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Performance ratio – Crucial parameter for grid connected PV plants

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ABSTRACT

Performance Ratio (PR) is a globally accepted indicator to judge the performance of grid connected PV Plants. There are good examples from countries like the US, Australia and those in the European Union who have used PR as a key performance indicator to judge the performance of their PV systems. Such an analysis has helped these countries in continuously increasing the performance of their plants by rectifying system faults and thus plan for better investment decisions.

The main focus of the paper is to highlight the importance of PR as a crucial performance indicator citing literature and research progress. In literature review, mainly, we discuss and compare few internationally acclaimed PV monitoring standards, guidelines, expert works and company methodologies, as to how they calculate the PR of a grid connected PV plant. Important issues over the definition of PR have also been discussed briefly. Later, arguments have been presented to support our claim of sticking to a bare minimum PR approach as defined by IEC 61724. This could significantly help countries in ramping up their grid PV capacities in the initial stages of development. At the end we have also highlighted economic and environmental benefits of using PR as a performance indicator by illustration of a case example from the SolMap project in India.

Contents

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1. Introduction

There exist several parameters to judge the performance of a PV plant such as specific yield, capacity utilization factor (CUF), Performance Ratio (PR), performance index (PI) etc. Specific yield and CUF are commonly reported parameters in plant performance sheets. The Final (or specific) yield is an important indicator for the performance of a PV system. It is defined as the ratio of the final energy output (kW h) of the system to that of its nominal d.c. power (kW). Another important parameter used by plant operators is the performance ratio of a PV plant. PR is the proportion of the energy that is actually available for export to the grid minus the energy lost due to various environmental factors (e.g. degradation, soiling, etc.) and energy consumed in the operation process.

Performance Ratio is assumed to be a better indicator as compared to the final yield of the PV plant because of its ability to capture the actual insolation better. Thus, final yield cannot be used for comparing PV systems located in different regions because of significant variance in their actual insolation values. Standard specific yield values from different PV plant locations are useful in healthy estimation of expected yields for nearby plants as well as those located in far off places. For example, in Germany a specific yield of 950 kW h/kWp is a quite reasonable value per year [1]. In northern Germany this value may be a bit too high and in southern Germany in real life it can also go up to 1050 kW h/kWp [1]. But, as a thumb rule, it is a useful tool for the pre-design of a PV system.

Final yield is a good indicator to compare the performance of PV systems located at the same place and which use the same or differing mounting structure. PV plants at the same location in Freiburg, Germany; with varying dates of installation, using different modules and inverters have shown a deviation of up to 10% in their final yield values [2]. If there is no insolation measurement device installed at the PV plant or if the data from the sensors are not reliable, final yield may be the most suitable indicator for the performance of a PV system. Typically, time periods monitored for the final yield values are equal or longer than one day. For e.g. daily, monthly or annual final yield values are common.

Capacity utilization factor (CUF) or the capacity factor (CF) is another common indicator used by plant personnel for judging the performance of grid connected PV systems. It is defined as the maximum output from the PV plant to that of the maximum output from it under ideal conditions. Capacity utilization factor doesn't reflect the actual performance of the PV plant as it doesn't account for factors such as environmental effects, availability of the grid, system faults etc. Also, it doesn't take into account the threshold irradiation needed to generate electrical energy, the irradiation levels at a given period of time, and the temperature effect of the panels [3]. PR on the other hand is influenced by climatic factors but is independent of the plant size and location.

CUF is a good tool but it doesn't provide the complete picture and deeper insights as compared to PR of a grid connected PV plant [4]. A continuous monitoring of the PR has significantly helped plant personnel to rectify the problems in the plant and improve its performance in the future. According to [5], "…*good engineering construction and procurement (EPC) companies today guarantee PR as one of the most important technical parameters (specific yield and plant availability being the other two) during provisional acceptance and production guarantee period, to ensure the correct operation of the plant*".

Performance Ratio is a unit-less quantity and has gained wide acceptance to judge PV system performance globally. The higher the PR of the system, better is the performance of the system as compared to other systems in similar climatic conditions. According to the EU PERFORMANCE project, a PR of 0.8 and above is an indicator of a good performing system [6]. PR is one of the main performance indicator adopted in PV monitoring schemes established by several countries such as the US, Australia, and the European Union. Experiences of a large number of PV plant operators indicate that a continuous monitoring of PR is helpful in correcting system faults. A NREL report [7] further elaborates that a low system PR or a PR value below an average value is an indication of a problem.

1.1. PR – a key parameter used in performance studies of grid connected PV plants

202 PV plants in Taiwan were analyzed to check the operational performance and system performance [8]. Monthly energy yields and failure data for three years (2006–2008) were used for the study. The PR of the observed plants varied between 0.6–0.9 and the average PR value for whole Taiwan was found to be 0.74 indicating a comparatively above average plant performance.

The study [9] analyzed the performance of 993 residential PV systems in Belgium over a period of two years. ANOVA (Analysis of Variance) tool was used to analyze the quality of different modules. One of the key parameters used to judge the quality of the PV systems was PR. The average value of the performance ratio was found to be 0.78 indicating an almost well performing system. The same authors performed another study [10] using the same approach to analyze the performance of operational data from 6868 residential PV systems in France and the average PR of the PV systems was found to be 0.76. This indicated that the PV systems in Belgium performed slightly better than their French counterparts.

A comparative study using three different PV module technologies for a grid-connected photovoltaic system in Malaysian conditions was studied [11]. The PR was found to be different for the three module technologies: polycrystalline – 78.2%, monocrystalline – 81% and 94.6% for a-Si thin film. Thus, it is evident that amorphous silicon module technology provides the highest reliability and conversion performance under the Malaysian climatic conditions.

Performance analysis of a 3 MW_p grid connected PV plant was carried out for the period of two years (2010 and 2011) in the state of Karnataka in India as per the IEC 61724 standard [12]. During 2010, the average PR was less than 0.6 due to inverter failure for three months but in 2011 this problem was rectified and the average PR value reported was 0.7 clearly indicating that better PR monitoring and larger data sets would help in further (or continuous) improvement in system performance leading to higher PR values.

The study [13] analyzed the performance of a 200 KW_p ground mounted PV system in Koya city in Iraq using PVGIS simulation software as per the standard IEC 61724. The climatic conditions in Iraq is almost similar to Iran and Turkey. The PR of system ranged between more than 0.79 to nearly equal to 0.81. The average PR was around 0.8 indicating a good performing system.

Energy performance of three different PV module technologies; crystalline (*c*-Si), multi crystalline (mc-Si) and cadmium–telluride (Cd-Te) as a roof top grid connected PV system was analyzed at Izmit, Kocaeli in Turkey from October 2013 to December 2014 [14]. PR was used as one of the main performance indicators. The average PR for the three module technologies was found to be: c-Si – 82.05%, mc-Si – 83.8% and Cd-Te – 89.76%. Cadmium-telluride showed low variability with climatic changes and performed the best as compared to c-Si and mc-Si. Hence, Cd-Te may be assumed to be the most reliable module technology for Kocaeli conditions.

Performance analysis of a grid connected PV system was conducted at an administrative building in Algiers and results were presented for a particular year [15]. The PR of the plant varied between 62% and 77%. The performance of the system was compared with other such system globally and the power generation met international standards for similar systems.

The study [16] presents the performance analysis of a 2 kW grid connected rooftop system at an educational institute in Nis, Serbia for a period of one year (Jan 2013–Jan 2014). The performance ratio of the PV system was found to be 93.6%. Such an experiment indicated a satisfactory integration of renewable energy into the transmission grid in Serbia.

The paper [17] analyzes the performance of a 9 KW_p grid connected high concentrating photovoltaic (HCPV) plant in Kunming, China for the period 1 April 2014 and 31 March 2015. The annual average PR of the HCPV system was found to be 79.9% which was assumed to be low performing system as compared to similar HCPV systems reported elsewhere.

This paper is trying to achieve two objectives: Firstly, the intent of this work is to provide a thorough literature review and comparison between different methodologies used to calculate the PR of a grid connected PV plant. Second objective is to present to the plant operators and policy makers the applicability power, ease and potential of using PR as an important parameter to gauge the performance of the grid connected PV systems.

Following introduction, rest of the paper is organized as follows: The approach and methodology for the literature review are presented in Section 2. Section 3 presents the detailed literature review. In addition, it also discusses important issues over the definition of PR and gives the case on the SolMap project. Section 4 covers the conclusion of the study.

2. Approach and methodology

The paper discussion is restricted mostly to defining the PR formula, terminologies used in definition, and presenting PR ranges (if any) observed in reference literature. Detailed discussion about the performance parameters and their variability has not been considered. Following selected works has been used as a reference for the literature review part, these are: Definition used by Haeberlin et al. [22]; IEC 61724 Methodology [25]; IEA PVPS TASK 2 Methodology; NREL/CP-520-37358 Performance Parameters for Grid-Connected PV Systems [7]; EU Performance Monitoring Guideline for Photovoltaic Methodology-PERFORMANCE Project [6]; SMA Methodology; Definition used by Kymakis et al. [20]; Definition used by Ransom et al. [21]; PR-FACT Mack and Decker GmbH In-house Methodology [30]; NREL/TP-5200-57991 Weather-Corrected Performance Ratio [19]; and Australian PV System Monitoring Guideline Version 1.0 [29].

The above presented references represent one of the most cited works in literature on performance ratio of PV plants and are a perfect mix of international standards and monitoring guidelines; national monitoring guidelines; company tools and methodologies; working papers from research labs of international fame; insights from global projects and individual researches. The references have been sorted via a desktop research and using the database Scopus. The article, papers and reports are then screened based upon their relevance and citation. The typical time period covered is from 1995 to 2013. Apart from the above mentioned sources, several other reference works have also been used in different sections but the main reference used is IEC 61724 standard. The European PV guidelines Report EUR 16339, Document B [18] shouldn't be confused with the European Performance Monitoring Guidelines for Photovoltaic [6] under the PERFORMANCE project. We have discussed only the guideline under the PERFORMANCE project.

In Section 3.3, the paper throws light on some of the critical issues on PR definition of a PV plant such as reference yield calculations at Standard Test Conditions (STC), use of Pyranometer or a reference cell for irradiation measurements etc. The discussion is based upon references from peer reviewed journals and research articles. Further, the discussed works on PR definition are presented in the form of a summary table highlighting the key statistics such as PR definition, parameters used in the definition, PR range (if any) etc.

Section 3.4 of the paper discusses and presents strong reasons for using PR as one of the main performance indicator for grid connected PV plants. A bare minimum PR approach as defined by IEC 61724 has been used as a supporting base of the discussion. Section 3.5 presents a separate section on the new initiative of Government of India, called the SolMap Project. The case study highlights the brief description about the structure and intended outcome of the project aiming to set a PV benchmark and monitoring system in India. Finally, using key results and findings from the SolMap project, economic and environmental benefits have been presented.

3. Literature review

3.1. Performance ratio – crucial parameter for grid connected PV plants

Since the time PV plants became operational, evaluating and predicting their actual performance has been of great interest to researchers, scientists, PV manufacturers, and PV plant developers. Performance Ratio (PR) of a PV plant is one of the most important parameters (de-facto standard) used by industry today to evaluate performance of the PV plants. PR is a globally accepted PV plant performance parameter and its use would help investors in evaluating different proposals and technologies, giving them greater confidence in their own ability to procure and maintain reliable, high-quality systems [7]. The PR represents the actual energy generated by the PV plant to its expected energy with reference to its nameplate rating. In other words, the PR is an indicator of losses resulting from invertor problems, wiring, shading, cell mismatch, reflection, outages, module temperatures etc. [19]. PR of the plant is usually independent of the site location and system size but it has strong dependence upon weather variability. A continuous monitoring of the PR could be very helpful in fault detection and system analysis. IEA PVPS task 2 programme and several other studies [19–22] have presented examples where continuous monitoring of PR ranges or levels had helped plant personnel to rectify several problems pertaining to inverter failures, module performance, shading etc.

