11.4

PV System Monitoring and Characterization

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11.4.1 Introduction

In the past few years the development of photovoltaic (PV) solar technology has led to enormous price reductions that, in combination with low installation and maintenance costs, have made PV modules a popular form of renewable electricity generation (IEA-PVPS, 2014). Besides impressive developments in very large-scale (VLS) PV power plants of >100 MWp, this especially pertains to small and medium-sized residential systems whose owners have embraced PV as a profitable means to reduce their electricity bill as a result of grid parity in many countries around the globe. Economic benefits can be guaranteed only if the performance of the PV system is as expected. Hence proper monitoring of power and energy generation is a prerequisite. Implementation of monitoring depends on the size of the PV system and its purpose, such as the control of the commercial systems for which any malfunction directly may lead to financial loss. This pertains to VLS PV systems as well as much smaller grid-connected residential systems. Monitoring of stand-alone PV systems usually has a different purpose in that not the energy but rather the function that is provided should be guaranteed, such as water pumping or communication.

Two approaches to monitoring can be discerned, i.e., analytical and global monitoring (Blaesser and Munro, 1995a, 1995b). Analytical monitoring requires measurement of many parameters, such as array output voltage and current, irradiance, ambient temperature, inverter DC input and AC output power, where all these are measured at a certain time interval, such as hourly, every 15 minutes, every minute, or even at the level of seconds. In view of the cost and complexity of analytical monitoring, global monitoring of energy (instead of power) can provide sufficient data to ascertain the expected performance, and requires fewer measured parameters, such as array output energy, energy to grid and irradiation (kWh/m^2) on a monthly, weekly, or daily time resolution.

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The majority of residential PV electricity generation is due to a large amount of small (1 to 5 kWp), geographically scattered systems. Many of these systems have insufficient monitoring so that system owners cannot assess by themselves whether their systems are generating the expected amount of energy. Consequently, failures and energy losses may remain undetected for a long time. For example, Jahn and Nasse (2004) showed in a study of German grid-connected residential PV systems of 1 to 5 kWp size that once every 4.5 years a statistical failure occurred per system. In 63% of the cases, inverters caused the failure; in 15% of the cases modules were to blame, and in 22% of the cases other system components. Today, fee-based services are offered to PV system owners that allow also small PV systems to assess the performance of their system in an automatic way. Large systems (>10 kWp to multi-MW size) usually are equipped with proper extensive monitoring equipment, as its cost is small compared to the possible incurred financial losses due to energy losses. Requirements for this analytical monitoring are laid down in the IEC 61724 standard (IEC, 1998): an automatic data acquisition system with a minimum set of parameters that are to be monitored.

The performance ratio (PR) is usually employed as a proxy for system performance; it is a measure of the degree of utilization of an entire PV system (Blaesser and Munro, 1995a, 1995b; IEC, 1998) with respect to its nameplate nominal power. It indicates the overall effect of losses on the overall performance of the PV system, and thus includes effects of PV module temperature, intensity dependence of the module efficiency, partial shading, soiling, incomplete utilization of irradiation, system component limited efficiencies, module mismatch and any malfunctions (Reich *et al.*, 2012; Van Sark *et al.*, 2012). Systems that perform well reach $PR=0.85$ (note that PR is also commonly expressed in percentages, i.e., 85%). PV systems installed in the late 1980s showed PR values between 0.5 and 0.75 (Decker and Jahn, 1997). Nordmann (2007) analyzed the performance of systems installed since 1991: a trend in PR was observed from $PR=0.65$ to $PR=0.72$ for the systems installed in 2005. Reich *et al.* (2012) reported maximum $PR=0.90$ for systems installed in 2010, and argued that the upper bound may be $PR=0.92$.

Although a large PR value is a good indicator of system performance, the customer usually is interested in maximized energy yields and low levelized cost of electricity. Therefore, other figure of merits, such as energy efficiency (energy out divided by energy in) or energy production rate (kWh per kWh/m^2) would be of higher interest to the system owner. Low PR values do not necessarily mean bad system performance, as in high irradiation areas also high ambient (and module) temperatures are common practice. The same system would have a high PR in milder climatic zones.

