsequent modelling. The guidelines formulated by DERlab contains the basic parameters to be measured and the procedures to be measured. Guideline adopted in Australia has defined the frequency and complexity of measurements as per the length of monitoring need within the IEC61724 standard. The IEC 61724-1 will be a benchmark for a long time to come as it addresses the range from simple residential systems to the utility scale systems. The guidelines formulated under the PERFORMANCE project have been mentioned in different literatures, but it is not accessible and available at the present.

The performance of a PV system depends primarily on the parameters discussed above but is not confined to just them. Parameters like shading, soiling, angle of incidence, tilt and spectral response among others are also crucial for the performance monitoring as different module technologies have a varying response to these parameters. For instance, amorphous silicon modules have a better temperature response but suffer more on spectral response than the crystalline modules, indicating that the same monitoring regime may not be useful to compare the performance of these modules. Statistical methods of monitoring is also applied in the places unable to install the monitoring equipment, but the interpretation of such monitoring needs to be done clearly as the correlation between power produced by the system and actual weather conditions could lead to unrealistic PR values.

The initial work done under the COST Action PEARL PV is summarized in Table 3. The monitoring regime has been categorized under different headings and all the necessary topics and measurements have been enlisted under them. Experts were provided with the questionnaire which contained the classification of variables under the sections mentioned on the Table 3 and their response is being tabulated. The experts have provided their opinions regarding each parameter that are necessary. Some of the parameters are desired to have, but not necessary to include in the monitoring. These types of parameters like cabling, lightening protection and the details of battery storage and surveillance system should be included in the detailed monitoring which may be required when investigating the PV system in detail. But in normal conditions where the monitoring is to be done for the life time of a PV systems, these minute informations may not be a preferred one due to the storage issues of huge amount of data and need to continuously monitor these factors too. The guidelines will be prepared based on the parameters under categories summarized in Table 3, below.

Table 4: Summary of the sections formulated for the development of monitoring guidelines

Section	**Contents**	**Elaboration of Contents**
Quality Control	General requirements to ensure the data and equipment quality	• Instrumentation/sensor Accuracy • Data accuracy and Calibration procedures • Data quality control and handling process
File Format	File format required for the storage and transfer of the data.	• XML/ASCII/CSV Formats • Date and Time stamp format. • Reporting of the missing data and required format
Metadata: Site	General information regarding the PV site	• Site name and address • GPS Coordinates with site elevation and Time Zone (UTC)
Metadata: PV system and Components	General information regarding the PV system	• Fixed or Tracking installations and details • Installation type (BIPV/BAPV/Free Standing) • PV Module technology and the electrical/mechanical parameters • PV String design, PCU and Inverters • Shading and Soiling losses • Balance of System components
Metadata: Sensors	Instrumentation, sensors and data logging	• Irradiance, Temperature and Wind Sensors • Other Meterological sensors (Rain, Humidity and others) • Current and Voltage transducers • Power meters • IR and Electroluminescence Imaging • System status
Monitored data: Meteorological	Meterological informations	• Solar Radiation • Climate and Weather • sampling and recording rate of data
Monitored data: Yield and Durability	Information regarding the yield of PV systems and degradation analysis through various methods	• Time series of the available data • PV module / String yields • sampling and recording rate of data • PV module/String degradation 1. IV curves 2. Soiling 3. Other degradation or failure indicators
Monitored Data: PV in the Built Environment	Information about the integration of PV system as a part of buildings or other energy systems	• Building integration / Architectural integation • Hybrid Energy Systems • Environmental footprint • Economical consideration
Monitored Data: PV in Grids	Grid integration of PV systems, parameters and measurements	• Inverter power, phase, voltage, power factor, harmonics and frequencies • Load Characteristics • Utility characteristics • Energy Storage • Protection and Management systems • sampling and recording rate of data
Modelled Data: PV Simulation	Simulation of the PV output to be compared with the measured data	• Weather and Irradiance data files • Simulation models • Comparison of modelled vs measured data • Modelling system performance external influences and thermal properties • Modelling grid interaction and forecasting models for PV production

