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MONITORING OF PHOTOVOLTAIC SYSTEMS: GOOD PRACTICES AND SYSTEMATIC ANALYSIS

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ABSTRACT: Over the last 20 years, the statistical average performance ratio of a new photovoltaic (PV) installation in moderate climates has improved from 0.65 to approximately 0.85. This continuous improvement in the field would not have been possible without operational monitoring and the continued analysis of monitoring data by the PV system community. The paper starts with a historical review of the performance of PV systems. It documents the current state of the art and good practices in PV system monitoring. Finally, it presents periodic linear regression as a simple though systematic approach for the visual and mathematical analysis of monitoring data.
Keywords: Grid-connected, Monitoring, Modelling, Performance, Yield

1 INTRODUCTION

Research and industry have gathered comprehensive experience with photovoltaic (PV) system operations in many parts of the world. In order to learn from this experience, operational monitoring and monitoring data analysis are essential. Both can improve the operation and reliability and, consequently, the energetic and economic yield of photovoltaic power systems.

The present paper is a result of collaborative work within the International Energy Agency’s Photovoltaic Power Systems Programme (IEA PVPS), Task 13 *Performance and Reliability of Photovoltaic Systems* with the objective to improve the operation, reliability and, consequently, the electrical and economic output of photovoltaic power systems. The paper presents results of Subtask 2 *Analytical PV System Assessment*.

The authors describe the main parameters that affect the performance of a PV system and review how this can be maximized. They review the current state of the art and good practice in PV system monitoring. Finally, they present guidelines for the interpretation of PV system monitoring data. Technically, the interpretation guidelines are derived from matching measured data to known analytical relationships.

2 PERFORMANCE OF PV SYSTEMS

2.1 Performance and Loss Factors

The performance ratio (*PR*) is the most important quantity to be measured for evaluating the overall behaviour of a PV plant. The performance of the power plant depends on several parameters including the site location, the climate and several loss mechanisms. The specific plant losses are differentiated into capture losses (L_C) and system losses (L_S). Capture losses are caused, e.g., by attenuation of the incoming light, temperature dependence, electrical mismatching, parasitic resistances in photovoltaic modules and imperfect maximum power point (MPP) tracking. System losses are caused, e.g., by wiring, inverter, and transformer conversion losses. A good PV system design accounts for, and minimizes, losses associated with a variety of system components. One of the first empirical analyses of losses in PV systems was published in [1]. A recent and detailed overview of loss factors typically occurring in practice has, e.g., been published in [2]. The most important causes for reduced *PR* values are briefly explained in the following paragraphs.

Temperature: Module output power reduces as module temperature increases. When integrated into a roof, a solar module will heat up substantially, reaching back of the module temperatures of up to 80 °C depending on whether air gaps are present or not to exploit natural ventilation [3].

Dirt and dust: Dirt and dust can accumulate on the solar module surface, blocking some of the sunlight and reducing output. Although normal dirt and dust are often cleaned off during rain, it is more realistic to estimate system output taking into account the reduction due to dust build-up during dry periods. While often the soiling losses are low, for some locations, soiling can account for up to 70% of all losses [2].

Mismatch and wiring losses: The maximum power output of the total PV array is always less than the sum of the maximum output of the individual modules. This difference is a result of slight inconsistencies in performance from one module to the next and the module mismatch may contribute to at least a 2% loss in system power. Power is also lost to ohmic resistance in the system wiring. These losses should be kept to a minimum but it is difficult to keep these losses below 3% for the system [4].

DC to AC conversion losses: Some of the DC power generated by the solar modules is lost in the conversion process to AC current. Modern inverters commonly used in residential PV systems have peak efficiencies of up to 98% indicated by their manufacturers.

