

How to calculate PV performance ratio and performance index

According to the latest IEC 61724 standard series

The IEC 61724 “Photovoltaic system performance” series of standards is the best available source that defines parameters such as “performance ratio” and “performance index.” The purpose of this document is to clarify the logic behind IEC 61724 and its vocabulary. For the sake of brevity, we do not mention all parameters and performance metrics. If you want to know more, you may purchase the IEC standards.

Introduction

IEC has issued a series of 3 standards for PV system performance testing:

- **IEC 61724-1 “monitoring”**: provides requirements for measuring (revised in 2021)
- **IEC TS 61724-2 “capacity evaluation method”**: defines performance analysis based on the monitoring data over a short period of several sunny days, typically during commissioning, to verify if the system meets specifications (NOTE: This standard is under revision.)
- **IEC TS 61724-3 “energy evaluation method”**: defines performance analysis based on the monitoring data over a long period of 1 year or more (NOTE: This standard is under revision.)

Purpose of performance monitoring

IEC gives the following as possible purposes of PV performance monitoring:

- identification of performance trends in an individual PV system
- localization of faults in a PV system
- comparison of PV system performance to design expectations and guarantees
- comparison of PV systems of different configurations
- comparison of PV systems at different locations

Important factors in PV performance

The most significant and direct impacts on PV performance are:

- in-plane irradiance received by the PV array
- the PV cell temperature
- shading losses due to soiling, snow, or row-to-row shading

Secondary factors that may enter the assessment are:

- clipping of the inverter, if the inverter cannot output more than a certain power in [W]
- curtailment; the network may not accept the available power
- losses (see next pages)

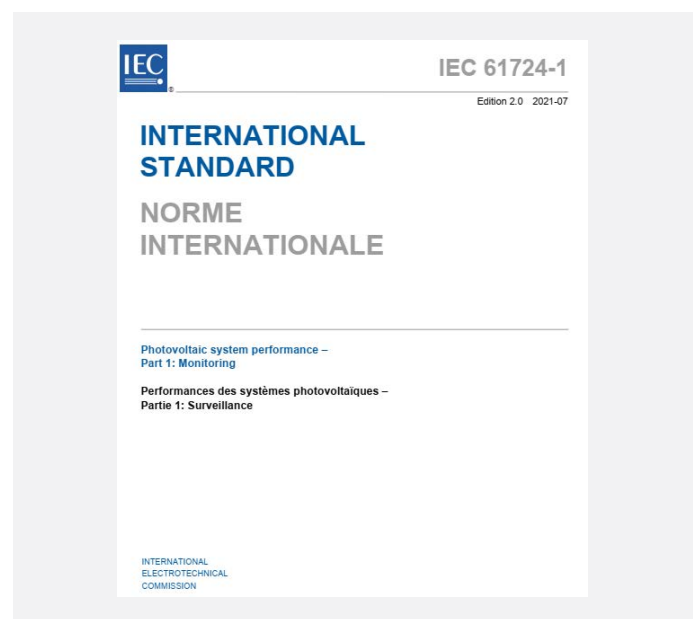


Figure 1 Cover of the new IEC 61724-1 standard, published in July 2021.



Figure 2 PV system performance monitoring with pyranometers measuring GHI and POA.

IEC 61724-1:2021

This standard outlines requirements for measuring equipment (sensors), methods, and terminology for performance monitoring and analysis of photovoltaic (PV) systems. It also serves as a basis for other standards which rely upon the data collected, such as 61724-2 and 61724-3.

The standard defines 2 classifications of monitoring systems: Class A and Class B. Class A systems are intended for high accuracy measurement at utility-scale and large commercial PV systems.

The standard addresses sensors, installation, and accuracy for monitoring equipment, in addition to measured parameter data acquisition and quality checks (system calibration and cleaning/maintenance), calculated parameters, and performance metrics.