5 REFERENCES

1. King, R.R., et al., *Solar cell generations over 40% efficiency*. 2012. **20**(6): p. 801-815.
2. Sark, W.v., *Detailed Workplan of Working Group 1, PV Monitoring COST ACTION PEARL PV-CA16235*. 2017: Brussels.
3. Kontges, M., et al., *IEA-PVPS {Task 13}: Review of failures of PV modules.* Technical report, 2014.
4. Woyte, A., et al. *Monitoring of photovoltaic systems: good practices and systematic analysis*. in *Proc. 28th European Photovoltaic Solar Energy Conference*. 2013.
5. Nordmann, T., U. Jahn, and W. Nasse. *Performance of PV systems under real conditions.* in *European Workshop on Life Cycle Analysis and Recycling of Solar Modules, The" Waste" Challenge, Brussels, Belgium.* 2004.
6. Chouder, A. and S. Silvestre, *Automatic supervision and fault detection of PV systems based on power losses analysis.* Energy Conversion and Management, 2010. **51**(10): p. 1929-1937.
7. Guasch, D., S. Silvestre, and R. Calatayud. *Automatic failure detection in photovoltaic systems*. in *Photovoltaic Energy Conversion, 2003. Proceedings of 3rd World Conference on*. 2003. IEEE.
8. Pearsall, N.M., *6 - Prediction and measurement of photovoltaic system energy yield*, in *The Performance of Photovoltaic (PV) Systems*, N. Pearsall, Editor. 2017, Woodhead Publishing. p. 183-208.
9. Decker, B. and U. Jahn, *Performance of 170 grid connected PV plants in Northern Germany—Analysis of yields and optimization potentials.* Solar Energy, 1997. **59**(4): p. 127-133.
10. Kymakis, E., et al., *Performance analysis of a grid connected photovoltaic park on the island of Crete.* 2009. **50**(3): p. 433-438.
11. Ghiani, E., et al., *Evaluation of photovoltaic installations performances in Sardinia.* 2013. **76**: p. 1134-1142.
12. Sharma, V. and S.J.E. Chandel, *Performance analysis of a 190 kWp grid interactive solar photovoltaic power plant in India*. 2013. **55**: p. 476-485.
13. Bogdanski, N., et al. *PV reliability (cluster II): results of a German four-year joint project—part II, results of three years module weathering in four different climates.* in *Proceedings of the 25th European Photovoltaic Solar Energy Conference*. 2010.
14. Lockertsen, E.O., *The Performance and Potential for PV systems at Northern Latitudes*, in *Department of Electric Power Engineering*. 2015, Norwegian University of Science and Technology: Trondheim. p. 215.
15. Imenes, A.G., et al. *Performance of grid-connected PV system in Southern Norway*. in *2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC)*. 2015.
16. Ndiaye, A., et al., *Degradations of silicon photovoltaic modules: A literature review.* Solar Energy, 2013. **96**: p. 140-151.
17. Charki, A., R. Laronde, and D. Bigaud, *The Time-Variant Degradation of a Photovoltaic System.* Journal of Solar Energy Engineering, 2012. **135**(2): p. 024503-024503-4.
18. Jordan, D.C. and S.R. Kurtz, *Photovoltaic Degradation Rates—an Analytical Review.* Progress in Photovoltaics: Research and Applications, 2013. **21**(1): p. 12-29.
19. Osterwald, C.R. and T.J. McMahon, *History of accelerated and qualification testing of terrestrial photovoltaic modules: A literature review.* Progress in Photovoltaics: Research and Applications, 2009. **17**(1): p. 11-33.