2.2 Trends in PV System Performance

A tendency of increasing annual *PR* values during the past years has been observed in several studies (Table I). Observed averages of *PR* for given populations of PV systems rose from reportedly 0.5 to 0.75 in the late 1980s, and 0.65 to 0.7 in the 1990s, to more than 0.8 nowadays. These early PV systems often did not generate the expected energy yield. Dominating performance constraints were defects of the DC installations, poor reliability or bad MPP tracking of inverters, long repair times and shading problems [1], [5]. Several studies have investigated the performance of PV systems providing insight about the trends in increasing *PR* and decreasing spread between low and high range values. In studies performed under the IEA PVPS Task 2 [6], [7], PV systems in 11 countries were analysed during eight years of installation. In a study performed in year 2000 [6], 170 grid-connected PV systems were analyzed, where the average annual yield (Y_f) was found to fluctuate only slightly from one year to another. However, there was considerable scattering around these average values for individual systems. In fact, the annual *PR* differed significantly from plant to plant ranging between 0.25 and 0.9 with an average value of 0.66. This spread was due to system and component failures, shading effects, MPPT mismatch, badly oriented PV arrays and high module temperatures. It was found that well-maintained PV systems show an average *PR* value of typically 0.72 at an availability of 98 %. Furthermore, for PV systems installed before 1995 the average *PR* was 0.65, while for newer installations, installed after 1995, the average *PR* equalled 0.70. The improvements of PV system performance were due to more realistic PV module ratings, higher component efficiencies (e.g. inverter) and increased reliability of PV systems. Furthermore, the *PR* values of newer installations were spread between 0.50 and 0.85 where this interval decreased further between 1998 and 2002 as a result of improved quality of the newer systems [7].

In 2004, from the performance analysis of 235 grid-connected PV systems in Germany [5], a clear tendency to improved performance was also found for new PV installations. At the same time, the broad spread of annual *PR*, decreased, indicating improved quality of PV system performance.

In [8], [9] and [10] a review of residential PV systems in France and Belgium, was published analyzing the operational data of 10 650 PV systems. After a mean exposure time of two years, the mean value of *PR* was found to be 0.76 in France and 0.78 in Belgium.

For another review of 2011 [11], three years of operational data of 202 grid-connected PV systems, such as monthly final energy yields and failure records, collected by ITRI in Taiwan were used to analyze the performance and system availability. The average *PR* value was 0.74, the average mean time to failure (*MTTF*) was found to be 3.96 years, average mean time to repair (*MTTR*) 65 days and the average availability 95.7%. The installation of real-time monitoring systems for PV plants was suggested to improve the system availability and *PR* value.

Finally, in a study performed in 2012 [12], the *PR* of about 100 German PV system installations were investigated. Notably, a systematic influence on calculated *PR* values was found depending on the reference used to measure irradiance. Monitored *PR* is 2 to 4% systematically lower when calculated with irradiation data obtained by pyranometers compared to crystalline silicon cells. Annual PR_{Si} (subscript Si: measured with a crystalline silicon cell) for the approximately 100 systems for the year 2010 was found to be between approximately 0.7 and 0.9 and showed a median *PR* of 0.84. For the case of German PV systems, *good* performances were above 0.84. An analysis of the historical development of *PR*s over the past 10 years revealed, however, that also in recent years (2007 and 2008) system with very low *PR* had been installed. Such systems showed PR_{Si} as low as 0.75, primarily due to row shading and bad inverter performance. On the other hand, systems using highly efficient components and designed appropriately, as well as realized on the ground with good workmanship, showed PR_{Si} very close to 0.90.. Loss heights of simulated loss mechanisms showed that even for very well performing systems, there is still room for some further optimization.

Table I: Average values and ranges of performance ratio for installations from different decades

Installed	Location	Range of *PR*	Avg. *PR*	Ref.
1980s	Worldwide	0.50 - 0.75	Individual estimates	
1990s	Worldwide	0.25 - 0.90	0.66	[6]
1990s	Worldwide	0.50 - 0.85	0.65 - 0.70	[7]
1990s	Germany	0.38 - 0.88	0.67	[5]
2000s	France	0.52 - 0.96	0.76	[9]
2000s	Belgium	0.52 - 0.93	0.78	[10]
2000s	Taiwan	<0.3 - >0.9	0.74	[11]
2000s	Germany	0.70 - 0.90	0.84	[12]

3 PHOTOVOLTAIC SYSTEM MONITORING

3.1 State of the Art

The main purposes of a monitoring system are to follow up on the energy yield, to assess the PV system performance and to timely identify design flaws or malfunctions. Many large PV systems use analytical monitoring to prevent economic losses due to operational problems. As stated by [13] and [14], the requirements which refer to so-called analytical or detailed monitoring include an automatic dedicated data acquisition system with a minimum set of parameters to be monitored. A study where failures for grid-connected residential PV systems of 1 to 5 kWp installed in Germany in the 1990's were analysed [5], found that a statistical failure happened every 4.5 years per plant. Inverters contributed 63%, PV modules 15% and other system components 22% to the total number of failures. An adequate monitoring system can allow the timely detection of operational problems, thus warranting a high final energy yield. Based on these and later results from the IEA PVPS Task 2, a lack of long-term experience in performance and reliability of PV systems was identified and linked to a lack of detailed and more reliable monitoring campaigns [6], [7].