To be able to reach such high performance ratio values, proper monitoring followed by immediate action should malfunctions occur is necessary. Recently, the participants of Task 13 of IEA-PVPS (International Energy Agency, Photovoltaic Power Systems program) have presented an analytical method for fast and accurate performance analyses (Woyte *et al.*, 2014). This method makes use of a collection of data plots, such as final energy yield versus reference (or expected) energy yield, and linear regression analysis. Depending on the availability of specific data of a PV system, more plots can be made, which makes detection of malfunctions easier and faster, thus optimizing the performance. These methods can also be used for residential systems, with limited data availability (Tsafarakis and Van Sark, 2014). Ransome *et al.* (2005) have introduced another collection of plots and interpretation guidelines based on normalizing the measured performance parameters. In addition, a so-called Sophisticated Verification (SV) method was developed that allows the identification of twelve different loss factors based on seven parameters that should be measured (Ueda *et al.*, 2009). Finally, Pearsall and Atanasiu (2009a) have developed new monitoring guidelines that can be used in spreadsheet form (Pearsall and Atanasiu, 2009b).

When only energy yield data is available, statistical methods to analyze performance can be employed to assess performance on regional or country level (Moraitis and Van Sark, 2014; Nordmann, 2014). Comparison of yields with nearby systems was suggested as a peer-to-peer performance indicator (Leloux *et al.*, 2013).

In this chapter, we will provide a short overview of monitoring practices and parameters, which we illustrate with a few examples.

11.4.2 Monitoring Practice

In general, a grid-connected PV system can be described in four parts, see Figure 11.4.1: (1) modules; (2) module/inverter connections; (3) inverter(s); and (4) inverter/grid connections. In a stand-alone system the solar array is connected to a battery and loads via a charge controller; in this case part 3 is the charge controller, and part 4 the battery. In all these parts, malfunctions may occur. A number of possible malfunctions for grid-connected systems are listed in Table 11.4.1, which can be linked to a specific part in the PV system, see also

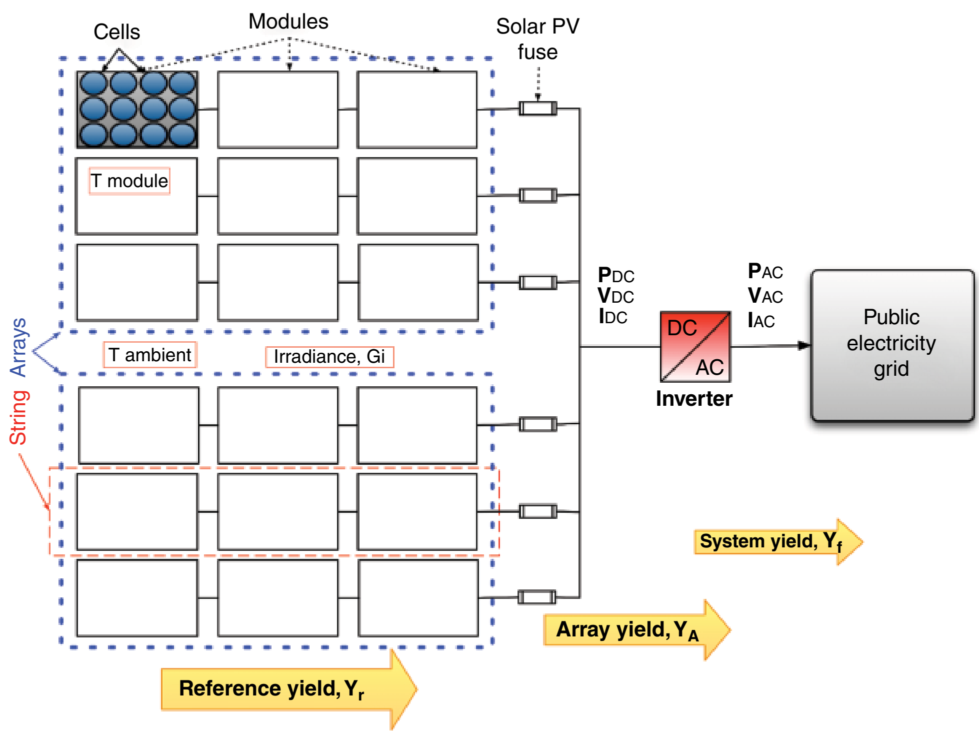

Figure 11.4.1 Overview of PV system with components. Four parts can be discerned: (1) modules; (2) connections between module and inverter; (3) inverter; (4) connection between inverter and public electricity grid. Definitions of string and array are indicated, as well as several measured parameters. Source: (Tsafarakis, 2014)