For PV system performance assessment, electrical and environmental measurements are required. For Class A system monitoring stations, mandatory electrical measurements are:

- AC and DC output current
- AC and DC output voltage
- active power
- active energy

For Class A system monitoring stations, mandatory environmental measurements are:

- POA (Plane of Array) irradiance
- GHI (Global Horizontal Irradiance)
- soiling ratio
- PV module temperature
- ambient air temperature
- wind speed and direction
- PV module temperature (3 sensors per station)

Optional measurements are:

- reflected or rear side solar irradiance
- diffuse solar radiation

Performance model, ratio, index

IEC uses the following definitions:

- **performance model:** a mathematical description of the electrical output of the PV system as a function of meteorological conditions, system components, and system design. This model is typically agreed upon in advance by the stakeholders of the test.
- **predicted output:** the output for a given period, as calculated using the performance model based on historical weather data
- **expected output:** the output calculated using the performance model when entering measured weather data
- **measured output:** the output measured at the power plant
- **rating:** performance as specified by the manufacturer, usually confirmed via the name-plate on the panel, or as agreed upon by a supplier, typically under reference conditions such as STC Standard Test Conditions
- **performance ratio (PR):** the ratio of measured output to expected output for a given reporting period, based on the system name-plate rating
- **performance index:** the ratio of measured output to expected output for a given reporting period, based on a more detailed model of system performance than the performance ratio
- **Power Performance Index (PPI):** performance index based on power,
- **Energy Performance Index (EPI):** performance index based on energy

IEC TS 61724-2:2016

This standard defines a procedure for measuring and analyzing the power [W] production of a photovoltaic system, with the goal of evaluating the quality of PV system performance. It does so by comparing the measured power produced to the expected power, calculating the PPI over a few relatively sunny days.

The point of this test is that it can be done fast. The minimum test duration is 2 days, provided that these days meet certain boundary conditions. (NOTE: The new draft of this standard proposes 3 to 5 days of testing.)

Class A monitoring systems must be used. Panels have to be "nominally clean," operation unconstrained (no clipping), and the panels unshaded. Irradiance must be between pre-defined limits, such as 0.5 to 1.2 TRC (Test Reference Condition), or, for example, above 500 W/m². (NOTE: The new draft of this standard proposes 400 W/m².)

In this test, we accept a higher uncertainty than the IEC 61724-3 standard. Hukx suggests working with irradiances greater than 600 W/m² only. The expected angle of incidence of the solar beam is then around 52°, which is lower than the Brewster's angle for glass (56°). Working at high angles of incidence reduces uncertainty due to the variation of reflectance and lowers the uncertainty of the ratio between generated power and POA irradiance measurement.

A typical test outcome is a test report, which includes a PPI involving a temperature correction and an expanded uncertainty.

IEC TS 61724-3:2016

This standard defines a procedure for measuring the energy [kWh] production of a photovoltaic system for comparison to expected electrical energy production, under actual weather and other operating conditions over a year or more. A practical reporting period is 1 or multiple years.

The test offers a full assessment of electricity production. It covers all operating conditions and offers insight into performance under all weather conditions and times of the year. It also provides a picture of how other factors, such as maintenance, plant degradation and hardware failures, impact the plant performance.

The expected electrical energy is calculated using a model. A simple temperature-corrected PR can still have misleading variations due to seasonal effects and local conditions. More complex models, such as the Sandia PV Array Performance Model (SAPM), the System Advisor Model (SAM), and PVSyst, take into account measured weather conditions along with estimates for soiling and degradation.

In IEC 61724-3, the energy production is characterized separately for periods when the system is operating (available) and when the system is not operating (unavailable).

A typical test outcome is a set of performance indicators, most importantly a yearly "in service EPI" including an estimated expanded uncertainty.



Figure 3 Hukx model SR30 (right) is the first heated pyranometer compliant with the requirements of IEC 61724-1 for Class A monitoring systems. SR30 and the later model SR300 mitigate dew and frost, unlike the non-heated pyranometer on the left. Dew and frost deposition on the pyranometer dome reduce data availability and accuracy.