Common reference documents for monitoring of PV systems are the standard IEC 61724 [13] and the guidelines of the European Joint Research Centre in Ispra, Italy [14], [15].

Monitoring guidelines should provide clear instructions on how to make and analyze the measurements and how to determine whether the system is performing as expected.

A failure detection routine (FDR) for comparing the monitored energy yield with the simulated one for a given period was presented in [16] and [17]. The routine consists basically of three parts: the failure detection system, the failure profiling method and the footprint method. For this method, failure patterns for 12 characteristic failures have been pre-defined for profiling the failures.

Another example of automatic failure detection from PV monitoring data is the so-called Sophisticated Verification Method [18]. This method allows identifying six kinds of system losses using basic information and four simple quantities to be measured.

Based on the extended collection of monitoring data from the IEA PVPS Task 2, operational performance results of 21 grid-connected PV systems have been compared and presented in [19]. Graphical analysis methods have been applied to these data sets for analysing the frequency distributions of energy yields and the *PR* values. Through a collection of plots and interpretation guidelines (e.g., plotting final yield versus reference yield, DC voltage versus power, *PR* over time and *PR* versus module temperature), the authors show different system behaviour affecting the *PR*.

A similar study [20] presents a collection of plots and interpretation guidelines using different combinations of scatter plots and time series plots. Values modelled with empirical formulae are compared with measured data. Discrepancies between these two values point towards irregular PV system operation.

3.2 Instruments and Required Precision

In the case of utility scale PV plants, monitoring typically serves for comparison of the current plant performance with an initial energy yield assessment. In order to be able to distinguish the performance of the PV system from the variability of the solar resource, monitoring should always include both a measurement of the energy generated and the incoming irradiation.

For electricity yield measurements, energy meters or true-rms power meters should be used. The inverter-integrated measurements are usually not sufficiently precise. Nevertheless, they may prove useful for identifying relative changes over time.

When selecting irradiation sensor technology, generally two possibilities exist: thermopile sensors (pyranometer) and solar cell sensors. In solar cells, only crystalline silicon sensors provide the required stability. No long-term stable irradiation sensors exist for CIS, amorphous silicon and CdTe [21]. In case of amorphous silicon (single junction), a silicon-based sensor with a filtered glass can be used as it has a similar spectral response.

Pyranometers are based on a thermocouple device. These devices are spectrally almost unselective and measure the irradiance between 280 and 2800 nm. The parameters that influence the uncertainty of pyranometers are [22]:

- Irradiance level and spectral distribution of the solar radiation,
- Irradiance change rate during the measurement,
- Cosine effect,
- Ambient temperature,
- Pyranometer tilt angle,
- Pyranometer dome temperature.

The response time of pyranometers is in the range of 5-30s. Therefore, they react to changing irradiance conditions much more slowly than the PV modules. However, this effect is negligible in the monitoring of utility scale PV plants.

Pyranometers are calibrated under indoor and outdoor conditions. The calibration uncertainties of experienced laboratories that calibrate according to ISO 9846, ISO 9847 or equivalent, are in the range of 1-2% [23].

The expected daily uncertainty for pyranometers according to [24] is below 2% for secondary standard pyranometers, below 5% for first class pyranometers and below 10% for second class pyranometer.

According to [25] and [26], the overall uncertainty of the instantaneous irradiance measurement based on secondary standard pyranometers is approximately 3%.

Pyranometers are widely used in meteorological measurements and nearly all existing irradiation databases are validated on these measurements. With few exceptions [27], satellite-derived irradiance data is compared with ground based pyranometers. This should be considered if the performance of a PV plant is compared with an initial energy yield assessment.

Crystalline silicon sensors have basically the same layout as the crystalline silicon PV modules of the plant. They are spectrally selective in the range of 400 nm to 1150 nm. The lower wavelength is determined by the transmission of the front glass and encapsulant whereas the longer wavelength is determined by the material’s band gap. The factors that influence the uncertainty of crystalline silicon sensors are mainly:

- Irradiance level,
- The angular distribution,
- Shift of transfer function over time,
- The ambient temperature,
- The temperature of the sensor.

Crystalline silicon reference sensors are calibrated under indoor and outdoor conditions. The calibration should comply with IEC 60904-2 and -4 respectively. According to IEC 60904-2, the calibration traceability of crystalline silicon sensors can be divided into:

- Primary reference devices,
- Secondary reference devices,
- Working reference devices [28], [29].