Table 11.4.1 Examples of malfunctions (after Stettler, 2005)

Energy loss	Module	Module/inverter connection	Inverter	Inverter/grid connection
Constant	Degradation Module overrating Shadowing Module defect	Incorrect connections String defect		Incorrect connections
Changing	Hot modules		Part load behavior Maximum power point tracking Grid outage	
Total blackout		Defect control devices	Defect inverter	Defect control devices

Chapter 11.1 for more details about system failures. Analysis of performance ratio values on different time scales is used to elucidate the origins of malfunctions (Stettler *et al.*, 2005; Drews *et al.*, 2007).

The performance ratio PR is defined as the ratio of utilizable AC electricity (at the feed-in meter) or final PV system yield Y_f (in kWh/kWp) to the amount of energy that could be generated if modules were operated under STC (standard test conditions: irradiance 1000 W/m^2, air mass 1.5 spectrum (AM1.5G), and a cell temperature of 25 °C) continuously and without any further losses in the system or reference yield Y_r in (kWh/kWp) (IEC, 1998):

$$PR = \frac{Y_f}{Y_r}, \text{ with } Y_f = \frac{E_{AC}}{P_{STC}} \text{ and } Y_r = \frac{H_{POA}}{G_{STC}} \tag{11.4.1}$$

with E_{AC} the AC energy delivered to the grid in (kWh), P_{STC} the (DC) rated capacity of the PV modules in (kWp), H_{POA} the summed plane-of-array (POA) irradiance in (kWh/m^2), and G_{STC} the STC reference irradiance of 1 kW/m^2 at AM1.5G, and cell temperature of 25 °C. Performance ratio values can be calculated for different periods (annual, monthly, weekly, even daily), which may serve different purposes, such as studying seasonal effects on performance.

Parameters that should be measured (IEC, 1998) for adequate analytical monitoring comprise of PV array output voltage, current and power (V_{DC}, I_{DC}, P_{DC}), utility grid voltage, current and power (V_{AC}, I_{AC}, P_{AC}), ambient and module temperature (T_{amb}, T_{mod}), POA irradiance (G_{POA}), wind speed (S_w), and durations of system outage (t_{outage}). Clearly, for autonomous systems, parameters related to the grid are not required to be measured, while the battery state of charge (SOC) and voltage are relevant parameters.

Measurement of electrical parameters should be done with calibrated energy or power meters, as usually inverter-integrated measurements are not accurate enough (Woyte *et al.*, 2014), or sometimes even show higher power or energy values than actually generated. Nevertheless, system functionality can certainly be tested using inverter-integrated measurements.

On-site measurement of POA irradiance requires irradiation sensors, which are usually too expensive for small PV systems. Pyranometers or crystalline silicon reference cells are commonly used as irradiation sensors. Both are calibrated under indoor and outdoor conditions. Alternatively, on-site irradiation measurement is possible using satellite-based irradiation estimates (Drews *et al.*, 2007), however, this is associated with large short-term inaccuracies, leading to PR values with large errors. Also, for residential systems irradiation from ground-based meteorological stations may be used for *PR* determination, while it should be noted that conversion from global horizontal irradiation to POA irradiation requires empirical models that may lead to even greater inaccuracy in *PR* values. Clearly, if one aims for early detection of malfunctions based on *PR*, on-site irradiation monitoring permits much higher certainty (Reich *et al.*, 2012) and better failure response times. Examples of performance of PV systems can be found in the IEA-PVPS Task 13 public database (Task 13, 2014).