20. Munoz, M.A., et al., *Early degradation of silicon PV modules and guaranty conditions.* Solar Energy, 2011. **85**(9): p. 2264-2274.
21. Triki-Lahiani, A., A. Bennani-Ben Abdelghani, and I. Slama-Belkhodja, *Fault detection and monitoring systems for photovoltaic installations: A review.* Renewable and Sustainable Energy Reviews, 2018. **82**: p. 2680-2692.
22. Kajari-Schröder, S., et al., *Spatial and orientational distribution of cracks in crystalline photovoltaic modules generated by mechanical load tests.* Solar Energy Materials and Solar Cells, 2011. **95**(11): p. 3054-3059.
23. Sander, M., et al. *Investigations on crack development and crack growth in embedded solar cells*. in *Reliability of Photovoltaic Cells, Modules, Components, and Systems IV*. 2011. International Society for Optics and Photonics.
24. Kempe, M.D., *Modeling of rates of moisture ingress into photovoltaic modules.* Solar Energy Materials and Solar Cells, 2006. **90**(16): p. 2720-2738.
25. Wohlgemuth, J.H., Kurtz, S., *Reliability Testing Beyond Qualification as a Key Component in Photovoltaic's Progress Toward Grid Parity.* , in *IEEE International Reliability Physics Symposium* 2011.
26. Vázquez, M. and I. Rey-Stolle, *Photovoltaic module reliability model based on field degradation studies.* Progress in Photovoltaics: Research and Applications, 2008. **16**(5): p. 419-433.
27. Carlson, D.E., et al., *Corrosion effects in thin-film photovoltaic modules.* Progress in Photovoltaics: Research and Applications, 2003. **11**(6): p. 377-386.
28. Osterwald, C.R., et al. *Degradation analysis of weathered crystalline-silicon PV modules*. in *Conference Record of the Twenty-Ninth IEEE Photovoltaic Specialists Conference, 2002*. 2002.
29. Herrmann, W., W. Wiesner, and W. Vaassen. *Hot spot investigations on PV modules-new concepts for a test standard and consequences for module design with respect to bypass diodes*. in *Conference Record of the Twenty Sixth IEEE Photovoltaic Specialists Conference - 1997*. 1997.
30. Sharma, V. and S. Chandel, *Performance and degradation analysis for long term reliability of solar photovoltaic systems: a review.* Renewable and Sustainable Energy Reviews, 2013. **27**: p. 753-767.
31. Jordan, D.C., et al., *PV degradation curves: non-linearities and failure modes.* Progress in Photovoltaics: Research and Applications, 2017. **25**(7): p. 583-591.
32. Oreski, G. and G.M. Wallner, *Evaluation of the aging behavior of ethylene copolymer films for solar applications under accelerated weathering conditions.* Solar Energy, 2009. **83**(7): p. 1040-1047.
33. Quater, P.B., et al., *Light Unmanned Aerial Vehicles (UAVs) for cooperative inspection of PV plants.* IEEE Journal of Photovoltaics, 2014. **4**(4): p. 1107-1113.
34. Berman, D. and D. Faiman, *EVA browning and the time-dependence of $I-V$ curve parameters on PV modules with and without mirror-enhancement in a desert environment.* Solar Energy Materials and Solar Cells, 1997. **45**(4): p. 401-412.
35. Realini, A.J.F.R., Federal Office for Education and B. Science Tech. Rep., *Mean time before failure of photovoltaic modules.* 2003. **99**.
36. Molenbroek, E., D.W. Waddington, and K.A. Emery. *Hot spot susceptibility and testing of PV modules*. in *The Conference Record of the Twenty-Second IEEE Photovoltaic Specialists Conference - 1991*. 1991.