Crystalline silicon reference devices are used in order to estimate the STC power of a PV plant. This is done when measuring IV curves of modules, strings or complete arrays in a PV plant. These devices are calibrated according to STC conditions (1000 W/m2, 25ºC and AM1.5 spectrum). Therefore they indicate the intensity of the equivalent AM1.5 spectrum, even though the instantaneous solar spectrum is, most of the time, not identical to the AM1.5 spectrum. Assuming that the spectral response of the device is equal to that of the PV modules in the PV plant, the actual STC power of a PV plant can be estimated by extrapolating the instantaneous irradiance and module temperature to STC conditions. In cases where the spectral response is not equal, a spectral mismatch correction has to be undertaken.

On an annual basis, crystalline silicon sensors measure less irradiation than pyranometers. The highest absolute difference between the signal measured by a crystalline silicon sensor and a pyranometer is at clear sky conditions with a low diffuse/direct ratio [30]. The annual difference between the two sensor types depends very much on the sensor and the location. Recent publications ([31], [32]) indicate that the deviation between different sensors installed in Germany varies considerable. On average, the annual irradiation measured by crystalline silicon sensors is 2-4% less than the irradiation measured by pyranometers. Hence, the annual *PR* of a PV plant in Germany that is calculated on the basis of crystalline silicon sensors may be on average 2 to 4% higher than the *PR* based on a pyranometer measurement (see also Section 2). This has to be taken into account when comparing the *PR* of an operating PV plant with the *PR* estimated in the energy yield assessment.

In light of the points discussed above, the installation of thermopile sensors (pyranometers) in the module plane is recommended for measuring the solar irradiation in utility scale PV plants. In order to reduce the uncertainty of the measurement, either a first class or a secondary standard pyranometer should be installed and in any case it should be asked for a traceable calibration and the associated calibration certificate. The sensor should be installed in a place were no near or far shading can affect the measurement, even if parts of the plant are affected by shading.

The irradiance sensors should be checked and cleaned frequently. Depending on the location and season, an interval between 1 to 2 weeks is recommended. The sensors should be recalibrated in order to correct any bias in the measurement. If two sensors are installed and constantly compared, a recalibration every two years is reasonable and can be considered to comply with [33]. If only one sensor is installed, a yearly recalibration should be considered. During the recalibration the sensor should be replaced by a sensor of the same quality.

The use of **satellite derived irradiance data** might be an option where the cost of the irradiance sensor cannot be justified. A recent study shows quite good results for some providers of such data [34]. For shorter periods satellite derived data has higher uncertainty and bias than calibrated sensors on site. When applied for computing the reference yield, the uncertainty of the data source should be watched in the same way as this is good practice for a sensor on site.

4 REGRESSION-BASED LINEAR MODELLING

4.1 Concept

In this section we introduce, illustrate and discuss the method of periodic linear regression that was developed as part of the IEA PVPS Task 13 work. The method is based on simplified physical relationships between the quantities most frequently monitored. It allows for deriving linear model parameters from regression. The relationships presented cover the full energy conversion chain as illustrated in Figure 1. Notably, for the classical yield and loss quantities, here we use small letters when referring to instantaneous values or averages over a short recording period. Consequently, performance ratio derived from these quantities is denoted as *pr*.

The analysis method introduced here may serve for identifying and interpreting common design flaws and operational problems or simply for documenting the proper operation of the PV system.

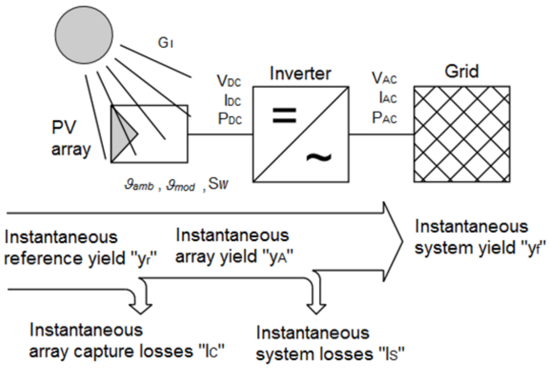


Figure 1: Energy flow in a grid-connected PV system

In practice, the analysis should serve for identifying a simplified physical relationship between two variables. Such physical relationships can then be approximated as a straight line by means of linear regression. The thus identified linear relationship may be considered characteristic for the energy conversion step to be monitored. In the practical application, this relationship can be identified periodically: recent samples or regression lines may be compared to historical lines and updated periodically in order to identify trends or sudden changes.