Standard graphs that are used in analyzing performance are shown in Figure 11.4.2: (1) a scatter plot of normalized hourly mean array power (P_{AC}/P_{STC}) versus hourly POA irradiance H_{POA}; (2) a bar graph of daily array Y_f and reference yields Y_r for a month (alternatively, a daily *PR*

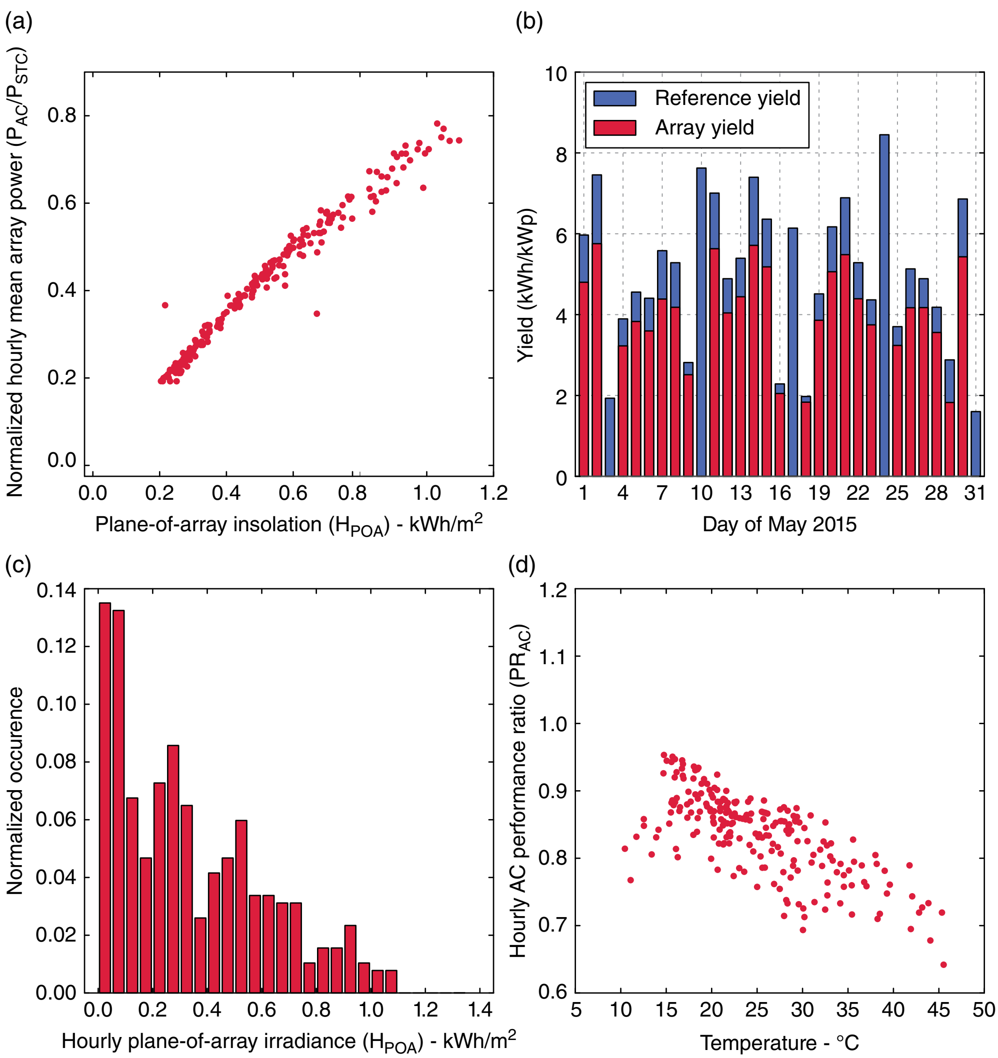

Figure 11.4.2 Standard graphs used in PV performance analysis: (a) normalized hourly mean array power versus hourly POA irradiance; (b) bar graph of daily array (light) and reference (dark) yields for a month; (c) normalized histogram of hourly mean POA irradiance values; and (d) performance ratio versus module temperature. Data (May 2015) are from a system at Utrecht University campus

can be used); (3) a normalized histogram of hourly mean POA irradiance values; (4) performance ratio versus module temperature. Many more are possible, and approaches to show all $1/2\,n(n-1)$ possible graphs for n parameters have been denoted a "stamp collection" (Woyte *et al.*, 2014). Analysis of these graphs reveals any malfunction occurring in the PV system; however, this still requires experts, as automated analysis is not yet sophisticated enough for automatic malfunction detection.

