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Chapter

Measuring Solar Irradiance for Photovoltaics

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Abstract

In recent years, solar energy technology has emerged as one of the leading renewable energy technologies currently available. Solar energy is enabled by the solar irradiance reaching the earth. Here we describe the characteristics of solar irradiance as well as the sources of variation. The different components of the solar irradiance and the instruments for measurement of these components are presented. In photovoltaics, the measurement of solar irradiance components is essential for research, quality control, feasibility studies, investment decisions, plant monitoring of the performance ratio, site comparison, and as input for short-term irradiance forecasting. Some more details are also provided related to physics of measuring instruments, their calibration, and associated uncertainty.

Keywords: OCIS codes: (350.6050) solar energy, (010.5630) radiometry, (120.0120) instrumentation, measurement, and metrology

1. Introduction

1.1 The sun

The sun provides 99.97% of the energy at the earth’s surface (the rest is geothermal), and it is responsible, directly or indirectly, for the existence of life on earth. The energy, generated by nuclear fusion of hydrogen, emitted by the sun, is approximately 63 MW for every m² of its surface, about $3.72 \times 10^{20}$ MW in total. The surface of the sun is very hot, and the layer emitting most of the radiation, the photosphere, is at about 5770 Kelvin. This means that there is a lot of short-wave radiation, ultraviolet and visible, and it takes approximately 8.3 minutes to reach the earth.

The unit for the measurement of irradiance (radiative flux [1]) is watts per square meter (W/m²). At the mean distance between the earth and sun of 150 million kilometers (1 astronomical unit (AU)), the total solar irradiance (TSI) reaching the Earth’s atmosphere is $1,360.8 \pm 0.5$ W/m² at a solar minimum [2] (over all wavelengths and perpendicularly). This quantity is named the “Solar Constant” [3]. However, it is not actually constant as is shown in Figure 1. The solar activity [3] varies with an 11-year cycle by ± 0.1% [2, 5]. This variation coincides with the number of sunspots. More sunspots mean more solar activity (solar flares and coronal mass ejection) and therefore a slightly larger amount of solar irradiance reaching the earth. Additionally, there is a larger variation of the solar irradiance reaching the top of the atmosphere by the sun to earth distance variation. This
variation is due to the earth orbit eccentricity. At the perihelion (in January), the earth is close to the sun (147 million km), and at the aphelion (in July), the earth is further from the sun (152 million km).

This results in a variation of \( \pm 3\% \) in solar irradiance, described in [5], which can be approximated with the following equation [6]:

\[
I(n) = I_0 \left[ 1 + 0.034 \cdot \cos \left( \frac{2\pi \cdot n}{365.25} \right) \right]
\]  

(1)

Where \( n \) is the day of the year, and \( I_0 \) is the solar constant. Interestingly enough the temperature is actually higher during the aphelion when the sun is further away. This is due to the tilt and land distribution; the land is distributed more in the northern hemisphere. During the northern summer, the North Pole is tilted more toward the sun, and more land is irradiated. The land heats up easily compared with oceans, and this leads to a higher temperature on earth when the earth is further away from the sun. When passing through the atmosphere, some solar radiation reaches the earth’s surface as a direct beam, and some is scattered or absorbed by the atmosphere [5], aerosols (fine solid particles and liquid droplets), and clouds. Gaseous molecules, aerosols, and clouds cause most of the absorption, which heats up the atmosphere. All of the UV-C and most of the UV-B are absorbed by oxygen and ozone in the stratosphere.

1.2 Scattering

The amount of scattering of light is influenced by the length the light travels through the atmosphere. This length can be defined as the air mass:

\[
AM = \frac{L}{L_0} \approx \frac{1}{\cos(\theta_z)}
\]  

(2)

Where \( L \) is the length through the atmosphere, \( L_0 \) the length at perpendicular incidence, and \( \theta_z \) the solar zenith angle [7].

The scattering processes can be described by two different processes: Mie scattering and Rayleigh scattering. The scattering process is determined by the particle diameter in relation to the wavelength of the light. For water droplets and ice crystals, the particle diameter is typically of the same order as the wavelength, and therefore, Mie scattering applies. Mie scattering is equal for all wavelengths and
tends to give the scattering particles a white appearance, such as for clouds. An example of this phenomenon in nature is shown in Figure 2a.

For gas molecules in the atmosphere, the particle diameter is much smaller than the solar wavelength, and therefore, Rayleigh scattering applies. The scattering cross section for Rayleigh scattering is given by:

$$\sigma_s = \frac{2\pi^5}{3} \frac{d^6}{\lambda^4} \left( \frac{n^2 - 1}{n^2 + 2} \right)^2$$  \hspace{1cm} (3)

Where $n$ is the particle refractive index, $d$ the particle diameter, $\lambda$ the light wavelength. The scattered fraction is given by:

$$\frac{\sigma_s}{C_1 N}$$  \hspace{1cm} (4)

Where $N$ is the number of particles. What we can conclude from Eqs. (3) and (4) is that the shorter the wavelength is, the more scattering occurs. Additionally, a longer path through the atmosphere (air mass), which will increase $N$, will result in more scattering. A diagram depicting the effect of Rayleigh scattering is shown in Figure 2c. What the phenomenon can look like in nature is shown in Figure 2b.