The selection of simplified relationships and plots for visualisation (Figure 2) can go more or less into detail. In practice the level of detail will depend on the specific purpose of the analysis and on the quantities to be measured.

When only the PV power to the utility grid and the in-plane solar irradiance are available, the performance can be followed on the system level. If available, module temperature is the most useful complement here. This is indicated in the upper row of Figure 2.

The middle row shows plots, recommended for a more specific analysis of different conversion steps, namely, the thermal behaviour of the module, the performance on array level rather than on system level and the resilience of the utility grid voltage on active power injected at the connection point.

Finally, the bottom row shows specific or secondary relationships. The most important one is the array voltage versus module temperature. Any effects that manifest themselves between PV array and inverter, first of all would lead to a DC voltage deviating from the linear voltage-temperature behaviour. Moreover, this row also shows how to take into account secondary effects such as wind speed.

The relationship between system yield and reference yield stands for the overall conversion efficiency of the installation. It is based on two measured quantities only and it does reflect all kinds of phenomena during the operation of a PV system.

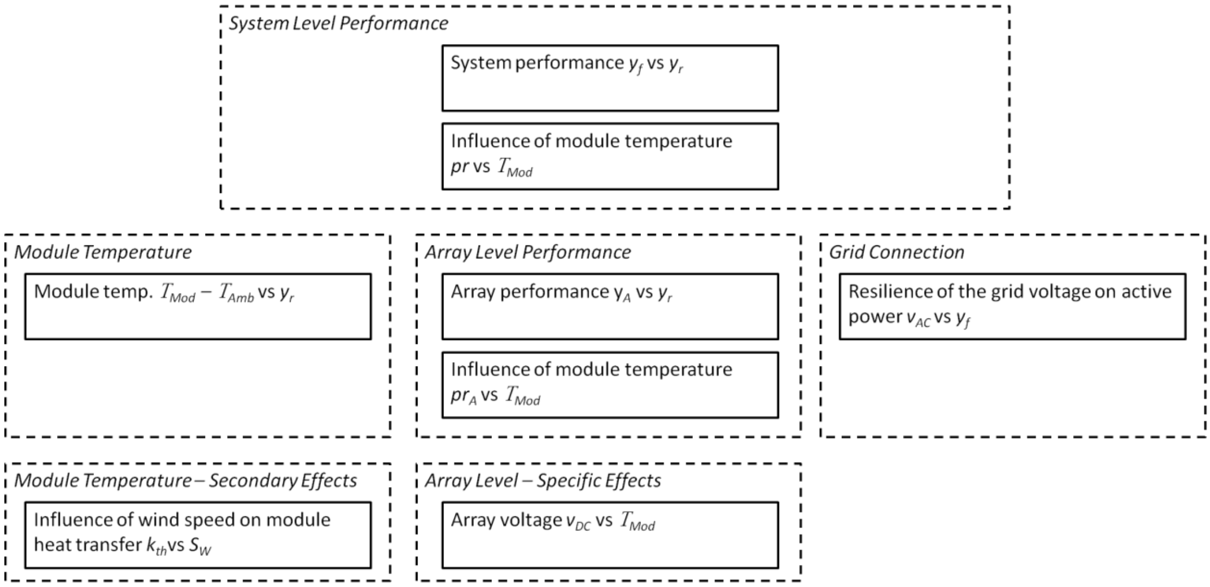


Figure 2: Overview of linear relationships for the description of PV systems and components using monitoring data

In the following sub-section we present and discuss some of these relationships along with illustrative plots of measured data for a selection of examples from different IEA PVPS member countries. The full analytical description for all relationships listed in Figure 2 will be published in a report by the IEA PVPS Task 13 in the spring of 2014.

4.2 Examples

Photovoltaic System Performance

System yield versus reference yield is the most general global set of performance parameters for a grid-connected PV system. This relationship represents the overall efficiency of PV energy conversion. The required quantities *power to utility grid* and *in-plane irradiance* are always the first to be monitored.

As a linear approximation, the system yield is proportional to the reference yield. When measurements of system yield are plotted over reference yield, their relationship can be approximated by a straight line through the origin. This line can be determined by linear regression throughout all data samples. Its slope reflects the average performance ratio over all samples.