11.4.3 Monitoring Examples

11.4.3.1 Normal Operation

Figure 11.4.3 shows a plot of system yield versus reference yield for a system consisting of 18 crystalline silicon modules with 4.14 kWp total DC capacity installed at the European Academy of Bolzano (EURAC), Italy (Moser, 2014). Data were collected from January to August 2012. The plot shows hourly data, for three different weeks (winter, spring, summer). It is clear that during days with higher solar radiation (spring, summer) the yields are higher (dark and light data points have higher maximum values than shaded ones). Linear regression on weekly data, as suggested by Woyte *et al*. (2014) shows that slopes differ for the three periods: for spring and summer, slopes are smaller than for winter. In winter $PR=0.92$, while in spring and summer $PR=0.84$. This is commonly observed in well-functioning systems and is due to the higher ambient and module temperatures in spring and summer.

11.4.3.2 Shading

Figure 11.4.4 shows a plot of system yield versus reference yield for a system consisting of 30 crystalline silicon modules with 3.2 kWp total DC capacity installed at the Development

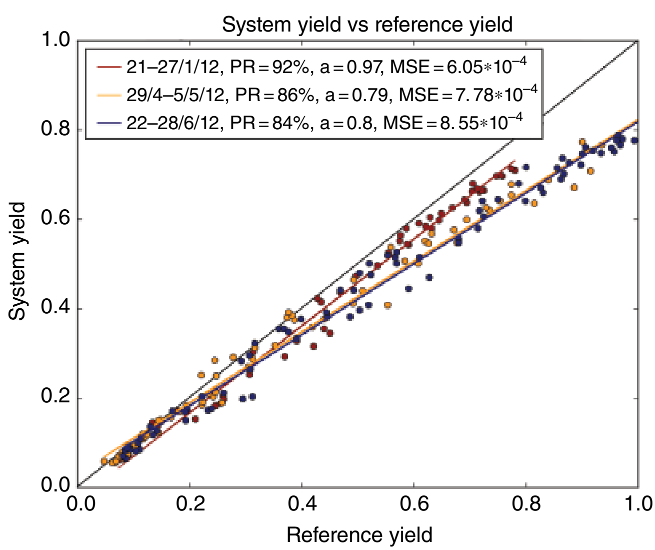

Figure 11.4.3 System yield versus reference yield for a 4.14 kWp PV system. Source: (Tsafarakis, 2014). (*See insert for color representation of the figure*)

Centre of Renewable Energies, Algiers, Algeria (Silvestre *et al.*, 2013). Power as a function of time (for 15-min time intervals) for a clear day without shading on the system is shown in Figure 11.4.4 (a), while a shade is visible in Figure 11.4.4 (b). From the system yield versus reference yield plot, one can infer that the slopes are about equal and the daily PR values are $PR = 0.737$ (no shade) and $PR = 0.731$ (with shade). From these values alone it is difficult to