37. Kumar, M. and A. Kumar, *Performance assessment and degradation analysis of solar photovoltaic technologies: A review*. Renewable and Sustainable Energy Reviews, 2017. **78**: p. 554-587.
38. Wendlandt, S., et al. *Operating principle of shadowed c-Si solar cell in PV-modules*. in *ISES*. 2011.
39. Schmidt, J. *Light-induced degradation in crystalline silicon solar cells*. in *Solid State Phenomena*. 2004. Trans Tech Publ.
40. Lindroos, J. and H. Savin, *Review of light-induced degradation in crystalline silicon solar cells.* Solar Energy Materials and Solar Cells, 2016. **147**: p. 115-126.
41. Meydbray, J. and F. Dross, *PV module reliability scorecard report 2017*. DNV-GL Google Scholar, 2017.
42. Dallas, W., O. Polupan, and S. Ostapenko, *Resonance ultrasonic vibrations for crack detection in photovoltaic silicon wafers.* Measurement Science and Technology, 2007. **18**(3): p. 852.
43. Rueland, E., et al., *Optical u-crack detection in combination with stability testing for in-line inspection of wafers and cells.* Proceedings of 20th EU PVSEC Barcelona, 2005: p. 3242-3245.
44. Schütze, M., et al. *Laboratory study of potential induced degradation of silicon photovoltaic modules*. in *2011 37th IEEE Photovoltaic Specialists Conference*. 2011.
45. Hacke, P., et al. *System voltage potential-induced degradation mechanisms in PV modules and methods for test*. in *2011 37th IEEE Photovoltaic Specialists Conference*. 2011.
46. Pingel, S., et al. *Potential Induced Degradation of solar cells and panels*. in *2010 35th IEEE Photovoltaic Specialists Conference*. 2010.
47. Mathiak, G., M. Schweiger, and W. Herrmann. *Potential-induced degradation—Comparison of different test methods and low irradiance performance measurements*. in *27th European Photovoltaic Solar Energy Conference and Exhibition*. 2012.
48. Hoffman, A. and R. Ross. *Environmental qualification testing of terrestrial solar cell modules*. in *13th IEEE PVSC*. 1978.
49. Jiang, H., L. Lu, and K. Sun, *Experimental investigation of the impact of airborne dust deposition on the performance of solar photovoltaic (PV) modules.* Atmospheric Environment, 2011. **45**(25): p. 4299-4304.
50. Berghold, J., et al. *Electrochemical corrosion within solar panels*. in *27th European Photovoltaic Solar Energy Conference and Exhibition, Frankfurt*. 2012.
51. Siddiqui, R. and U. Bajpai, *Deviation in the performance of solar module under climatic parameter as ambient temperature and wind velocity in composite climate.* International Journal of Renewable Energy Research, 2012. **2**(3): p. 486-490.
52. Paudyal, B.R. and S.R. Shakya, *Dust accumulation effects on efficiency of solar PV modules for off grid purpose: A case study of Kathmandu.* Solar Energy, 2016. **135**: p. 103-110.
53. Wakim, F., *Introduction of PV power generation to Kuwait.* Kuwait Institute for Scientific Researchers, Kuwait City, 1981.
54. Mani, M. and R. Pillai, *Impact of dust on solar photovoltaic (PV) performance: Research status, challenges and recommendations.* Renewable and Sustainable Energy Reviews, 2010. **14**(9): p. 3124-3131.
55. Tahri, A., T. Oozeki, and A. Draou, *Monitoring and Evaluation of Photovoltaic System.* Energy Procedia, 2013. **42**: p. 456-464.
56. Pearsall, N. and B. Atanasiu. *The European PV system monitoring guidelines-Modernisation under the PERFORMANCE project*. in *Photovoltaic Specialists Conference (PVSC), 2009 34th IEEE*. 2009. IEEE.
57. IEC61724, *Photovoltaic System Performance Monitoring Guidelines for Measurement, Data Exchange and Analysis*. 1998: Geneva, Switzerland.
58. S. R. Madeti, S.N.S., *Comparative analysis of solar photovoltaic monitoring systems.* AIP Conference Proceedings, 2017. **1859**(1): p. 020116.
59. Reinhardt, S., Eggers, C., Grünsteidl, S., Vodermayer, C., Becker, G. *Influence of Technology Differences in Performance Ratio Calculations*. in *27th European Photovoltaic Solar Energy Conference and Exhibition*. 2012. Frankfurt, Germany.
60. Copper, J., et al., *Australian Technical Guidelines for Monitoring and Analysing Photovoltaic Systems*. 2013, Australian PV Institute.
61. 61724-1, I., *Photovoltaic System performance - Part 1: Monitoring*. 2017. p. 57.
62. Beuttell, W., *IEC 61724-1: What's it all about?*, in *PV Tech*. 2017.