Plotting the scatter plot with a new regression line for each week (Figure 3) allows identifying the slope and, hence, the average performance ratio per week. Consequently, sudden changes from week to week as well as significant trends are indicated by the change of the slope.

Figure 3 shows data from an installation over four weeks during which it was increasingly overgrown by vegetation. The slope of the regression lines was decreasing from week to week. During proper operation, after the vegetation had been cut, the regression lines were almost identical.

Influence of Module Temperature on System Level

Photovoltaic module temperature is the most significant parameter affecting the PV system performance. The instantaneous performance ratio can be considered a linear function of module temperature [19]. In practice this applies for high irradiance levels only and we recommend omitting the samples measured at low irradiance from the regression. When *pr* values based on measurements are plotted over the module temperature, their relationship can be approximated by a straight line. Its slope can be interpreted as temperature coefficient of the PV array's output power.

Plotting the scatter plot with a new regression line for each week (Figure 4) allows identifying the slope and intercept per week. During proper operation, both values are expected to remain approximately constant over time.

Figure 4 shows the plot of performance ratio as a function of module temperature for an installation that suffered from an inverter failure in week 2. The inverter failure has caused a reduction of *pr* by one third that is visible in Figure 4 by a parallel shift of the regression lines towards lower intercept values. For week 2, the recorded samples are situated either on the line for week 1 (normal operation) or on the lines for weeks 3 and 4 (inverter failure). As a consequence, regression through the points of week 2 returns a line that is situated somewhere in the middle.

Array Performance and Influence of Module Temperature – Array Level Analysis

If PV array output power is measured, array performance and the impact of module temperature can be assessed on array level, hence, excluding the system losses occurring in the inverter. The analysis is done in analogy with the one presented in the previous paragraphs for the system level.

For each of the four plots in Figure 5, the regression lines for the different weeks are virtually identical, hence over the period, the system operation is stable. Comparing the amorphous silicon installation (a and b) with the crystalline silicon installation (c and d) reveals a significantly larger scatter for crystalline silicon. The

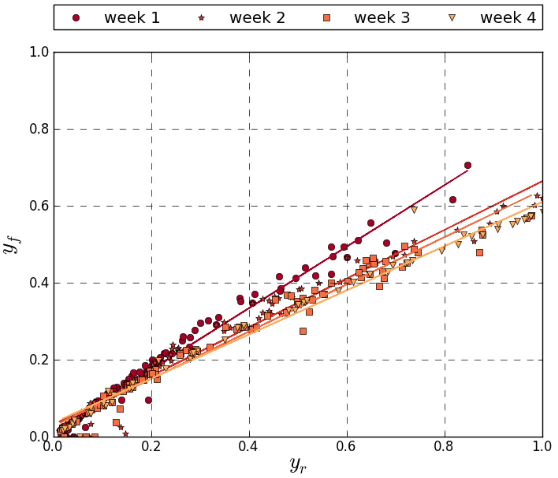


Figure 3: Hourly system yield (y_f) versus reference yield (y_r) in May 2012; system monitored by 3E and situated in Belgium

array performance ratio (pr_A) is relatively low for the crystalline silicon plant. The influence of module temperature on the array performance ratio is much stronger for crystalline silicon than for the amorphous silicon plant. This is immediately visible when comparing Figure 5b) and d) and it may also why in Figure 5c) the scatter of y_A versus y_r bends to the right for high y_r values.

DC Voltage and Module Temperature

The open circuit voltage (V_{OC}) of a solar cell and, hence, of a PV module, linearly depends on the module temperature (T_{mod}). The dependency on T_{mod} is stronger than any other dependency of V_{OC}, and hence, as a first approximation, it may be applied to the PV array output voltage V_{DC}. Under ideal operating conditions V_{DC} is equal to the MPP voltage of the PV array.

Plotting a scatter plot of V_{DC} versus T_{mod} together with a regression line for each week (Figure 6) allows identifying the temperature coefficient of voltage being the slope of such a line. As long as the measured PV array output voltage is close to the MPP voltage the recorded samples should be situated on this line whose slope and intercept should stay approximately constant over time. Consequently, any sample away from this line points towards deviations from the common MPP.