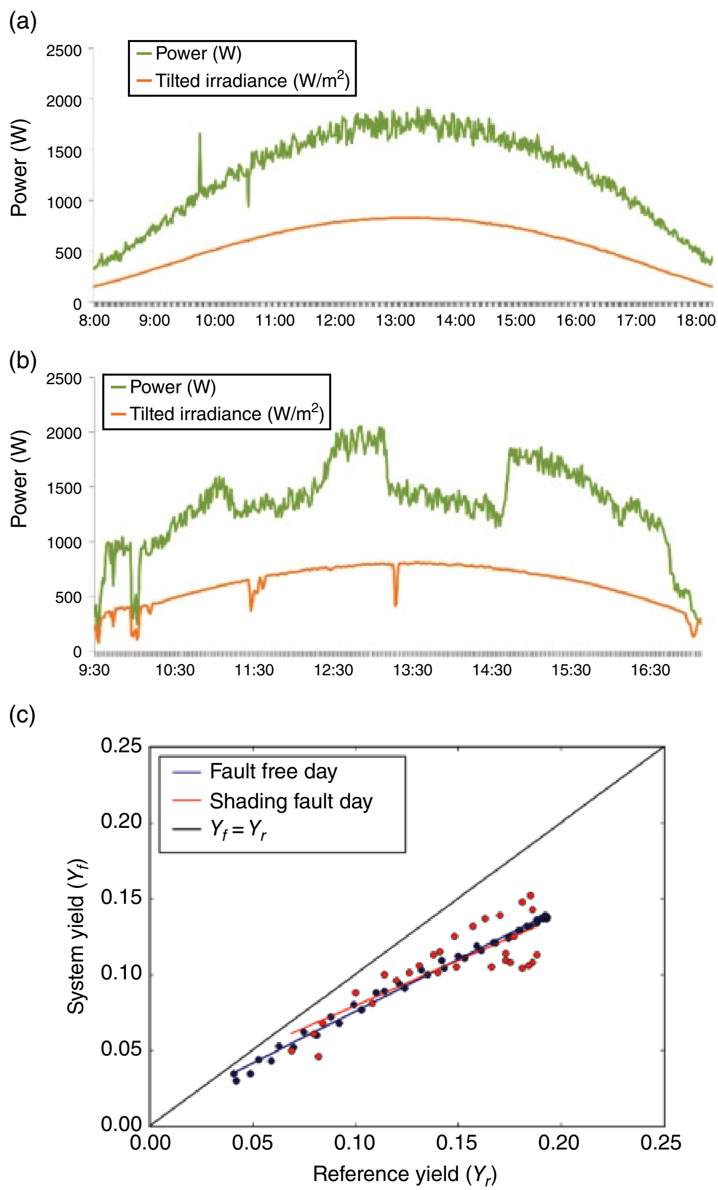

Figure 11.4.4 PV system power and irradiance for a clear day without shade (a), and with shade (b). Panel (c) shows system yield versus reference yield. Source: (Tsafarakis and Van Sark, 2014). (*See insert for color representation of the figure*)

conclude that shading is the cause of a somewhat lower *PR*. However, from the scatter of points around the linear fit, one can infer that something is wrong with the system. The scatter can be quantified using the mean square error: $MSE = 1/2\sum(Y_f - \hat{Y}_f)^2$, where Y_f and $\hat{Y}_f$ are true and predicted values of the final yield, respectively. Predicted yield results from fitting the data and for every reference yield value a final yield prediction is made, and compared to the true (or measured value). In this example, the MSE value for the shading case is 26 times higher than the one for the non-shading case, thus demonstrating that MSE could be an additional metric for performance analysis: plots as in Figure 11.4.4 (c) can be made for daily data and analyzed automatically. Any large MSE value is an indicator for operators to check the data and perform some action to resolve the issue at hand.

11.4.3.3 Statistical Analysis

For small-scale systems, monitoring of energy yield is increasingly being performed using various web tools provided by inverter manufacturers or independent monitoring service companies. Hardware and software are integrated that allow owners to monitor system performance and the production of their system at any time of the day (Moraitis and Van Sark, 2014). For statistical analysis of performance so-called web-scraping techniques can be used to collect performance and system data from the web portals and to organize it in databases for automatic analyses. In this way daily yields (AC and DC) can be analyzed for tens of thousands of systems. Determination of performance ratio is only possible when irradiation data is available. As an attempt to determine the performance ratio variation in a large Dutch data set of systems that were not equipped with an irradiation sensor, hourly global horizontal irradiation data from the Royal Netherlands Meteorological Institute (KNMI) stations was used. Every PV installation was linked to the closest of the 31 weather stations according to geographical coordinates. Total POA irradiation was calculated on a daily basis using a model for every system independently in accordance with the orientation and the tilt of each system (Olmo *et al*., 1999).