Performance Ratio is a unit less quantity and its value usually ranges in between 0 and 1. As PR value approaches unity, it shows a PV system with high performance. According to the European PV Guidelines, a good PR value ranges between 0.8–0.85 and a value below 0.75 indicates a problem. Also, this may be a normal range for a BIPV system due to higher operating temperatures and the shading effect [6]. Low value of PR usually corresponds to a problem but it may not indicate the typical cause for this behavior. For identifying the actual cause, detailed experiments and analysis have to be carried out. According to a study by Reich et al. [23], typical ranges of the PR rose from reportedly 50–75% in the late 1980s and 70–80% in the 1990s to $>80\%$ nowadays, see Fig. 1. The same study while investigating 100 photovoltaic installations in Germany recently using highly efficient components and appropriate design was able to achieve PR close to 90% with mono-crystalline Si reference cells (see Fig. 1). Another study undertaken by NREL in 2009, for new systems, reports a typical range of PR from 0.6 to 0.9 [19]. In a popular study on monitoring of PV systems good practices and system analysis, Woyte et al. [24] has tried to showcase average values and ranges of PR for installations from different decades using several cited journal sources as shown in Table 1 below.

3.2. Defining the PR of a PV plant

The standard method followed globally to define the PR of the PV plant is the International Electro Technical Commission's standard IEC 61724 [25], which is also one of the main reference documents for monitoring of a PV Plant. Other popular reference

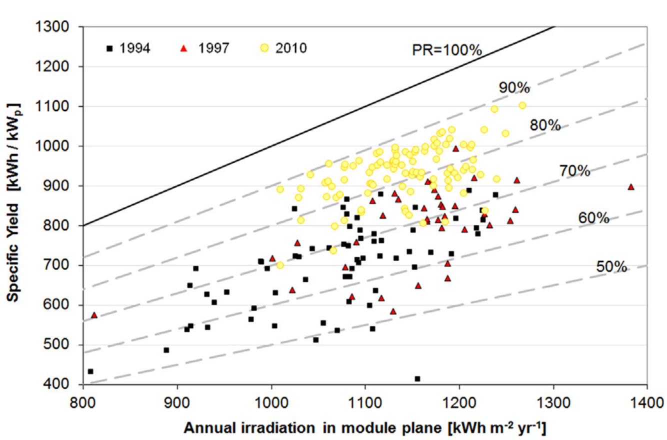

Fig. 1. PR values measured by Fraunhofer ISE for the years 1994 and 1997 in the context of the "1000 Dächer Jahresbericht", and system evaluation of PV plants connected to the grid in year 2010 with corresponding performance ratio contour line (Source: Reich et al. [23]).

Table 1
Average values of and ranges of performance ratio for installations from different decades. Source: Woyte et al. [24].

Installed	Location	Range of PR	Average PR
1980s	Worldwide	0.50–0.75	Individual estimates
1990s	Worldwide (source 1)	0.25–0.90	0.66
1990s	Worldwide (source 2)	0.50–0.85	0.65–0.70
1990s	Germany	0.38–0.88	0.67
2000s	France	0.52–0.96	0.76
2000s	Belgium	0.52–0.93	0.78
2000s	Taiwan	<0.3 to >0.9	0.74
2000s	Germany	0.70–0.90	0.84

documents include the guidelines of the European Joint Research Centre, ISPRA Italy, Report EUR 16339, Document B [18], NREL/CP-520-37358 report [7], and the European PV System Monitoring and Analysis Guidelines under PERFORMANCE project [6].

According to SMA [26], performance ratio shows the proportion of the energy that is actually available for export to the grid after deduction of energy loss (e.g. due to thermal losses and conduction losses) and energy consumption for operation. IEC standard [25], NREL [7], IEA PVPS Task 2 [27,28], European Guidelines [6], and Australian PV System Monitoring Guideline [29], all report PR as the ratio of final system yield (Y_f) to that of reference yield (Y_r).

$$\text{Performance Ratio (PR)} = \frac{Y_f}{Y_r} \tag{1}$$

The final yield of the system (Y_f) is defined as the ratio of the final or actual energy output of the system to its nominal d.c power. The Y_f normalizes the energy produced with respect to the system size [7].

$$\text{Final Yield } (Y_f) = \frac{Final\ \ Energy\ \ Output\ \ (kWh)}{Nominal\ \ d.c\ \ power\ \ (kW)} \tag{2}$$

The reference yield (Y_r) is the ratio between total in-plane irradiance to that of the PV's reference irradiance. The PV reference irradiance at STC condition is equal to 1000 W/m^2. The reference yield is also called the Peak Sunshine Hours.

$$\text{Reference Yield } (Y_r) = \frac{Total\ \ in\text{–}plane\ \ irradiance\ \ (kWh/m^2)}{PV\ \ reference\ \ irradiance\ \ (kW/m^2)} \tag{3}$$

Clearly, it is evident from Eq. (3) that reference yield is dependent on location.

Kymakis et al. [20] and Ransom [21] have evaluated the performance ratio using various losses apart from the general definition as mentioned in Eq. (3). The losses include panel degradation, temperature, soiling, inverter, internal network etc. The authors also found uncertainties such as degradation, shading, module calibration, flash test, balance of system (BOS) etc. PR-FACT methodology divides the PR in several single correction factors to account for various parameters determining the performance or the electric yield following a seven step calculation process [30]. Similarly, Haeberlin et al. [22] and NREL [19] and have predicted the performance ratio after defining the temperature correction factors. Kymakis et al. [20] has used generation correction factors to define the PR in addition to accounting the losses in the PV system. The following section now discusses all the selected works one by one in detail.

3.2.1. Definition used by Haeberlin et al. [22]

The PR calculation methodology is based on the work presented in the paper titled, "Normalized representation of energy and power for performance and online error detection in PV systems". The paper has defined normalized instantaneous quantities

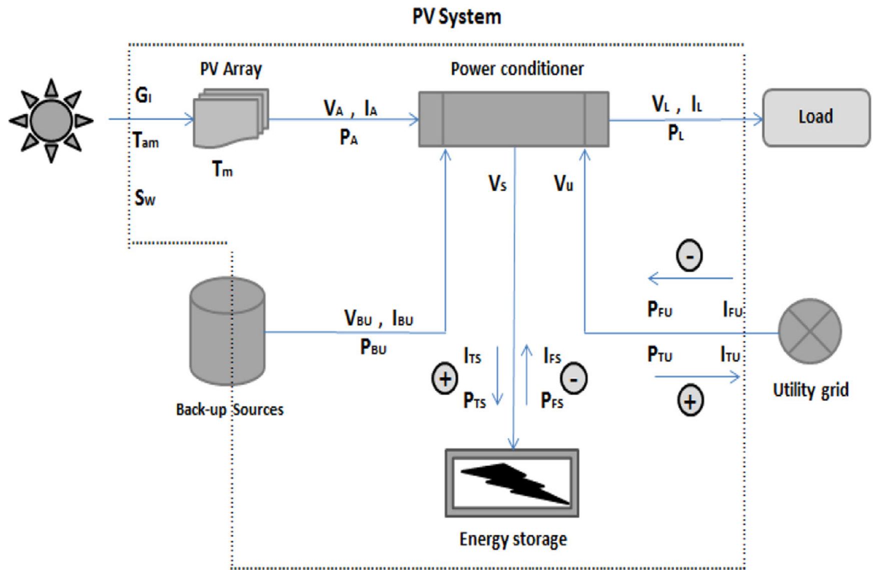

Fig. 2. Parameters to be measured in real time (adopted from IEC 61724).

analogous to standard energy yields of the IEC 61724 standard [25]. The storage interval of data is considered to be less than 1 h (e.g. 5 min). The authors have tried to show with examples that the normalized daily diagrams resulting from the normalized instantaneous quantities (represented by small alphabets) allow for a more detailed system analysis and online data error detection. The methodology has also used temperature correction factor (K_T) and generation correction factor (K_G). The PR of the PV system is presented as the product of the two defined correction factors and the inverter efficiency (n_I).

The temperature corrected nominal solar generator power (P_{0T}) is defined as:

$$P_{0T} = P_0\left[1 - c_T(T_C - T_0)\right] \tag{4}$$

where, $c_T \sim 0.0044/K$ is the temperature coefficient of the crystalline cell used, P_0 is the nominal solar generator power, T_C is the cell temperature, and $T_0 = 25$ °C at STC.

Temperature corrected irradiance (y_T) can be defined as

$$y_T = y_r \times \frac{P_{0T}}{P_0} = y_r\left[1 - c_T(T_C - T_0)\right] \tag{5}$$

where, y_r is the reference yield. All other abbreviation has usual meanings as presented in Eq. (5). Instantaneous thermal capture losses (l_{CT}) and Miscellaneous losses (l_{CM}) could be calculated using the following equations

$$l_{CT} = y_r - y_T \tag{6}$$

$$l_{CM} = y_T - y_a \tag{7}$$

The Temperature correction factor and generation correction factor are defined as under

$$k_T = Y_T/Y_r \tag{8}$$

$$k_G = Y_a/Y_T \tag{9}$$

where, Y_T is the temperature corrected reference yield (reference irradiance = 1 kW/m^2), Y_r and Y_a are the normalized system reference and array yields respectively.

Inverter efficiency (n_I) for the grid connected system is calculated as the ratio of the final yield to that of the array yield of the system.

$$n_j = \frac{Y_f}{Y_a} \tag{10}$$

Finally, the actual Performance Ratio (PR) as calculated by the online data acquisition system is defined as the product of the

$$PR = Y_f/Y_r = K_T \times K_G \times n_j \tag{11}$$

All abbreviations in Eq. (11) has usual meanings as detailed in Eqs. (5)–(10).

The authors have recommended to position reference cells and temperature sensors at appropriate positions in the middle of the array to reduce impact of the temperature difference between the two on various associated parameters.

3.2.2. IEC 61724 methodology

The IEC 61724 Standard titled, "Photovoltaic system performance monitoring-Guidelines for measurement, data exchange and analysis" is primarily based upon the European Guidelines Document B [18] and presents an international consensus in the area of PV system performance and monitoring analysis. Today, it is used as the main reference for PV system performance and monitoring globally.

The different parameters of a PV system to be measured in real time according to IEC 61724 are shown in Fig. 2. The derived energy quantities as per the IEC 61724 guideline are defined by the following equations:

$$E_{i,\tau} = \tau_r \times \sum_{\tau} P_i \tag{12}$$

where, E_i is energy quantity expressed in kW h and $_{Pi}$ is power parameter measured in kW. τ_r is the recording interval and τ is the reporting time period. Both are reported in hours (h). Reporting time period τ is longer than the recording interval τ_r. Using Eq. (12) various net energy quantities such as those from array, storage, back-up, utility grid and those to load, storage, utility grid as well as total system input and output energy are defined. Refer to Eqs. (15)–(20).

In a similar fashion, mean daily irradiation quantities are evaluated from the recorded irradiance using the following formulae

$$H_{I,d} = 24 \times \tau_r \times \left(\sum_{\tau} G_I\right) / \left(\sum_{\tau} \tau_{MA} 1000\right) \tag{13}$$

where, $H_{I,d}$ is the mean irradiation quantities G_I is the total irradiance in the plane of array, τ_{MA} is availability of the monitored data in the reporting time. The availability of monitored data A_{MD} is calculated by dividing the availability of monitored data τ_{MA} (in hours) to that of the reporting time period τ(in hours).

$$A_{MD} = \frac{\tau_{MA}}{\tau} \tag{14}$$

The net energy delivered to the storage device in the reporting time period τ is

$$E_{TSN,\tau} = E_{TS,\tau} - E_{FS,\tau} \tag{15}$$

where, E_{TSN} is the net energy delivered to the storage device in reporting period τ, $E_{TS,\tau}$ is the energy to the storage device in reporting period τ and $E_{FS,\tau}$ is the energy from the storage device in reporting time period τ. Similarly, the net energy delivered from the storage device in the reporting time period τ is

$$E_{FSN,\tau} = E_{FS,\tau} - E_{TS,\tau} \tag{16}$$

The net energy delivered to the utility grid in the reporting period τ is

$$E_{TUN,\tau} = E_{TU,\tau} - E_{FU,\tau} \tag{17}$$

The net energy delivered from the utility grid in the reporting period τ is

$$E_{FUN,\tau} = E_{FU,\tau} - E_{TU,\tau} \tag{18}$$

The total system input energy is

$$E_{in,\tau} = E_{A,\tau} + E_{BU,\tau} + E_{FUN,\tau} + E_{FSN,\tau} \tag{19}$$

where, ‘A’ stands for array and BU indicates backup unit. All other abbreviations have usual meanings.