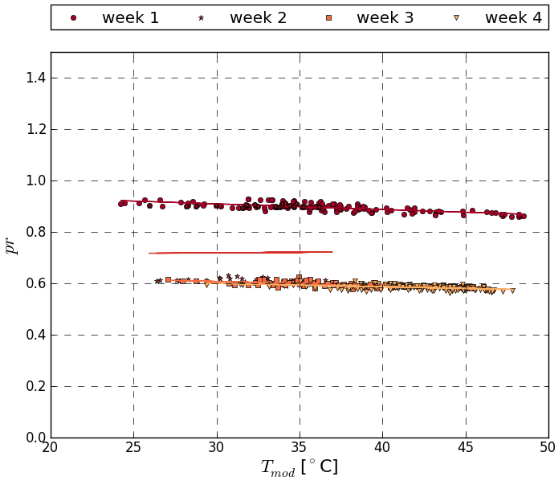


Figure 4: Fifteen-minute performance ratio (pr) versus module temperature (T_{mod}) in May 2012 (samples with G_I > 600 W/m^2); system monitored by ABB and situated in Sweden

For the installation analysed in Figure 6, the voltage-temperature correlation was very high in the first three weeks of April 2010 (not shown here). In May, many samples appear with very low array voltage while most samples still follow the linear relationship determined before.

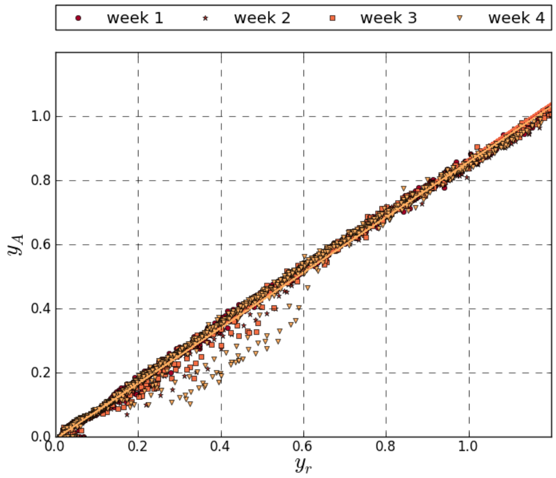
A site visit has shown that this phenomenon was caused by a scaffold tower nearby, which had been put up during the last week of April. The scaffold led to partial shading of the PV array and, as a consequence, the array was no longer operated at its MPP for homogeneous illumination. Since the shadow effects were relatively small, they could not be easily identified from the plots of system yield versus reference yield or performance ratio versus temperature. Only the deviation of array voltage clearly indicated the abnormal operation.

The array output voltage is more specific than the power values (y_f, y_A, y_r) that have been regarded before. As illustrated by the examples above, it complements the data set by information on the operating points of the equipment. In conclusion, PV array voltage is the most important electrical parameter to be monitored after the parameters required for final yield and reference yield.

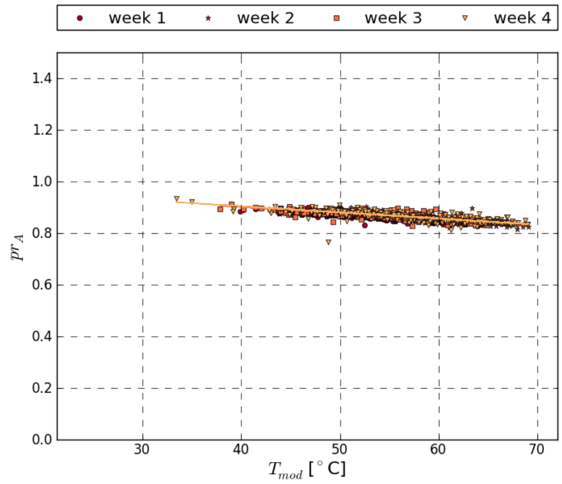
4.3 Summary on Periodic Linear Regression Models

The views and models shown above allow for characterizing a PV system in physical terms and based on the observed operational behaviour of the most important quantities measured. Based on simplified physical relationships, linear model parameters can be derived from the measurements.

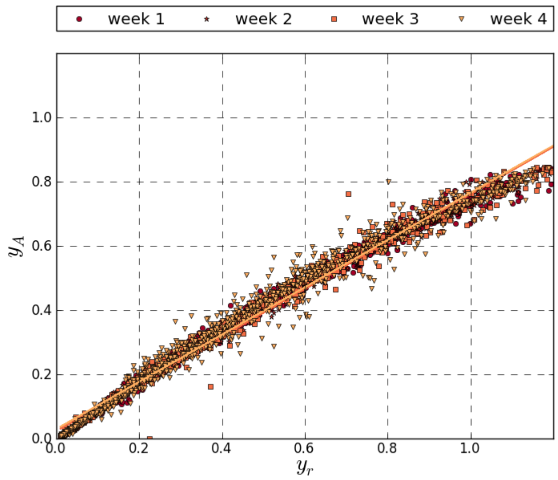
Further models which have not been shown here allow for describing the thermal behaviour of the PV array including the influence of wind speed and the interaction of PV output power with the utility grid voltage. The selection presented in Figure 2 covers the full energy conversion chain of a PV system. The analysis may serve for identifying and interpreting common design flaws and operational problems or simply for documenting the proper operation of the installation.