Figure 11.4.5 shows the results of the analysis of 590 systems (average size 10.65 kWp) in the Netherlands for the year 2014, mostly installed between 2011 and 2013: the average value

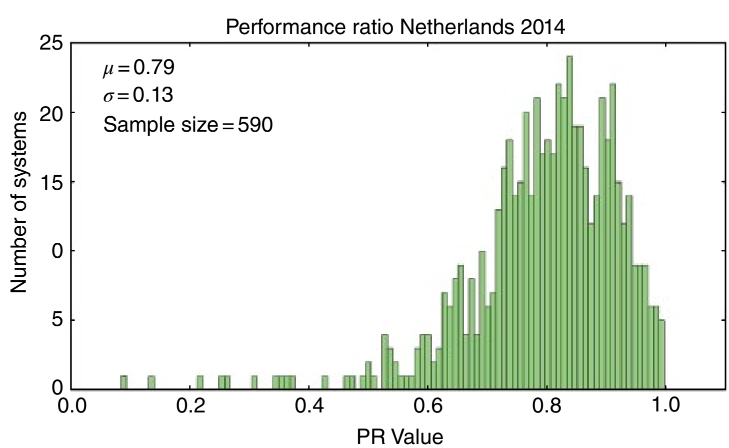

Figure 11.4.5 Distribution of PR values for a sample of 590 Dutch PV systems in 2014

of PR is 0.79 ± 0.13. Some systems clearly show malfunctions, with $PR < 0.50$. Systems with $0.6 < PR < 0.7$ most probably suffer from some kind of shading. About half of the systems perform well with $PR > 0.8$. Note that values of PR close to 1 are unrealistic, and these are due to incorrect irradiance values as the distance between irradiance sensor and system can be as large as 30 km. Also, the wide distribution shows that the accuracy of input data (yield, capacity, inverter readings) is unknown. Clearly, statistical approaches offer a rough indication of the performance of systems, and should be interpreted with care. Nonetheless, presenting maps based on geographical information systems is visually interesting to quickly see at which locations system performance may deviate (Moraitis *et al.*, 2015).

11.4.4 Conclusion

Once installed, PV systems need to be monitored in order to be able to assess if systems are delivering the energy as predicted by the installer. Large systems will be equipped with proper monitoring devices complying with IEC standards. This chapter summarized performance-monitoring issues and showed some examples.

Analysis of performance ratios at different time resolution or plotting various parameters versus another allows the detection of malfunctions, and prompt action to solve these leads to highly reliable power production. Smaller, residential systems are usually not monitored with the same attention, and automatic monitoring services are under development that ensure less knowledgeable system owners enjoy carefree PV energy. The introduction of smart meters that also are able to register PV production is particularly of interest in that respect, as these are increasingly being used in the energy management of home energy systems. Algorithms that analyse PV performance could be part of these systems, thus changing current monitoring practices.

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List of Symbols

Symbol	Description	Unit
E_{AC}	AC energy delivered to grid	kWh
G_i	Incident irradiance	(1000) W/m^2
G_{STC}	STC reference irradiance	(1000) W/m^2
H_{POA}	Summed plane-of-array irradiance	kWh/m^2
I_{AC}	AC current	A
I_{DC}	DC current	A
MSE	Mean square error	(kWh/kWp)^2

(*Continued*)

(*Continued*)

Symbol	Description	Unit
PR	Performance ratio	- (or %)
P_{AC}	AC power	W
P_{DC}	DC power	W
P_{STC}	DC rated capacity of PV system or modules	W (or Watt-peak)
S_w	Wind speed	m/s
t_{outage}	Duration of system outage	s
T_{amb}	Ambient temperature	°C
T_{mod}	Module temperature	°C
V_{AC}	AC voltage	V
V_{DC}	DC voltage	V
Y_A	Array yield	kWh/kWp
Y_f	Final yield	kWh/kWp
Y_r	Reference yield	kWh/kWp

List of Acronyms

Acronym	Description
AC	Alternating Current
AM	Air Mass
DC	Direct Current
IEA-PVPS	International Energy Agency, Photovoltaic Power Systems program
IEC	International Electrotechnical Committee
KNMI	Royal Netherlands Meteorological Institute
MSE	Mean square error
POA	Plane Of Array
PR	Performance Ratio
PV	PhotoVoltaic
SOC	State Of Charge
STC	Standard Test Conditions
SV	Sophisticated Verification
VLS	Very Large-Scale

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