The total system output energy is

$$E_{USE,\tau} = E_{L,\tau} + E_{TUN,\tau} + E_{TSN,\tau} \tag{20}$$

where, L stands for load and U for utility grid.

The fraction of the energy from all sources which was contributed by the PV array is

$$F_{A,\tau} = E_{A,\tau}/E_{in,\tau} \tag{21}$$

The efficiency with which the energy from all sources is transmitted to the loads is

$$\eta_{LOAD} = E_{USE,\tau}/E_{in,\tau} \tag{22}$$

The overall efficiency of the BOS components is given by

$$\eta_{BOS} = \left(E_{L,\tau} + E_{TSN,\tau} \quad E_{FSN,\tau} + E_{TUN,\tau} \quad E_{FUN,\tau}\right)/(E_{A,\tau} + E_{BU,\tau}) \tag{23}$$

The array yield is calculated as the daily array output to that of the installed power of the PV array (in kW).

$$Y_A = E_{AD}/P_O = \tau_r \times \left(\sum_{day} P_A \right)/P_O \tag{24}$$

where, E_{AD} is the daily total array output energy, P_O is the array nominal capacity in KW, $\sum_{day} P_A$ is the actual power generated by the array in monitoring interval τ_r.

The final yield (Y_f) of the PV plant is defined as the total energy output of the whole PV plant divided by the total installed capacity of the PV array. As per the IEC 61724 document, the final yield actually represents the number of hours per day that the array would need to operate at its rated output power P_O to equal its monitored contribution to the net daily load

$$Y_f = Y_A \times \eta_{LOAD} \tag{25}$$

where, Y_A is the array yield and η_{LOAD} is the load efficiency of the system.

The reference yield (Y_r) can be evaluated by calculating the total daily in-plane irradiation to that of the module's reference in-plane irradiance $G_{I,ref}$(kW/m^2). The reference yield is also called the Number of Peak Sun Shine Hours as it represents the time duration during which the monitored solar radiation is at the reference irradiance level (where $G_{I,ref} = 1$ kW/m^2). In other words, reference yield represents the same energy which was actually monitored.

$$Y_r = \tau_r \times \left(\sum_{day} G_I \right)/G_{I,ref} \tag{26}$$

The performance ratio (R_p) of the PV plant is calculated by dividing the final yield (Y_f) of the PV plant to that of the reference yield (Y_r). It indicates the overall effect of losses on the plant's rated array output due to temperature, irradiation, and system component inefficiency or failure effects etc.

$$R_P = \frac{Y_f}{Y_r} \tag{27}$$

The capture losses (L_C) and BOS losses (L_{BOS}) can be calculated using the following equations.

$$L_C = Y_r - Y_A \tag{28}$$

$$L_{BOS} = Y_A \times (1 - \eta_{BOS}) \tag{29}$$

IEC 61724 [25] has recommended use of several criteria and limits for different parameters in the monitoring method. For details please refer to Appendix B.

3.2.3. IEA PVPS TASK 2 methodology [2001]

The International Energy Agency (IEA)'s Photovoltaic Power Systems Programme (PVPS) is one of the most popular collaborative programmes globally. The PVPS has several tasks, each with a specific objective and outcome. Details about all the tasks up till TASK 14 could be found on IEA PVPS webpage (http://iea-pvps.org/). The TASK 2 of the programme specially focuses on performance, reliability and analysis of PV Systems. Twenty countries participated in the Task 2 experiments.

The PR calculation methodology presented is based on the Report IEA-PVPS T2-01:2000 [28]. The evaluation procedure for different parameters is primarily based upon the European guidelines document B [18] and IEC 61724 Standard [25]. Apart from this, the report gives specific comments and recommendations for the participating nations at the country level. Parameters used are presented only for the grid connected systems.

The various yields and losses are defined in tune with European guidelines [18] and IEC 61724 Standard [25]. Firstly, the yields are defined (see Eqs. (30)–(32)) followed by the system losses (see Eqs. (33)–(34)). All the abbreviations have usual meanings covered in earlier sections.

Reference yield (Y_r)

$$Y_r = \frac{\text{Total inplane irradiation kWh}/m^2}{\text{PV's reference irradiance kW}/m^2} = \int \text{day GI}\frac{dt}{G_{STC}} \tag{30}$$

Final yield (Y_f)

$$Y_f = \frac{\text{Total useful output energy kWh}}{\text{Nominal power of the PV system kW}} = E_{USE,PV,d}/P_0 \tag{31}$$

Array yield (Y_A)

$$Y_A = \frac{\text{Total energy dlivered by the PV array kWh}}{\text{Nominal power of the PV array system kW}} = E_{A,d}/P_0 \tag{32}$$

Array capture losses (L_C)

$$L_C = Y_r - Y_A \tag{33}$$

System losses (L_S)

$$L_S = Y_A - Y_f \tag{34}$$

The PR of the system is defined as the ratio of the final yield to reference yield of the system.

$$PR = Y_f/Y_r \tag{35}$$

Based upon the actual experience, PVPS TASK 2 reported PR values for 170 monitored PV plants [18]. The PR value of the PV plants ranged between 0.25–0.90 and the average PR value was found to be 0.66. Another PVPS TASK 2 document [27] has reported PR values for 334 PV systems across 14 countries comprising of 1142 annual datasets. According to this document, the annual mean PR between 1983 and 1995 was estimated to be 0.65 and between the period 1996–2002 the annual mean PR value rose to 0.70. This clearly indicates that monitoring the PR values over time has helped the plant operators to increase the average performance of the plants by nearly 8% over six years.

The outage fraction (O) is a parameter used to indicate the continuous operation of the PV system. It is calculated by dividing the time period for which data was not available (T_{NAV}) to that of the monitoring time period (τ).

$$O = \frac{T_{NAV}}{\tau} \tag{36}$$

The IEA PVPS TASK 13 report [31] recommends that the data should be sampled every second or faster. Averaged values should be stored every 5–15 min. Longer averages may hamper the analysis of the PV plant whereas shorter intervals may overload the database. For irradiance value, the report further suggests omission of GI values $< 600\ \text{W/m}^2$.

The report has correlated the PR with the efficiency of the PV system and a new parameter called the production factor (PF).

$$PF = E_A/(P_0 \times H_I/G_{STC}) = Y_A/Y_r \tag{37}$$

where, the quantity $(Y_A/Y_r)$is the efficiency of the PV system (η_{sys}).

We can also represent efficiency of the PV system as a fraction of PR to that of the production factor of the system as shown in Eq. (38)

$$PR/PF = \eta_{syst} = Y_f/Y_A \tag{38}$$

The report criticizes that IEC 61724 standard [25] and the European Guidelines [18] have only measured the system performance and have not distinguished between the quality of results due to poor sizing or a technical problem. Thus, in cases where the problem becomes difficult to detect, the newly defined parameters, usage factor (UF) and production factor (PF) allow overcoming the issue and give healthy signals to take proper action on the system operation. It further says that (PR/UF) or (PR/PF) curves may indicate the malfunction of the PV systems.

3.2.4. NREL/CP-520-37358 performance parameters for grid-connected PV systems [7]

The NREL paper has presented the three basic parameters used by IEC 6724 [25] (final yield, reference yield and performance ratio) to define the overall system performance. The paper further briefs about the PV USA rating method-PTC [32] in the beginning and then discusses about the D.C. and A.C. derate factors. Finally, the paper elaborates over the influence of weather on performance parameters. Our discussion and coverage from this paper would be limited to defining PR and any specific comment made with regards to it. Details about PTC, derate factors, weather influence, and example results for PR could be referred in the paper [7].

The three performance parameters defined by the paper are:

1. Final yield of the PV system (Y_f)

   It is defined as the net energy output (E) divided by the nameplate D.C. power (P_0) of PV system array.

$$Y_f = \frac{\text{Net energy output E}}{\text{Name plate d.c. power } P_0} \tag{39}$$

   Final yield actually normalizes the energy produced with respect to the system size. Thus, it is a convenient means to compare systems of different sizes.
2. Reference yield of a PV system (Y_r)

   It is calculated as the ratio of the PV's total in-plane irradiance (H) to that of the reference irradiance (G). In other words, it is equivalent to number hours at the reference irradiance or equal to peak sunshine hours.

   It is a representation of the PV system's solar resource at the location and depends upon the orientation of the PV array, month to month and year to year weather variability.
3. Performance Ratio (PR)

PR is defined as the ratio of the final yield (Y_f) of the PV system to that of the reference yield (Y_r).

$$PR = \frac{\text{Final yield } Y_f}{\text{Reference yield } Y_r} \tag{40}$$

Performance ratio of a PV plant represents the overall losses on the rated output of the plant resulting from module temperature effects, wiring, inverter inefficiencies, component failures etc. The report has cautioned that "*PR by itself shouldn't be treated as a representative of the amount of energy produced as it may depend upon the quantity of solar resource available (high or low) despite the low or high value of the PR*".

According to the authors, the typical reporting period for PR is either monthly or annually. But, reporting for even smaller intervals, such as weekly or daily could be very helpful while investigating and identifying component failures. The typical PR range reported for PV plants is between 0.6 and 0.8 [25]. The authors have further explained that an unusual value of the PR could show existence of a problem but may not give any hint about the cause of the problem. For e.g. a large decrease in the PR, may indicate events that significantly impact performance, such as inverters not operating or tipping of circuit-breakers. On the other hand, a smaller or an insignificant decrease indicates a minor issue. For events such as decrease in PR due to soiling or long-term PV system degradation, it is advised to observe the change over a large time interval, e.g. for several months or years as the changes over short period may be misleading and may not quantify the problem fully.

3.2.5. EU performance monitoring guideline for photovoltaic-PERFORMANCE project [6]

The European performance monitoring guidelines for photovoltaic were developed as part of the EC Integrated Project PERFORMANCE – Contract No. SES 19718 [6]. The guideline is primarily based upon the IEC 61724 Guidelines with some additional comments over few parameters. Also, there is a little difference in the symbols used in some equations or for some parameters. For e.g. it uses ST to represent summed across reporting period T, whereas IEC 61724 used $\sum$ symbol to represent the same. IEC 61724 has used R_P symbol for Performance Ratio whereas European PV System monitoring guidelines uses PR symbol for performance ratio. Energy quantities and parameters as defined by the guideline are discussed in the following section.

Energy quantities are calculated from the power quantities using the following equation

$$E_{i,T} = t_r \times \text{ST}\ P_i \tag{41}$$

where $E_{i,T}$ is the energy over the reporting period T for the parameter i, t_r is the recording interval for the power readings (expressed in hours) and $_{Pi}$ is the individual power reading for the parameter i. The power readings are summed across the reporting period T (as ST).

Measured irradiance values are used to calculate the mean daily irradiation $H_{I,d}$ using the formula

$$H_{I,d} = 24 \times t_r \times (ST\ G_i)/(ST\ t_{MA} \times 1000) \tag{42}$$

where, G_i is measured irradiance (W/m^2), t_r is the recording interval measured in hours, t_{MA} is the period of monitoring measured in hours and T is the reporting period (also in hours).

The yields are defined in the following manner.

Array yield (Y_A) is the total energy obtained from the PV array per kW installed capacity of the array.

$$Y_A = E_{A,d}/P_0 \tag{43}$$

where, $E_{A,d}$ is energy output of the array and P_0 is the rated capacity of the PV array.

Final yield (Y_f) is the daily overall energy output of the PV system ($E_{use,d}$) to the installed total rated capacity of the PV arrays.

$$Y_f = E_{use,d}/P_0 \tag{44}$$

Reference yield is calculated by dividing the total daily in-plane irradiation (ST G_i) in the recording period (t_r) by the module's reference in-plane irradiance ($G_{i,\ ref}$=1 kW/m^2)

$$Y_r = t_r \times ST\, G_i / G_{i,ref} \tag{45}$$

The reference yield is also equivalent to the number of peak sunshine hours of the day.