Parameter definition in IEC

The following parameters are defined in the IEC standards for PV system performance monitoring:

- **in-plane irradiance G_i or POA [W/m²]**: the sum of direct, diffuse, and ground-reflected irradiance incident upon an inclined surface parallel to the plane of the modules in the PV array, also known as Plane of Array (POA) irradiance (IEC 61724-1 3.13)
- **H_i [kWh/m²]**: in-plane irradiation
- **E_A [kWh]**: energy output from the PV system (DC)
- **E_{out} [kWh]**: energy output from the PV system (AC), i.e., after the inverter

- P_o [kW]: array power rating (DC), the total DC power output of all installed PV modules at the power rating reference condition, assumed to be Standard Test Conditions (STC) (1,000 W/m² irradiance at normal incidence and 25 °C PV cell temperature), typically as listed on the name plate
- $P_{or AC}$ [kW]: array power rating (AC)

Yields and yield losses

Models and test reports may involve yields and losses, which are calculated according to IEC 61724-1. Yields are ratios of an energy quantity to the array power rating P_o . They indicate actual array operation relative to its rated capacity.

Yields have units of [kWh/kW], where the numerator (kWh) describes the energy output and the denominator (kW) represents the system power rating. The yield ratio indicates the equivalent amount of time during which the array would be required to operate at P_o to produce the particular energy quantity measured during the reporting period.

- Y_A [kWh/kW]: PV array energy yield (DC per rated DC)
- Y_f [kWh/kW]: final system yield (AC per rated DC)
- Y_r [kWh/kW]: reference yield (DC)

Yield losses are calculated by subtracting yields. The yield losses also have units of [kWh/kW]. They represent the amount of time the array would be required to operate at its rated power P_o to provide for the respective losses during the reporting period.

- L_c : [kWh/kW] array capture loss ($Y_r - Y_A$)
- L_{BOS} : [kWh/kW] balance of system (BOS) loss ($Y_A - Y_f$)

Constrained operation

When the output of inverters is limited below its maximum capacity, this is referred to as "constrained operation." In some cases, the operation of the inverters is a bottleneck, as they can only supply power within a certain range. If the power hits the upper limit of this range, this condition is known as "clipping."

If constrained operation is caused by external factors, such as inability of the grid to receive the power, it is called "curtailment". In case of clipping, consider reporting performance metrics based on E_{out} , as well as E_A .

Curtailement may involve periods of reduced grid/load demand or availability. The system generates power but cannot supply it to the network. For purposes of performance assessments and performance guarantees, irradiation and yield sums should be calculated excluding such periods of curtailment.

Traditional Performance Ratio

The Traditional Performance Ratio indicates the overall effect of losses on the system output. It is defined as the quotient of the system's final yield Y_f to its reference yield Y_r :

$$PR = \frac{Y_f}{Y_r} = \frac{\left(\frac{E_{out}}{P_o} \right)}{\left(\frac{H_i}{G_{i,ref}} \right)} \quad (1)$$

Traditional PR neglects array temperature, typically resulting in seasonal variation

Temperature-Corrected Performance Ratio

Seasonal variation of the traditional PR is removed by calculating a Temperature-Corrected Performance Ratio:

$$PR'_{STC} = \frac{\left(\frac{E_{out}}{C_k P_o} \right)}{\left(\frac{H_i}{G_{i,ref}} \right)} \quad (2)$$

with

$$C_k = 1 + \gamma X (T_{mod,k} - T_{ref}) \quad (3)$$

Using 25 °C as T_{ref} gives PR'_{STC} .

The term C_k corrects for the difference between actual temperature and STC temperature used for power rating. The value of γ is usually negative and of the order of -0.3 %/K.

Module temperature is correlated with irradiance, so in case the performance is modeled, you must use a weighted average. PV panel temperature may rise up to 20 °C above ambient air temperature.

Annual Temperature-Corrected Performance Ratio

Annual Temperature-Corrected Performance Ratio approximates the value that would be obtained for traditional PR evaluated over one full year by compensating for seasonal variation.

Digital twins

PV system performance analysis is increasingly based on the modeling of the entire power plant using more complex models, such as the Sandia PV Array Performance Model (SAPM), the System Advisor Model (SAM), and PVsyst. These models no longer work with G_i (POA), but with GHI as input.

Where can I order the standards?

The standards can be purchased from the [IEC Webshop](#).

Critical measurements

In PV system performance measurement, the most critical quantities are solar irradiance and PV module temperature.

Below are some comments on the use of pyranometers and PV module temperature sensors.