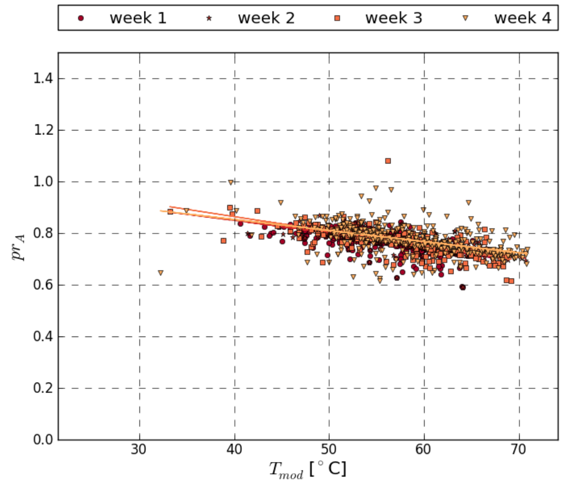
(a) a-Si, y_A vs y_r



(b) a-Si, pr_A vs T_{mod}



(c) c-Si, y_A vs y_r



(d) c-Si, pr_A vs T_{mod}

Figure 5: Five-minute values of array yield (y_A) and array performance ratio (pr_A) over module temperature (T_{mod}) for two installations (amorphous silicon & crystalline silicon) in Malaysia in October 2012; data provided by Universiti Teknologi MARA, Malaysia

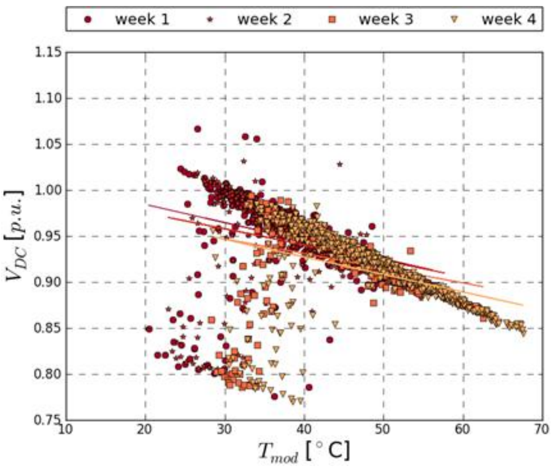


Figure 6: Five-minute average values of PV array output voltage normalized to MPP voltage versus module temperature (May 2010); by GL Garrad Hassan, situated in Spain

5 CONCLUSIONS

Over the last 20 years, the statistical average performance ratio of a new PV installation has improved from 0.65 to approximately 0.85. Among other causes, this improvement is due to more precise module rating, better design and installation, and more reliable components along with shorter times to repair. In the field, operational monitoring of the PV installations and the analysis of monitoring data has been the key to this continuous improvement.

General guidelines for PV system monitoring have been available and proven useful for many years. These have been complemented by more specific methods for data analysis, fault detection and classification and the automatic identification of faults.

For solar irradiation measurements pyranometers and crystalline silicon sensors can be used. For comparing the energy yield of the PV system to an initial energy yield prediction, pyranometers should be applied. When solar cell-based sensors are used, they should be made from crystalline silicon and accompanied by an individual calibration report. For longer periods, satellite-derived irradiance data may complement the on-site measurements. With all instruments, when applied for computing the reference yield, the uncertainty of the data source should be watched and reported as this is good practice for all measurements. For electricity yield measurements, energy meters or true-rms power meters should be used. The inverter-integrated measurements are usually not sufficiently precise. Nevertheless, they may prove useful for identifying relative changes over time.

The mathematical approach of periodic linear regression has been introduced and elaborated along with numerous examples from different PV installations in IEA PVPS member countries. It allows for describing and analyzing the energy flow in a grid-connected photovoltaic system with a limited but selected collection of variables. Together they describe the main energy conversion steps taking place within the PV system. They build a complete framework for the systematic analysis of PV monitoring data.

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