Now, the PR of the PV plant is defined as the ratio of the final yield to that of the reference yield of the PV plant as shown in Eq. (46).

$$PR = \frac{Y_f}{Y_r} \tag{46}$$

Performance ratio is an indicator of the system's overall performance after deducting various losses and inefficiencies resulting due temperature effects on module, inverter failure, non-availability of grid etc. It represents the output of the system with respect to an ideal system in a similar climatic condition and time interval. The PR of the plant is independent of the location and is an important parameter frequently used to compare systems of different sizes and location. For a grid connected PV system, the guideline treats a figure of around 0.8–0.85 to be a good PR. It also reports the PR value to be closer to the lower end of the range for building integrated PV systems due higher operating temperatures and more possibility of shading. The guideline also states that if the PR value is less than 0.75 then reason for the possible cause should be inquired and accordingly addressed.

The values and limit criteria laid down by the guideline for different parameters (such as irradiance, wind, accuracy of instruments etc.) are in-tune with IEC 61724 [25]. The guideline has presented additional set of values and limit criteria for different parameters. For e.g. Irradiance values in the array plane should vary between 0 and 1400 W/m^2; ambient temperature should be in the range – 40 °C and ~60 °C; module temperature (non-concentrating system) for open rack mounted systems should be between ambient and ambient plus 40 °C and ambient plus 60 °C is the recommended limit for building integrated systems. For array voltage and array current the report suggests values between zero and 1.3 × open circuit voltage and values between zero and 1.5 × short circuit current at STC respectively.

The guideline has also highlighted the role of strong seasonal dependence of PR and recommended proper analysis to be considered while comparing such cases. The report further alerts about the impact of DC rating of the system on the calculated yield. It argues that comparison of values using the same rating assumption are more reliable in terms of identifying changes in performance than comparing with predicted values [6].

3.2.6. SMA methodology

This PR calculation methodology is based upon the SMA's technical information report Perfratio-UEN100810 Version 1.0 titled Performance Ratio – Quality factor for PV plant [26].

The optimum analysis period for PR calculation recommended by the report is 1 year or shorter (daily, monthly etc.). For e.g. monthly monitoring could be very useful for observing variation of certain parameters such as module temperature etc.

The report defines the PR as the ratio of the actual reading of the plant output in kW h to that of the nominal plant output in kW h.

$$PR = \frac{\text{Actual reading of the plant output in kWh p.a}}{\text{Nominal plant output in kWh p.a}} \tag{47}$$

where, p.a stands for per annum.

The nominal plant output is calculated using the following formula.

$$\text{Nominal Plant output} = \text{Annual incident solar radiation} \times \eta_{rel} \text{ of the PV modules} \tag{48}$$

According to SMA, PR shows the proportion of the energy that is actually available for export to the grid after deduction of energy loss. The losses may include thermal losses and conduction losses, losses due to energy consumption for operation etc. The PR of a PV plant is independent of the location of the plant and thus serves as a quality factor. Based upon their experience, SMA reports that a high performance PV plant can reach a PR of up to 80%. The report further elaborates that PR value of more than 100% is also possible depending upon the way it is defined, under the influence of certain factors.

The report clearly indicates that PR is affected by environmental factors (such as temperature of the PV module, shading etc.), recording interval, efficiency of PV modules and inverters, use of different solar cell and module technologies etc. It further emphasizes that a regular monitoring of PR range could be useful in fault detection and taking appropriate actions to rectify the system faults.

3.2.7. Definition used by Kymakis et al. [20]

This definition is based upon the monitoring experiences of performance of PV plants presented in the paper, "Performance analysis of a grid connected Photovoltaic Park on the Island of Crete" in Greece [20]. For analyzing the PV system performance, the authors have used the standard definitions of the final yield, reference yield and performance ratio and the capacity factor as defined in the standard IEC 61724 [25]. The paper has also defined PR as a product of various loss factors (such as panel degradation, temperature, soiling, inverter etc.) as shown in Eq. (49). We have focused on this later definition of PR only. Thus, the PR as a product of various losses resulting from the PV system till the energy is finally exported to the grid can be represented in form of following equation:

$$PR = Y_F/Y_R = \eta_{deg} \cdot \eta_{tem} \cdot \eta_{soil} \cdot \eta_{net} \cdot \eta_{inv} \cdot \eta_{tran} \cdot \eta_{ppc} \tag{49}$$

where, η signifies respective efficiencies due to module degradation, soiling, DC wiring and interconnection losses, inverter losses, transmission losses, and availability and grid connection losses.

The authors have used the following methodology for analytically evaluating different losses presented in the Eq. (49)

(reproduced from [20]):

> The in-plane solar radiation, the ambient daytime temperature, the array DC power and the park AC output power are averaged with a 10 min frequency during a typical day per month. The nominal instantaneous array DC power per 10 min and the total array annual output energy are calculated using the solar radiation data and the technical specifications of the photovoltaic panels used. Then, the real array output power is simulated gradually by adding the various losses of the array such as the degradation modulus, the temperature and the soiling losses. Similar method is employed for calculation of the interconnection, inverter and transformer losses by correlating the real array power output with the PV park power output with a 10 min frequency.

The temperature losses coefficient (η_{tem}) and PV cell temperature (T_c) is obtained by using the following equations:

$$\eta_{tem} = 1 + \beta(T_c - 25) \tag{50}$$

$$T_c = T_a + \frac{G}{G_{NOCT}}(T_{NOCT} - 20) = T_a + \frac{G}{800}(T_{NOCT} - 20) \tag{51}$$

where, β is the temperature coefficient of the panel, T_c is PV cell temperature, T_a is the air temperature and NOCT is the nominal operating cell temperature and G is the power density at a particular time.

The losses due to soiling (η_{soil}), the monthly coefficients were empirically estimated based on the PVUSA study and the rainfall data of the site [20]. It is presented that soiling typically depends upon the type of dust, time gap between the two rainfalls, and the cleaning maintenance system. It was also find that soiling was more in summer months as compared to winter months.

The PV panel degradation losses ($\eta_{\deg}$) is based upon a quantified mismatch the analytically calculated array power output compared with real recorded output power. The quantification is also validated based upon experimental studies and the declarations and warranties cited by the manufacturers.

The inverter (DC to AC) conversion losses were calculated with a 10 min frequency by subtracting the array DC output power from the AC output power and by normalizing the DC wiring and interconnection losses (η_{net}) and the transformer losses (η_{tr}). Now, inverter losses (η_{inv}) are estimated.

Lastly, the monthly availability and the grid connection losses (η_{ppc}) are calculated as the ratio of the sold energy to the public power corporation, Greece (PPC) divided by the overall AC output energy of the park.

3.2.8. *Definition used by Ransom et al. [21]*

The PR definition is based on the paper, “How kW h/kWp modeling and measurement comparisons depend on uncertainty and variability” [21]. The main argument of the paper is to question the accuracy of the predicted yield by the simulation programmes as compared to the actual yield which depends upon several factors. The final yield is defined by incorporating different uncertainty functions in the AC kW h produced per year and the nominal power rating of the system. The paper has presented variability and uncertainty of final yield determining effects such as soiling, dirt, shading in a tabular form referring various literature and research. The reference yield (YR) issues and dependencies have not been discussed in this paper.

Final energy yield (YF) is defined as per the IEC 61724 standard [25]. AC kW h and nominal power rating of the system is based upon the actual ground conditions and variability factors, and are calculated by using the following equations:

$$\mathrm{YF} = \frac{\mathrm{kWh_{AC}}}{\mathrm{kW_P}} \tag{52}$$

$$\mathrm{kWh_{AC}} = \mathrm{kWh_{AC.OPTIMAL}} \times \left(\frac{\text{insolation yearly}}{\text{insolation nominal}}\right) \times \mathrm{f_{DOWNTOWN}} \times \mathrm{f_{DEGRADATION}} \times \mathrm{f_{DIRT}} \times \mathrm{f_{SEASONAL}} \times \mathrm{f_{SHADING}} \times \mathrm{f_{BOS}} \tag{53}$$

$$\mathrm{kW_P} = \mathrm{kW_{P.ACTUAL}} \times \mathrm{f_{REFERENCE.MODULE.CALIBRATION}} \times \mathrm{f_{FLASH.TEST.UNCERTAINTY}} \times \mathrm{f_{MODULE.BINNING}} \times \mathrm{f_{MANUFACTURER.DECLARATION}} \tag{54}$$

Eq. (53) clearly reflects the dependence of AC kW h upon the insolation (normalized) of the place, downtime correction, and other uncertainty functions such as dirt, shading effects, seasonal variations and BOS issues. Similarly, Eq. (54) shows that in actual conditions, the $\mathrm{KW_P}$ will incorporate uncertainties resulting from reference module calibration, flash test uncertainties, effects due to module binning, and lifetime module power guarantee claims by the manufacturer. Variability and uncertainty of some final energy yield determining effects is presented in Table 2. Further, detailed discussion about these uncertainties factors and their variability dependence could be found in the actual paper [21].

The reference yield (YR) can now be estimated with the standard IEC 61724 [25]. It is defined as the ratio of the total in-plane insolation to that of reference irradiance (=1 kW/m^2 at STC).

So, the Performance Ratio (PR) of the system in actual conditions can be estimated as the ratio of the actual final yield to that of the reference yield of the system.

$$\mathrm{PR} = \frac{\mathrm{YF}}{\mathrm{YR}} = \frac{\mathrm{kWh_{AC}/kW_P}}{\mathrm{YR}} \tag{55}$$

After, putting values of $\mathrm{kWh_{AC}}$ and $\mathrm{kWh_P}$ from Eqs. (53) and (54) we get the PR value in actual conditions as represented below.

$$= \frac{\mathrm{kWh_{AC,OPTIMAL}} \cdot \left(\frac{\text{Insolation yearly}}{\text{Insolation nominal}}\right) \cdot \mathrm{f_{DOWNTIME}} \cdot \mathrm{f_{DEGRADATION}} \cdot \mathrm{f_{SEASONAL}} \cdot \mathrm{f_{DIRT}} \cdot \mathrm{f_{SHADING}} \cdot \mathrm{f_{BOS}}}{(\mathrm{kW_{P,ACTUAL}} \cdot \mathrm{f_{REFERENCE\ MODULECALIBRATION}} \cdot \mathrm{f_{FLASHTEST}} \cdot \mathrm{f_{MODULEBINNING}} \cdot \mathrm{f_{MANUFACTRER\ DECLERATION}}) \cdot \mathrm{YR}}$$

All the abbreviations have usual meanings as detailed in Eqs. (52)–(55).

3.2.9. *PR-FACT mack and decker GmbH in-house methodology [30]*

PR-FACT was originally developed as an in-house method by Mack and Decker in 2006 depending upon the need and demand by their client's to account for all the system losses as precisely as possible. Since, 2006 the methodology has continuously evolved from version 1.0 to version 5.0 in 2013 after incorporating several well established models and continuously testing and checking the validity of the results.

The methodology works with 15 min or hourly time series data and in general calculates diffuse horizontal irradiation ($\mathrm{D_{hor}}$), direct normal beam irradiation ($\mathrm{B_n}$) and global reflected irradiation (ev) values from the global horizontal irradiation ($\mathrm{G_{hor}}$) by using appropriate models and popular equations with further input data.

PR-FACT has specified the following technical input data information about the layout and components [30].

3.2.9.1. Layout specific input information. Some of the specific input information required includes the PV module inclination and orientation or type of tracking (including special tracking modes, e.g. back-tracking); array dimension; and details about DC and AC connections. It also seeks knowledge about average voltage drop or power loss on DC and AC wiring, and the distance between the module racks or the tracking system.

Table 2
Variability and uncertainty of some (YF) kW h/kWp determining effects. Source: Ransom et al. [21].