Use of pyranometers

In PV system performance measurement, pyranometers are the instruments used to measure solar irradiance. Traditional systems were monofacial and statically mounted at fixed tilt facing the equator. Measurement models were historically based on Plane of Array irradiance. With the widespread use of single-axis trackers (using backtracking so that there is no single Plane of Array), of bifacial panels (also generating power from rear side irradiance) and installation on graded terrain nowadays often global horizontal as well as reflected and diffuse irradiance measurements serve as model input.

In Class A monitoring systems, the use of Class A pyranometers for GHI and POA is mandatory. Diffuse solar radiation measurement is optional.

IEC 61724-1 requires the use of ISO 9060 Class A pyranometers with dew and frost mitigation for use in Class A monitoring systems, unless very little dew and frost is expected at the measurement site.

The Hukx [pyranometer model SR30](#) complies with the requirements of Class A monitoring systems.

IEC 61724-2 section 6.5.3 recognizes that special attention should be given to the irradiance data. It recommends performing a regular quality check using a comparison of multiple instruments on a clear day. In particular, false readings due to instrument shading should be removed from the dataset. At the location of all POA measurements, IEC 61724-3, clause 5 requires measurement of the local albedo to verify that it is representative of the albedo of the total power plant, and if it is within the range required for valid modeling. For monofacial modules, the albedo measurement is used in the uncertainty evaluation of the performance test.

In case bifacial modules are used, the rear side solar irradiance may be:

- directly measured, or
- estimated using an optical model from GHI, albedo, and, optionally, diffuse irradiance.

The contribution of reflected radiation to the system performance is typically small. For measurement of reflected radiation, lower accuracy Class C pyranometers may be used.

IEC 61724-1 requires that pyranometers in Class A monitoring systems should be cleaned every week (unless proven unnecessary) and calibrated every 2 years.

Use of PV module temperature sensors

IEC 61724-2 (via Annex A) allows 2 methods to determine PV cell temperature:

- estimated, using a model based on measurements of POA irradiance, ambient temperature, and wind speed
- from direct measurements, using a PV module temperature sensor

The first method is rarely used because the uncertainty of this model-based approach is relatively high.

PV module temperature has a significant impact on the estimate of the performance ratio. Users should carefully select and install PV module temperature sensors. Poorly designed sensors will measure with a lower accuracy than the 2°C required by IEC 61724-1.

IEC 61724-1 Annex B gives directions for temperature sensor installation.

It is important to realize that sensors generally measure a temperature between the air temperature and panel temperature. Badly designed and poorly installed sensors tend to measure a temperature that is too low. PV panels have temperature coefficients in the order of $-0.4\%/K$; at a lower temperature, we expect PV panels to perform better. A temperature-corrected estimate of PV system performance (performance index) using a sensor that measures a PV temperature that is too low will result in a lower calculated level of performance (i.e, a lower performance index).

We expect that the absolute error in $^{\circ}C$ is proportional POA irradiance, so that the performance index is reduced by approximately the same percentage for all irradiance levels. At a lower measured PV panel temperature, we expect the PV system to perform better than it does in reality at its higher-than-measured temperature. In compliance testing or system commissioning, this systematic measurement error (or low estimate of the performance) is a disadvantage for the seller.

Hukx supplies model PVMT01 PV module temperature sensor. This well-designed sensor is designed to accurately measure the PV module temperature. PVMT01 fully complies with IEC requirements.

IEC 61724-1 requires a minimum of 3 such sensors for every monitoring station. A total of 6 or more sensors per PV system is required, depending on the size of the system.



Figure 4 PVMT01 installed on the rear side of a PV module. The sensors are preferably installed at the center of a cell, close to the center of the module. IEC requires 3 sensors per monitoring station.

About Hukx

Hukx is the leading innovator in solar radiation and heat flux sensor technology. We are proud to set the standard in high-accuracy measurement, and to be working at the heart of the energy transition.

Customers worldwide rely on our bestselling pyranometers and heat flux sensors. From sensor design and selection to supply and recalibration, we support you across the entire lifecycle.

Hukx is headquartered in the Netherlands, with locally owned representative sales offices in the USA, Brazil, India, China, Southeast Asia, and Japan.

Let us help you select the best sensor for your application. Get in touch with our experts today via: info@hukx.com

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Version 2506

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