Parameter	Variability and uncertainty
Insolation YR(KWh/m^2/y)	Yearly Site insolation variability (± 4%? NREL); microclimatic differences vs nearest measurement site; Ground albedo; Reference sensor calibration (± 2% typical); reference sensor type and stability (± 0.5–1%/y); Tilted plane calculations (rely on modeled diffuse factor and anisotropic sky distribution)
Effective Plane of Array	Yearly Site insolation variability (± 4%? NREL); microclimatic differences vs nearest measurement site; Ground albedo; Reference sensor calibration (± 2% typical); reference sensor type and stability (± 0.5–1%/y); Tilted plane calculations (rely on modeled diffuse factor and anisotropic sky distribution)
PV Performance	Module Pmax actual/nominal; Loss of output power (various dc failure mechanism); Reference module calibration factor (> ± 2.5%?); Seasonal thermal annealing (e.g thin films < ± 5%?); AOI and spectral response difference vs reference cells; Multi-junction matching (red, blue or green limited); Correlation between different weather parameters; Corrections needed for bad or missing data; Changes of time with PMAX, ISC , VOC, FF, RSH (low light efficiency change), RS (high I2R losses)
Shading	Near shading varies across arrays due to trees, lamp-posts etc, self-shading stops direct irradiance on some parts of the module, Horizontal shading affects whole array but only at certain times, PMAX vs shading depends on sun position , beam fraction, by-pass diode, string arrangements etc
Cell Temperature	Varies across large array with wind direction (upwind may be coolest) and across module (e.g hotter where junction box/mounting structure is behind the cell); NOCT dependency vs standoff; temperature depends on wind direction
Dirt/Soiling	How to estimate average value? ; amount depends on pollen pollution etc; Composition of dirt determines wash-off rates; dirt accumulation rate may change (if ARC); Depends on tilt angle and frame type (run off); random rain has less dirt loss than seasonal
Stringing	Depends on lowest current module; Are modules sorted by current or not?
Inverter Performance	Inverter efficiency varies with PIN, VIN; AC measurement accuracy ± 0.5%?; MPPT of common strings of varying performances

3.2.9.2. Component specific input information. It is suggested that all the electrical parameters of the PV modules (such as nominal power etc.) should be tested at the STC and the corresponding data for all PV modules installed should meet flash test measurement depending upon availability. Temperature coefficient of power, open-circuit voltage and short-circuit current; Irradiance performance data; DC and AC limits of the inverter; MPP tracking efficiency and conversion efficiency for minimum, nominal and maximum MPP voltage levels of the inverter and temperature derating specifications should be known.

PR-FACT presents the performance ratio as a product of several correction factors represented as f-x as shown below.

$$PR = fo \times f1 \times f2 \ldots f10 \tag{56}$$

where, f0, f1, f2…f10 are correction factors accounting various parameters affecting the performance or the electric yield.

The calculation of the correction factors is divided into seven steps focusing on plane of angle (POA) irradiation (f0, $f1_{hor}$, $f1_{mut}$); shading (f2 and f3); PV module (f3 and f4); PV module configuration and DC wiring ($f5_a$, $f5_b$, $f5_c$, and f6); inverter (f7, f8, $f8_{aux}$, and $f8_{temp}$); AC wiring and transformer ($f8_{ac}$, $f9_{trans}$, $f9_{ac}$, and $f10_{trans}$); and additional calculation steps such as those incorporating snow coverage, soiling, and reduced availability etc. Individual correction factors, explanation and its reference or calculation methodology are summarized in Table 3 as under.

3.2.10. Weather-corrected performance ratio methodology: NREL/TP-5200-57991 [19]

The NREL/TP-5200-57991 report [33] has presented a weather corrected PR which would correct for most of the weather related effects. The temperature correction strategy is based upon the fact that modules normally operate at 45 °C and a correction to cell temperature at 25 °C would generally exceed the actual performance resulting in a higher PR, which is practically incorrect.

The proposed correction is limited to the variations that affect the module temperature (ambient temperature, wind, and irradiance). The methodology doesn't cover or incorporate effects pertaining to soiling, snow coverage or irradiance variations that affect the efficiency of the PV module. The authors agree that these corrections would provide more accurate and consistent results. The report serves three key purposes: firstly, it highlights the importance of using weather corrected PR as a mandated performance indicator; second, it proposes the methodology of using the weather corrected PR; and lastly, defines a sample test protocol that can be referenced in binding contractual agreements.

3.2.10.1. Assumptions and parameters. All the terminologies used to define the weather corrected PR are same as those used by IEC 61724 [25] except the additional term used to translate modeled power to the average operating cell temperature. Ambient wind and temperature effects are taken care by the operating cell temperature. Average annual cell temperature is calculated using the project weather files (e.g. the TMY file) and the operating cell temperature is calculated using the Sandia Model proposed by King et al. in 2004 [34]. The spectral variations are not taken into account as a matched reference cell to measure irradiance has been considered.

The methodology [33] compares the PR calculated traditionally with the temperature corrected PR. The PRs are defined as under:

$$PR = \frac{\sum_i EN_{AC\_i}}{\sum_i \left[P_{STC}\left(\frac{G_{POA\_i}}{G_{STC}}\right)\right]} \tag{57}$$

$$PR_{corr} = \frac{\sum_i EN_{AC\_i}}{\sum_i \left[P_{STC}\left(\frac{G_{POA\_i}}{G_{STC}}\right)\left(1 - \frac{\delta}{100}\left(T_{cell\_typ\_avg} - T_{cell\_i}\right)\right)\right]} \tag{58}$$

where:

The summations are over a defined period of time (days, weeks, months, years); PR is the performance ratio; PR_{corr} is the corrected performance ratio; EN_{AC} is the measured AC electrical generation (kW); PS_{TC} is the summation of installed modules' power rating from flash test data (kW); G_{POA} is the measured plane of array (POA) irradiance (kW/m^2); i is a given point in time; G_{STC} is irradiance at STC (1000 W/m^2); T_{cell}=cell temperature computed from measured meteorological data (°C); $T_{cell\_typ\_avg}$ is the average cell temperature computed from one year of weather data using the project weather file (°C) and δ is the temperature coefficient for power (%/°C, negative in sign) that corresponds to the installed modules.

The authors have tried to simulate an ideal system to differentiate between the normal PR and corrected PR and the result clearly indicates that the uncorrected PR, i.e. the normal PR presented in Eq. (57), reflects a change of 10% over the year. Fig. 3 shows the annual trend for an actual 24 MW facility. It could be

Table 3
PR-FACT correction factor terminology explanation (adopted from Eagler et al. [30]).

Correction Factor	Explanation/Representation	Model reference/calculation methodology
f0	– Represents the effect of the variation of the irradiation spectrum on the PV system – Depends upon the type of solar cell, location of the plant etc.	– No fixed model – NREL/TP-520–47277 report by Marion, B. et al may be referred
$f1_{hor}$	– Represents horizon shadowing effect – Irradiation impacted	– Fish-eye imagery and interpolation used for finding horizon line – Application of albedo method also possible – Hourly/15 min value
$f1_{mut}$	– Represents mutual shadowing effect on the PV modules	– comparing the irradiation reduced by shading with the unaffected irradiation
f2	– Represents influence of low incidence irradiation / reflection	– Ruiz and Martin (2002) – Hourly/15 min value
f3	– Represents low irradiance performance of the PV modules	– Product-specific efficiency curve experimentation reviewed by Mack and Decker GmbH themselves – Hourly/15 min value
f4	– Represents the effect of the module temperature on the electric energy output – Temperature rise depends upon the type of PV module mounting	– Temperature coefficient of the MPP power of the PV module considered – Hourly/15 min value
$f5_a$	– Represents the mismatch effect of the electrical parameters of the PV module	– Deist, Laschinski and Wagner(2006) – Hourly value
$f5_b$	– Represents changes in the electric energy output due to power tolerance	– Deviations of the actual power installed compared to the nominal power as stated in the datasheet
f6	– Represents annual DC wiring losses	– Average line voltage drop or power loss on the DC wiring at STC used – Equations referred from DIN EN 50,530 (2011) – Hourly/15 min value
f7	– Represents effect of inaccurate (static) MPP-Tracking of the inverter	– Assessing published test results or data specification sheets of inverter manufacturers
f8	– Represents voltage dependent influence of the DC/AC efficiency of the inverter	– Product specific evaluation – Data specification sheets from manufacturers used – Hourly/15 min value
$f8_{size}$	– Represents power limitation (sizing ratio) of the inverter	– Maximum DC input power and the AC nominal power of the inverter used – Reactive power factor may also be used on case to case basis – Hourly/15 min value
$f8_{aux}$	– Represents the auxiliary power of the inverter – Auxiliary power varies proportionately to the change in AC power	– Peak values for auxiliary power are reached at maximum ac power of the inverter assumed – Hourly/15 min value
$f8_{temp}$	– Represents effects due to temperature de-rating of the inverter	– Data specification sheets from manufacturers used – Difference between de-rated and non-de-rated power considered – Hourly/15 min value
$f8_{ac}$	– Represents annual power losses due to AC low voltage wiring	– Average power loss on AC low voltage wiring at rated power used – Variation of the AC output power of the inverter relative to its nominal value. – Hourly/15 min value
$f9_{trans}$	– Represents effects arising from low voltage to medium voltage transformation	– Uses average power loss on AC medium voltage wiring at rated power – Variation of the AC output power of the low voltage to medium voltage transformer relative to its nominal value applied – Hourly/15 min value
$f9_{ac}$	– Represents annual power losses on AC medium voltage wiring	– Uses the average power loss on AC medium voltage wiring at rated power – The variation of the AC output power of the low voltage to medium voltage transformer relative to its nominal value applied – Hourly/15 min value
$f10_{trans}$	– Represents effects arising from medium voltage to high voltage transformation	– State-of-the-art equations – Rated power as well as load and no-load losses of the transformer considered – Hourly/15 min value
$f10_{ac}$	– Represents annual power losses on AC high voltage wiring	– Average power loss on AC high voltage wiring at rated power used – The variation of the AC output power of the medium voltage to high voltage transformer relative to its nominal value applied – Hourly/15 min value

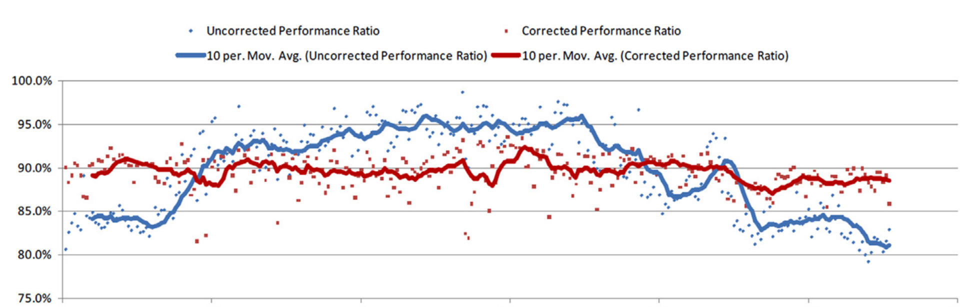

Fig. 3. Weather corrected and uncorrected, annual trend for a 24 MW facility (Source: NREL [33]).

Table 4
Recording interval and monitoring period for the PV system data (Source: Copper et al. [29]).

Use no.	Use of measured PV data	Monitoring interval	Monitoring period
1	Performance assessment of PV technologies under outdoor conditions	15 min max.	Min 1 year
2	Performance diagnostics	Hourly	System Lifetime
3	Degradation and uncertainty analysis with time	Hourly	Min 3–5 years
4	Understanding/improving system losses via comparisons to modeled performance data	Hourly	Min 1 year
5	Forecasting PV performance	[a]5 min, 30 min or hourly	Min 1 year
6	Interaction of PV systems with the electricity network	[a]1 to 15 min	Min 1 week
7	Integration of distributed generation and load control	[a]1 to 15 min	Min 1 week

[a] Recording interval depends upon the particular application.

clearly seen that weather corrected PR is more consistent and stable throughout the year. The report recommends using the weather-corrected calculation and the mutually agreed-upon project weather file if the PR is to be used for a contract guarantee [19]. Extending this further, the authors have also cited examples of cases such as grid unavailability, inverter clipping during high irradiance when the PR would be affected or wrongly penalized. Reactive power requirements have not been considered in this work.

According to the report [33] plant acceptance test under the proposed test protocol is 5 days long and each data is averaged into 15 min record. The report has also provided minimum irradiance and instrumentation criteria. For details please refer to Appendix C.

3.2.11. *Australian PV system monitoring guideline version 1.0 methodology [29]*

The Australian PV System Monitoring guidelines are primarily developed with reference to the IEC 61724 Standard and the European Commission's 6th Framework Programme: Monitoring guidelines for photovoltaic systems, adapted to the local Australian conditions [29].

The guideline defines PR as ratio of the final yield (Y_f) to the reference yield (Y_r). It also defines PR as a terminology that indicates the overall effect of losses on the array's rated output due to array temperature, incomplete utilization of the irradiation and the system component inefficiencies or failures.

$$PR = \frac{Y_f}{Y_r} \tag{59}$$

where, yields are defined as follows:

The array yield (Y_A) is the energy output of the PV array (EA) per kW of installed capacity.

$$Y_A = \frac{E_A}{P_O} \tag{60}$$

where, P_0 is the rated output power of the array under standard test conditions.

The final yield (Y_f) is the net energy output of the entire PV system (E_{out}) expressed per kWh/kW of installed capacity over the reporting period. The reporting period should be recorded with the yield to avoid misinterpretation of the figures.

$$Y_f = \frac{E_{out}}{P_O} \tag{61}$$

The reference yield (Y_r) can be calculated by dividing the total daily in-plane irradiation by the module's reference in-plane irradiance G_{ref} (kW/m^2), where G_{ref}=1 kW/m^2. For a reporting interval of 24 h, Y_r is effectively the number of peak sun-hours per day. In other words, it is the equivalent number of hours per day of irradiance of 1 kW/m^2 required to meet the actual irradiation.

$$Y_r = \frac{H}{G_{ref}} \tag{62}$$

Further, two normalized losses; the array capture losses (Lc) and the balance of system losses (L_{BOS}) are calculated as per the IEC 61724 method once the yields are known using standard equations.

On application front, the guideline lists seven important uses of the monitored data. The first three include the performance assessment of PV technologies in outdoor conditions, performance diagnostics, time bound degradation and uncertainty analysis. The other three uses focus on PV system interaction with electricity network, forecasting PV performance, integrating distributed generation, storage, and load controls. The last application deals with understanding or reducing system losses with reference to modeled performance data.

The guideline follows the European performance monitoring guidelines for PV systems [6] limits for minima or maxima values/typical range for various parameters such as irradiance, temperature, array voltage and current etc. The parameters to be measured and sensor accuracy presented are in tune with the IEC 61724 Standard [25]. List of parameters and type of measurement devices, ranked by budget and analysis option are based on the analysis of Emery, et al. [33].

The recording and monitoring interval recommended by the guideline based on the list of 7 typical uses of PV data mentioned earlier is presented in Table 4. In case the applicability of the PV system data is unknown, the guideline recommends a recording interval of 5 min over the system's lifetime.

Table 5 and Table 6 present the summary of the selected references. Table 5 compares different PR calculation methods in terms of: definition; presence of any recommended PR range; suggested monitoring or averaging intervals for different parameters; presence of any issue/limitation; and any suggested recommendation. Table 6 shows the PR formula used by all the selected references. It can be easily observed that out of the 11 references, four (IEA PVPS TASK 2 Methodology – 2001; NREL/CP-520-37358 report [7]; EU PERFORMANCE Project [6] and Australian PV System Monitoring Guideline [29]) use the standard equation used by IEC 61724 to define the PR. Three references namely Haeberlin et al. [22]; Kymakis et al. [20] and Ransom et al. [21] have presented the PR in two ways: one, as defined by IEC 61724 and second, a new definition using correction factors, inefficiencies and uncertainty functions respectively. NREL/TP-5200-57991 report [19] also uses the basic PR definition but has presented it with temperature correction. PR-FACT Mack and Decker GmbH methodology [30] have defined the PR using different correction factors. SMA has defined the PR in terms of the actual reading of the plant output and nominal output of the plant.

Table 5
Comparison and summary between different PR methodologies and definitions.

Guideline/Paper/ Methodology/ Report	PR definition	New parameters /factors Introduced in/with PR calculation	PR Range Indication/ Application	Monitoring &/averaging/ Sampling interval for plant Parameters	Any Issue/ Limitations	Any specific recommendation/ Comment
SMA	Ratio of actual plant o/p to that of calculated nominal plant o/p	Generator PV area	– High performance plant touch PR ~ 0.8 – There exists a PR range indicative of fault in the plant	5, 10 or 15 min for daily avg irradiation	– Deviating conditions in real operating conditions influence the performance ratio (e.g. environmental factors)	– Optimum period for PR calculation is 1 year – A minimum analysis period of 1 month should be selected to ensure that ambient conditions such as low solar elevations, low temperatures and shadows falling on the PV modules and/or measuring gage do not strongly influence the calculation
Haeberlin et al. [22]	As per IEC 61724 with modification in Yf and Yr definitions	Temperature and generation correction factors used	–	–	–	–
IEC 61724 [25]	Ratio of Yf/Yr, standard definition	Monitoring fraction (MF) used	–	Sampling interval of 1 min or less. For longer time constant parameters (1–10 min)	Issue with system definition (e.g. definition of E_{USE})	–
IEA PVPS TASK 2 [2001]	As per IEC 61724 and the European Guidelines	Usage factor (UF), Production factor (PF) and outage fraction (O)	Mean PR – 0.65 (1983–1995) – 0.70 (1996–2002) – Average PR till 2004 is 0.68	– Hourly means recording	– Applying IEC 61724 to Stand Alone Systems would give higher PR as compared to European Guidelines because of different meaning of the term E_{USE} – There is weakness in definition of E_{USE}, E_{in}, and E_{FA} by IEC 61724 and the European Guidelines for few cases (e.g. inverter efficiency has no effect on the PR when EFU > EA)	– IEC 61724 and European Guidelines do not distinguish between the good results and the bad results due to poor sizing/ technical problems
NREL/CP-520-37358 [7]	As per IEC 61724	–	– (0.6–0.8) – PR indicative of problem but not cause	–	– There is a need to verify the derate factors	– PR values typically reported on monthly or yearly basis, smaller reporting periods helpful in identifying occurrences of component failure – PVUSA rating method may be used to assign an a.c. rating to an existing system with historical data
EU Project PERFORMANCE [6]	As per IEC 61724	Monitoring fraction (MF) used in calculating various derived parameters	– A good PR ranges b/w (0.8–0.85) – PR < 0.75 indicative of problem	– Sampling interval for current/voltage quantities to be 1 min or less	– Low value of PR at the beginning and end of the day due to low light levels and resulting problems should be investigated (e.g. inverter drop out, monitoring system problem etc.)	– Seasonal variation of PR should be taken care of – Reference site is within 25 kms of the PV system site – Same reference device for site and lab measurements – Guarantee of performance should define the min PR at different times in operating life – System performance should be assesses in the 1st year and assessment interval to be no more than 1 month
Kymakis et al. [20]	As per IEC 61724 and also as product of typical PV Plant Loss factors	Loss factors included soiling, temperature effects, degradation, inverter failure, grid connection, system availability etc.	0.58–0.73 with avg. value to be 67.36	Solar radiation, ambient temp, DC power, system AC o/p avg with 10 min frequency in a typical day/ month	–	Dirt and dust coefficients based on PVUSA study

Table 5 (*continued*)

Guideline/Paper/ Methodology/ Report	PR definition	New parameters /factors Introduced in/with PR calculation	PR Range Indication/ Application	Monitoring &/averaging/ Sampling interval for plant Parameters	Any Issue/ Limitations	Any specific recommendation/ Comment
Ransom et al. [21]	Final yield as per IEC 61724 and also as product of uncertainty functions	Uncertainty functions defined for kWh_{AC} – downtime, degradation, seasonal effects, dirt, BOS and for kW_{P} – module calibration & binning, flash test, & manufacturer declaration	–	–	– The indoor matrix of measurements in IEC 61853-1 only uses all direct light at 0° AOI and AM1.5, which is not found in the field – Blue fraction and air mass depending upon whether spectrum mismatch exist for the site or not	– Reference cell with the smallest spectral mismatch to be used for thin film
PR-FACT Mack & Decker [30]	As a product of several correction factors affecting performance/ yield	7 factors affecting POA irradiation, shading, PV module, inverter, DC & AC wiring and transformer etc	–	Hourly or 15 min values	Measurement and meteorological uncertainties can never be fully avoided	– Contribution from several models and approaches used to define the 7 factors – A more detailed characterization of the PV modules at low irradiance levels and product-specific information on the reflection properties may substantially improve the methodology
NREL/TP-5200-57991 [19]	As per IEC 61724 with temperature correction	Additional term used to translate modeled power to the average operating cell temperature	0.6–0.9 and can even exceed 0.9	Collected data averaged into 15 min record	Correction limited to variations that affect module temperature. Soiling, snow coverage, irradiance coverage not addressed	– Spectral variation not considered as matched reference cell used for irradiance measurement – For contract guarantees weather corrected calculation and mutually agreed project weather files should be used – Seasonal variation in PR due to temperature effects could be ± 10%
Australian PV System Monitoring Guideline V 1.0 [29]	As per IEC 61724	–	Figures based on EU project PERFORMANCE guidelines	– Monitoring period of min 1 year – Recording interval of 15 min/hourly, 1 min/ 5 min and 30 min also reported for some use of measured PV data – Max sampling interval for averaged parameters to be 1 s, for some cases lower interval could also be set	Adopted to Australian conditions	– Defines 7 uses of PV performance & reliability data – Refers to several models (e.g SANDIA, Maxwell Disc model etc)

Table 6
PR formula used by the selected references.

Reference	PR formula used	Abbreviations
Haeberlin et al. [22]	$PR = Y_f/Y_r = K_T \times K_G \times n_j$	PR – performance ratio; Y_f – final yield; Y_r – reference yield; K_T – temperature correction factor; K_G – generation correction factor and n_j – inverter efficiency of the PV plant
IEC 61724	$R_P = \frac{Y_f}{Y_r}$	R_P – performance ratio; Y_f – final yield and Y_r – reference yield of the PV plant
IEA PVPS TASK 2 Methodology [2001]	$PR = Y_f/Y_r$	PR – performance ratio; Y_f – final yield and Y_r – reference yield of the PV plant
NREL/CP-520-37358 [7]	$PR = Y_f/Y_r$	PR – performance ratio; Y_f – final yield and Y_r – reference yield of the PV plant
EU PERFORMANCE Project [6]	$PR = Y_f/Y_r$	PR – performance ratio; Y_f – final yield and Y_r – reference yield of the PV plant
SMA Methodology	$PR = \frac{\text{Actual reading of the plant output in kWh p.a}}{\text{Nominal plant output in kWh p}\cdot\text{a}}$; Nominal Plant output = Annual incident solar radiation $\times\ \eta_{rel}$ of the PV modules	PR – performance ratio of the PV plant
Kymakis et al. [20]	$PR = Y_F/Y_R = \eta_{deg}\cdot\ \eta_{tem}\cdot\ \eta_{soil}\cdot\ \eta_{net}\cdot\ \eta_{inv}\cdot\ \eta_{tran}\cdot\ \eta_{ppc}$	PR – performance ratio; Yf –- final yield and Yr – reference yield of the PV plant; η_{deg} – panel degradation loss; η_{tem} – temperature loss; η_{soil} – soiling loss; η_{net} – DC wiring and interconnection loss; η_{inv} – inverter loss; η_{tran} – transmission loss; η_{ppc} – availability and grid connection loss of the PV plant
Ransom et al. [21]	$PR = \frac{YF}{YR} = \frac{kWh_{AC}/kW_P}{YR}$ $kWh_{AC} = kWh_{AC.OPTIMAL} \times \left(\frac{\textit{insolation yearly}}{\textit{insolation nominal}}\right) \times f_{DOWNTOWN} \times f_{DEGRADATION} \times f_{DIRT} \times f_{SEASONAL} \times f_{SHADING} \times f_{BOS}$ $kW_P = kW_{P.ACTUAL} \times f_{REFERENCE.MODULE.CALIBRATION} \times f_{FLASH.TEST.UNCERTAINTY} \times f_{MODULE.BINNING} \times f_{MANUFACTURER.DECLARATION}$	PR – performance ratio; Yf – final yield; Yr – reference yield; f – uncertainty function due to downtime, panel degradation, soiling, seasonal change, shading, balance of system effects, reference module calibration, flash effect, module binning and manufacturer declaration of the PV plant.
PR-FACT Mack and Decker GmbH [30]	$PR = fo \times f1 \times f2 \ldots f10$	fo,f1, f2…f10 are correction factors related to: f1 and f2 – plane of angle irradiation; f2 and f3 – shading; f3 and f4 – PV module; f5 and f6 – PV module configuration and DC wiring; f8, f9 and f10 – AC wiring and transformer of the PV plant.
NREL/TP-5200-57991 [19]	$PR_{corr} = \frac{\Sigma_i EN_{AC\_i}}{\Sigma_i\left[P_{STC}\left(\frac{G_{POA\_i}}{G_{STC}}\right)\left(1-\frac{\delta}{100}\left(T_{cell\_typ\_avg}-T_{cell\_i}\right)\right)\right]}$	PR_{corr} – weather corrected performance ratio; EN_{AC} – measured AC electrical generation; PS_{TC} – summation of installed modules' power rating from flash test data; G_{POA} – measured plane of array irradiance; G_{STC} – irradiance at STC; T_{cell} – computed cell temperature; $T_{cell\_typ\_avg}$ – average cell temperature and δ – temperature coefficient of power of the module of the PV plant
Australian PV System Monitoring Guideline [29]	$PR = Y_f/Y_r$	PR – performance ratio; Y_f – final yield and Y_r – reference yield of the PV plant

*Note: All the parameters are in their standard units.

3.3. Important issues over the definition of performance ratio of a PV plant

There are several factors on which the PR of a PV plant depends. Real time monitoring of these parameters is very important for accurately measuring the PR. Additionally, the monitored PR value also helps to identify and correct several faults and system failures. In the following section we have presented few important issues frequently discussed over the PR definition. These issues are:

i. Ambiguity over the reference yield (Y_f) definition at Standard Test Conditions (STC).
ii. Use of pyranometer or reference cells for irradiance measurements.
iii. PR calculation for shorter term or system comparison in different climates
iv. Availability factor of PV plants

3.3.1. Ambiguity over the reference yield (Y_f) at Standard Test Conditions (STC)

The reference yield is defined as the ratio of PV's total in-plane irradiation to that of PV's reference irradiance at [Irradiance G = 1000 W/m^2, cell temperature T = 25 °C and AM 1.5]. The performance of the PV modules is generally measured indoors in a lab or facility at the STC conditions. But, in real outdoor conditions due to seasonal variation, degradation, spectral variation etc., the AM changes as compared to standard values at the STC.

Literature suggests that spectral and seasonal response of different PV technologies is varying and this variation can be significant even on a day to day basis. For example, the spectral response of a-Si and c-Si typically lies in the range of 300–780 nm and 300–1100 nm respectively. Several field experiments at NREL and SANDIA have showcased that PV module do not meet their name-plate power rating under actual operating conditions. As response of different PV technologies is different, there is also need for devising separate standards for different solar technologies. The IEC 60904 standards which are reference standards for calibration of cells and modules are primarily focused upon crystalline silicon [35]. Seifert et al. [35] argue that the application of IEC 60904 over thin film or other solar devices may not be valid because the material properties are much different. Findings from Nann and Emery [36] state that, compared to crystalline-si cells (band gap = 1.1 eV), linearity in temperature and irradiance response is not valid for most of the thin film devices and the spectral sensitivity of the higher band gap devices like amorphous silicon (band gap = 1.75 eV), CdTe(band gap = 1.5 eV) or GaAs (band gap = 1.43 eV) is more pronounced. One of the publications by Ishii et al. [37] suggests that a PV module should be rated on the basis of total annual power output in each location.

So, it can be seen that the actual effect on the PV modules under real life condition is a big question and using STC irradiance as 1000 W/m^2 is not beyond criticism. This indirectly also questions the reliability of the reference yield (Y_f) values of the PV plant.

3.3.2. Use of pyranometer or reference cells for irradiance measurements

Universally, irradiance measurements are done using either a reference cell which is based on Photoelectric Effect or using a pyranometer which is based upon the 'Thermopile Effect'. It is often debated which of these two gives better results or which should be a reference for bankability of projects. Several studies [33,38–40] have presented different accuracies and error limits for the two measuring devices. But, the universal acceptability as a defacto standard for outdoor measurement goes in favor of pyranometers [25,36,39,45,46]. The IEC and ASTM standards allow use of reference cells under severe restrictions. California ISO does not allow the use of reference cells at all. Some studies like [31] have suggested modifications such as use of filters while using thin film or a-si materials.

One of the biggest advantages of pyranometer over the reference cells is its ability to measure the total spectrum over a broader wavelength range and present integrated measurement of the total short-wave solar energy available under all conditions. This is an important issue because different PV technologies such as CIS, a-si, thin film CdTe etc. spectrally behave differently in actual conditions when the air mass, dust, humidity etc. vary significantly throughout the day. Another issue with these technologies is that no long-term stable irradiation sensors exist for CIS, amorphous silicon and CdTe. In case of amorphous silicon (single junction), a silicon based sensor with a filter glass can be used as it has a similar spectral response [31].

The fundamental reason for preferring pyranometer is that reference cells generally over-estimate daily system efficiency and undermine uncertainties in measurement which couldn't be easily quantified [31,46]. Other important advantage of pyranometers is their special dome like shape which prevents them from dirt accumulation and having small directional errors as compared to reference cells when the originating irradiance has large Angle of Incidence (AOI) [30,31]. On an average, the annual irradiation measured by crystalline silicon sensors is 2–4% less than the irradiation measured by pyranometers [31]. But again, the applicability of reference cells cannot be ignored as they are more economical and could accurately measure very abrupt irradiance intensity changes which could actually be used for checking PV system's normal functioning and system failures. In one of the recent studies by [47], the authors have argued that the quantity of interest in monitoring a PV power plant is the equivalent irradiance under the IEC 60904-3 reference solar spectrum that would produce the same electrical response in the PV array as the incident solar radiation. For PV-plant monitoring applications, they found that the uncertainties in irradiance measurements of this type to be on the order of $\pm 5\%$ for thermopile pyranometers and $\pm 2.4\%$ for PV reference devices [50].

It is can be easily inferred from the above research findings and examples that the pyranometer in general, is the preferred tool criteria for accessing the bankability of PV projects in outdoor conditions, whereas, for indoor testing and PV system normal functioning over short intervals, reference cells are preferred. For accurate measurements it is suggested that the calibration procedures, environmental and measurement conditions should be checked and monitored regularly.

3.3.3. PR calculation for shorter term or system comparison in different climates

PR is a standard performance parameter used for detecting even a minor issue in a PV system [35]. It has also been shown from several studies [18,19,21,31,33,35] that PR of a PV plant is dependent on several factors such as soiling, dirt, BOS, temperature, snowing etc. The standard definition of PR (used by IEC and NREL) serves as a benchmark for investors and plant personnel. They prefer PR for an annualized (or long term) comparison of plants as compared to shorter term or seasonal variations because the reliability of PR as a tool for short term becomes weaker [19]. The long term and short term issue has been nicely presented in report [44] which evaluated two similar systems in CA using PVWATTS to represent an actual system, a 100 kW system in San Francisco with latitude tilt had a calculated PR of 0.73 with an output of 145,000 kWh/year, while a 100 kW system in Daggett with latitude tilt had a PR of 0.69 with an output of 171,000 kWh/year. So, it is clearly evident that even if the PR of the Daggett plant is lower than the PR of the plant at San Francisco, the performance of Daggatt plant is better.

Estimating impact of all the factors on the PR accurately and at shorter intervals such as hourly, daily, or weekly is a tedious task and is almost impractical. Recommendations in [44] suggests that.

> "…if compensation other than temperature is desired, it is more practical to calculate Long-Term Energy Performance Index (EPI) using actual irradiation and temperature in one of the accepted models, such as SAM or regression model. On the other hand, if the purpose of the assessment is only to evaluate a specific system, trend analysis using a temperature compensated PR is reasonable because it is not influenced by the accuracy and/or uncertainty of a PV model."

3.3.4. Availability of PV plants

Availability (AL) in general is defined as the ratio between actual production and expected production. The expected production is actual production plus lost production. These production values are measured by the real time monitoring of the PV system.

Availability of the PV plants can be of two types: the plant availability (due to problems within the plant, e.g. inverter failure, mismatch, panel burnouts, line failure etc.) and the grid availability (due to unavailability of the grid though the plant is ready to feed and is healthy).

IEA PVPS task 2 experiments while monitoring PV systems in several countries by 2004-05 reported a system availability of around 94% for all systems. In one of the experiments conducted by researchers on 202 PV systems at ITRI [8], it was found that there is very good dependence between PV operational performance and system availability and the system availability for the considered plants was 95.7%. In general, a higher PR of the plant would reflect better system availability but there were also some differing results reported from the same study which stated that when the system availability value was equal to 1, the PR values still distribute within a big range from 0.43 to 1.0 which indicated that except for availability, there are other parameters as well such as inverter efficiency, shading condition, array orientation and module temperature which will have an impact on the PR value [8]. In present times because of better monitoring and improved systems, plant availability above 99% could also be found around the globe. Such a high availability is assumed to be good system availability.

Grid availability issue is a common problem across the globe, more pronounced in the developing countries which want to vastly expand their grid infrastructure to meet the increasing demand. For example, in India, there are several grid availability issues being reported across the country. The state of Tamil Nadu in

India which is having the highest installed wind capacity in the country is constantly facing the grid availability issue.

Availability is one of the important parameters utilized for judging a system performance. There are some issues which need to be addressed to get better and accurate insights about the availability of the PV system. For example, the reference period for availability needs to be defined. If there is problem due to plant availability, say inverter was not operational for two days in a month then one should ignore these two days for PR calculation. The Performance Ratio (PR) will go down as the yield will be low. Moreover, in case of non-grid availability, say that grid is not available for 2 h out of its normal 12 h feed to the grid then the PR should be calculated for 10 h only. Experts also suggest that while making an availability guarantee in project bankability bids certain causes of plant failure such as accident, earth quake, transport restrictions, events leading to disruption of the use of monitoring system etc. should be excluded.

3.4. Sticking to PR as the main performance indicator

PR is one of the main performance indicators and a simple tool used globally to broadly assess the overall plant performance. PR has been used as one of the main performance indicators by several institutions, international projects and experiments such as NREL, the IEA PVPS Task Experiment, PERFORMANCE project of the European Union etc. One of the advantages of using PR is that the expected performance is not calculated, therefore, a PV computer model is not needed and the inaccuracies and uncertainty introduced by the model and the derate-factor assumptions are avoided [44]. Following points further strengthen the candidature of PR as one of the main performance indicator.

I. PR better captures the performance of a grid PV plant as compared to the CUF of a grid PV plant. It is not the most accurate performance indicator and also suffers errors and uncertainties in measurement. For e.g., there are many uncertainties which pose difficulty in predicting very accurate energy yields ($<4\%$ kW h/kWp) for every location and module type [39]. Studies [30,39] have reported yearly insolation variability to be nearly $\pm 4\%$. The uncertainty in irradiation measurements using pyranometer and a reference cell is almost unavoidable. Different values ranging between 2% and 10% have been reported by [38,39,41] for expected daily uncertainties and an overall instantaneous irradiance measurement using different, standard or different class pyranometers. Results from PV plant studies [30,42,43] reflect that the annual PR of a PV plant in Germany calculated on the basis of crystalline silicon sensors may be on an average 2–4% higher than the PR based on a pyranometer measurement. Thus, even if there are few degrees of errors and uncertainties in PR measurement, it is better to use an indicator which reflects true performance of a grid PV plant with some uncertainty than to have a figure such as those given by CUF of a grid PV plant, which doesn't capture the actual performance of a grid PV plant.

II. For identical climates or plants in the similar region, it is the most important tool to detect even small variations of the PR [48]. A recently published report [44] from Sunspec Alliance, which is a global trade alliance of nearly 70 organizations, admits that PR is more appropriate to trend a specific system or to compare systems in similar geographic locations. IEA PVPS Task 2 experiments which studied the performance of first 21 plants in Europe and Japan and which is also the first global effort to monitor the performance of PV plants used PR as one of the most important tool in detecting short term and long term variations. The Final Yield could be a reasonable alternative tool to compare performance of different PV plants under certain conditions if there is no insolation measurement available.

III. Using the PR without correction factors such as those for temperature etc. could be a low cost option. For e.g, measuring the actual temperature variation using sensors on individual module or array would be a costly affair for the project developers. Also, as temperature doesn't vary significantly in the same plant location, a single or 3–4 temperature sensors would be sufficient to give a fair idea about the temperature variation and its impact on the plant performance.

IV. An uncorrected PR or PR with least correction factors would also require less volume of data handling and storage facility, this would help in sending the monitored data quickly and on short duration of interval, say weekly or 10 days as compared to monthly or annually because of large processing and filtering time.

Thus, we feel that in the initial stages, when PV plant deployment is gaining momentum in a country or region (for e.g. a developing country like India), efforts should be made for the grid PV infrastructure to stick to a bare minimum performance benchmarking scheme particularly focusing on PR as the main indicator. Once, the basic infrastructure is developed and we have monitoring results for several years, more comprehensive tools and techniques may be implemented to make the grid PV infrastructure more robust.

3.5. The SolMap project

Sol Map is a Renewable Energy project under the Indo–German Energy Programme (IGEN). It is financed by the German Federal Ministry of Environment, Nature Conservation, Building and Nuclear Safety (BMUB).

Under the programme, the Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH or GIZ is supporting Ministry of New and Renewable Energy (MNRE) in developing a country-wide system for the collection and analysis of solar and other relevant meteorological data. The programme is divided into two phases (phase I from Aug. 2011 to Feb. 2014; phase II from Sep. 2014 to Aug. 2015).

The idea of a countrywide PV performance benchmarking system (see Fig. 4) in India is to collect PV plant operation data at a central location, do an automatic data analysis and calculation of plant comparison performance indicators, and distribute appropriate feedback information for plants to improve the performance [50]. The system will also build a substantial knowledge pool for estimations of the yield under real operating conditions during the planning stage. Such an important infrastructure system and policy will significantly help India achieve its massive solar target of 100 GW by 2022.

Under the project, by Feb 2014, 119 PV plants (5–20 MWp) covering 12 Indian states were covered for performance benchmark using datasets from Jan 2012 to Dec 2013. The project has implemented several analysis algorithms in order to extract useful information from the PV plant data sets, such as inverter performance, influence of module technology on plant performance, long term degradation, etc. [50]. Correlations between different measured data are used to indicate possible reasons for low performance. Cause-effect diagrams have been elaborated to further support plant operators to identify reasons for low performance and at the end enable the plant operator to correct them. The software programme utilizes additional filter such as inverter-technology, geography, size, and time of installation for more accurate analysis.

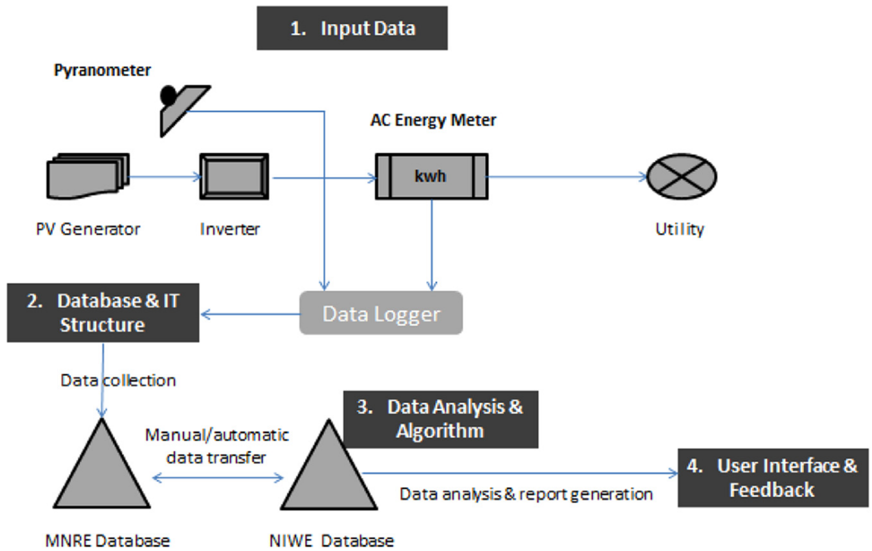

Fig. 4. Structure of the PV Benchmarking Approach under the SolMap (adopted from [50]).

The benchmarking study of the first phase has yielded some very good results. But, there has been a substantial variation in initial result for different parameters like final yields, PR values etc. because of inadequacy and nominal quality control in data. Around 60% of the dataset after filtering were found to be realistic and indicated an average and median PR of 76.6 and 80 respectively [49]. The performance data analysis also found that thin film PV technology performed slightly better than crystalline technology in the state of Rajasthan located in the north-western region of India.

The analysis of the findings and results of the phase II of the project (Sep. 2014 to Aug. 2015) have not been considered in this paper.

3.5.1. Economic and environmental benefits: example based upon findings of SolMap project

Today, from the point of view of an investor and the government; economics and environmental aspects of the grid connected PV projects is crucial. This is evident from the fact that these plants use huge resources (land, money, machinery etc.). Thus, the performance of these plants is very crucial for the plant operators and the nation as a whole.

Common performance indicators used by industry to judge the bankability of the PV projects include yield, CUF, PR etc. PR finds an edge over its close competitors such as plant yield and CUF because it indicates how much energy actually has been delivered by the plant as compared to a theoretical possible value under a given insolation and climatic condition.

Under the SolMap Project, the first hand results of monitoring of PV plant dataset till 2013 indicated a median PR of 80 and a median yield of 1342 kW h/KWp annually [50]. Just by improving the PR of the plants, say by 1%, from median 80-81 could have added additional 8.73 million units[1] to the grid till 2013. On the bigger picture, let us translate this increase in PR by 1% with the same median yield of 1342 kWh/KWp annually to India's installed capacity by March 2015 which was ~3.5 GWp. The 1% increase is equivalent to nearly 16,775 additional units per MWp. It is estimated that annually 58.64 million units would have been added to the national grid, saving 0.043 million ton of precious coal,[2] avoiding a maximum of 0.056 million ton of CO_2 emission[3] to the atmosphere, and saving nearly 65.09 million INR.[4]

4. Conclusion

A regular monitoring of PR of a grid connected PV system is helpful to correct underperforming systems and could help reduce economic losses due to operational problems. Adoption of monitoring guidelines and international codes such as IEC 61724 and European PV Monitoring Guidelines could significantly improve performance and reliability measurements of the grid PV systems. Using PR as a performance indicator has far more practical advantages than using CUF of a grid connected PV plant.

Estimating Performance Ratio accurately is a difficult task and has practical limitations, since an accurate insolation measurement is needed and depending on the sensor different values may result. Even to be more accurate, it is reasonable to normalize PR with module temperature to be able to compare PV systems located in different climate zones, which is a very costly and difficult option. But, still for countries like India which are scaling up their grid PV capacity as a means to fulfilling their burgeoning energy demand and as a solution to address climate change, the advantage of using temperature uncorrected PR (with typical 2–4% error or uncertainty in actual values) as a grid PV plant performance indicator, are many. In initial stages when resources are limited and monitoring infrastructure is either absent or naive, it is highly beneficial for countries to use a basic minimum PR as defined by IEC 61724 while assessing the performance of their grid connected PV plants.

SolMap is a landmark project for India which aims to establish a basic monitoring and benchmarking system to improve the performance of PV plants and follows global benchmarking

[1] Assuming 1 MW PV Plant generates typically 1.5 Mio. Units kWh annually. Minimum availability of plants on an average is considered to be 90%. Under the SolMap, by the end of 2013, data from 119 PV plants constituting 517.8 MWp. So, the calculation becomes: Additional Units generated = 18,750 × 517.8 × 0.90 = 8.73 Mio. Units kWh

[2] According to [51], the region wise specific coal consumption in the thermal power plants during the period 2000–01 to 2009–10 ranged between 0.7 and 0.78 kg/kWh. We have assumed an average value of 0.74 kg/kWh in the calculation.

[3] According to [51], the emission per unit of electricity is estimated to be in the range of 0.91–0.95 kg/kWh for CO2. We have used the maximum value of 0.95 kg/kWh for estimation.

[4] According to [52], Coal India sells coal to the power sector at average price of Rs 1100–1200 per ton. E-auctioned coal fetched about Rs 1500 in 2014 on average, about a third lower than this year's figure of Rs 2000 per ton. We have used Rs. 1500/ton in calculation

standards. PR is one of the key performance parameters utilized in this benchmarking analysis. There is an urgent need to further mainstream such projects, upgrading them from a pilot level to a nationwide scale and finally integrating them in the national renewable energy policy frameworks.

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Appendix A

Abbreviations

AL – Availability (plant); AM – Air mass; AOI – Angle of incidence; ASTM – American society for testing and materials; BMUB – German federal ministry of environment, Nature conservation, building and nuclear safety; BOS – Balance of system; BU – Backup unit; CdTe – Cadmium telluride; CIS – Copper indium selenide; CUF – Capacity utilization factor; EPI – Energy performance index; GIZ – Deutsche gesellschaft für internationale zusammenarbeit gmbH; IEA – International energy agency; IEC – International electro-technical commission; IGEN – Indo-German energy programme; INR – Indian rupee; ISO – International organization for standardization; IREDA – Indian renewable energy development authority; ITRI – Industrial technology research institute (Taiwan); kWh – Kilo watt hour; MNRE – Ministry of new and renewable energy; MPP – Maximum power point; MPPT – Maximum power point tracking; NIWE – National institute of wind energy; NOCT – Nominal operating cell temperature; NREL – National renewable energy laboratory; NVVN – NTPC vidyut vyapar nigam limited; PF – Production factor; POA – Plane of angle; PPC – Public power corporation (Greece); PR – Performance ratio; PTC – PVUSA test conditions; PVPS – Photovoltaic power systems programme; SAM – The system advisor model (developed by NREL); SCADA – Supervisory control and data acquisition; SolMap – Solar mapping; STC – Standard test condition; TMY – Typical meteorological year; PVWATTS – PV tool (developed by NREL).

Appendix B

Recommendations, criteria and limits for different parameters for monitoring a grid connected PV Plant as per IEC 61724 [25].

I. In-plane irradiance has to be measured with the calibrated reference devices or pyranometres in the plane of the module array. Calibration and maintenance of the reference device or module should be in sync with IEC 60904-2 and IEC 60904-6.
II. The accuracy of air temperature sensors, including signal conditioning, shall be better than 1 K.
III. The accuracy of the wind speed sensors shall be better than 0.5 m s^{-1} for wind speeds $\leq$5 m s^{-1}, and better than 10% of the reading for wind speeds $\geq$ 5 m s^{-1}.
IV. PV module temperature should be measured at locations which are actual representation of module conditions. Selection of module location should be made by referring to Method A of IEC 61829.
V. The accuracy of voltage and current sensors, including signal conditioning, shall be better than 1% of the reading
VI. DC power can either be calculated in real time as the product of sampled voltage and current quantities or measured directly using a power sensor. AC power shall be measured using a power sensor whose accuracy including the signal conditioning shall be better than 2% of the readings.
VII. The sampling interval for parameters which vary directly with irradiance shall be 1 min or less. For parameters which have larger time constants, an arbitrary interval may be specified between 1 min and 10 min
VIII. Processed data should be recorded hourly. Even frequent recordings are permitted till the recording period is an integral multiple of hour.

Appendix C

Irradiance minimum criteria and instrumentation data selection guidelines recommended by NREL/TP-5200-57991 [33].

Minimum irradiance criteria

I. At least for three days irradiance must be measured in the plane of the array that is greater than 600 W/m^2 for three continuous hours, and the daily total irradiance must exceed 3000 Wh/m^2/day.
II. If for five continuous days the minimum irradiance criteria is not met, the test period may be extended until five sufficient days have been recorded. There will not be any liquidated damages triggered as a result of this weather-related test delay.
III. Even if the minimum irradiance criteria for continuous five days is not met and the corrected PR of the five strongest days meets the contract guarantee, then the plant acceptance test will be deemed a success.

Data from the following instrumentation will be used to determine performance

I. Power meter(s) at each delivery point should be defined as in the contract (kW).
II. Calibrated reference cells or reference modules should determine POA irradiance with a target measurement uncertainty of 3%. Reference cell/module technology (poly, crystal, or thin-film) should match installed panels, but other irradiance measuring devices may be used if there are no strict requirements from the stakeholders. For long term performance (W/m^2) projections, use of reference cells are recommended.
III. Anemometer should be used to measure wind speed [m/s].
IV. Ambient temperature measurements should have an accuracy to the tune of ± 1 °C.

Data from the following instrumentation will be collected for reference only

I. Calibrated pyranometer should be used to measure horizontal irradiance with a target measurement uncertainty of ± 3%.
II. Type-T surface-mounted shielded thermocouple should be used to measure module temperature (with a measurement uncertainty of ± 1 °C) or an equivalent resistance temperature detector (RTD) device should be used.
III. There should be arrangements for other backup meteorological measurements.

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