Figure 2. Measuring the components of solar irradiance: (a) natural appearance of Mie scattering with white clouds as the Mie scattering scatters light of different wavelengths equally [8, 9]. (b) Natural appearance of Rayleigh scattering. (c) Schematic of Rayleigh scattering with colors with long wavelengths (red, yellow, and green) scattering little and the short wavelengths (blue and UV) scattering more [10].
1.3 Zenith angle effect

However, the largest influence on the irradiance that is received at a horizontal surface is the angle at which it hits the earth surface. The irradiance on the surface is proportional to $\cos(\theta_z)$ where $\theta_z$ is the solar zenith angle [7], which is defined as the angle between the zenith and the sun. A diagram depicting this effect [11] is shown in Figure 3.

The solar zenith angle is a.o. dependent on the location, time of day and season, and can be calculated using SOLPOS [13].

1.4 Solar spectrum

The solar spectrum at the top of the atmosphere is very similar to the Planck’s curve (black body radiation), as shown in Figure 4. The atmosphere influences the irradiance, and absorptions occur due to gaseous molecules such as $\text{O}_2$, $\text{H}_2\text{O}$, $\text{O}_3$, and $\text{CO}_2$, which are also depicted in the same figure.

The regions of the spectra can be subdivided in: UV: 200–400 nm, visible: 400–780 nm, and near infrared: 780–3000 nm [14].

![Figure 3.](image-url) Diagram [12] depicting the solar zenith angle effect, which has the largest effect on the amount of solar irradiance that is received on a horizontal surface on the earth. Shown here is a case on the equator (b) and a case close to the North Pole (a).

![Figure 4.](image-url) The spectrum of solar radiation on earth (with slight adjustment) from: “Spectrum of Solar Radiation,” by Tuwalkin is licensed under CC BY-SA 3.0.
With changing air mass (in other words, the solar zenith angle), the amount of scattering and absorption changes, and therefore, the spectrum does as well. An example of this is shown in Figure 5 where solar spectrum curves have been calculated using the Dr. Christian Gueymard’s SMARTS software [15–17]. This software allows for setting various clear sky atmospheric parameters for calculating clear sky solar spectra.

Additionally, also the cloudiness influences the spectrum that is visible on the earth surface. Three examples, for clear, cloudy, and hazy sky conditions are shown in Figure 6. Generally, there can be said that increase of cloudiness, just as increase of air mass (or solar zenith angle), generates a shift (in the relative spectrum) toward the red part. There will be relatively less blue and more (infra) red for more cloudy conditions than for clear sky.

1.5 Components of solar radiation

The irradiance from the sun interacts with the atmosphere, and when it arrives on the earth, it can be detected as different components (shown in Figure 7). These components are: direct normal irradiance (DNI), solar irradiance from the direction of the sun on a surface perpendicular to the solar rays. Diffuse horizontal irradiance (DHI) is scattered solar irradiance from the sky (except the sun) measured horizontally. Global horizontal irradiance (GHI) is the solar irradiance from the
hemisphere above on a horizontal surface, and plane of array (POA) or global tilted
irradiance (GTI) is solar irradiance incident on a tilted plane (PV panel) including
radiation reflected from ground and shadowing. POArear is the solar irradiance
incident on the back of the tilted plane, which is relevant for bifacial modules that
can generate power from rear side irradiance.

For concentrated solar power (CSP) [19], generation of DNI is of most interest
and for PV panels POA, POArear, and GHI are of interest.

The three solar components as measured on a clear day are as shown in Figure 8.
The direct irradiance shows a typical parabola, and the diffuse is more or less
constant sufficiently after sunrise or before sunset. The global irradiance is less than
the direct component and is less peaked due to the solar zenith effect.

These different components can be measured with pyranometers, pyrheliome-
ters, and solar trackers as shown in the next paragraph.

2. Measurement of solar irradiance

Solar irradiance is measured with many different radiometers depending on the
desired measurement. For the UV region, radiometers are available that measure
the UV-B, UV-A, total UV, or UV erythema (irradiance that causes sunburn). There
are thermopile radiometers, also called pyranometers, that measure from 280 to
roughly 2800 nm. Also, there are photodiode variants of the pyranometer that
typically measure from 300 to 1000 nm. And there are pyrgeometers that measure in the infrared.

For PV applications, the most relevant radiometers are the thermopile and silicon pyranometers as well as the pyrheliometers.

A pyranometer, its name derived from Greek (Πυρά–ἀνω–μετρέω, pyra–ano–metreo, fire–heaven–measure), is a thermopile-based instrument, with broadband black coating, which measures the net radiation coming from a 180° half dome above the instrument, allowing measurement of GHI, POA, or DHI. The pyrheliometer, its name derived also from Greek (Πυρά–ἥλιος–μετρέω, pyra–helios–metreo, fire–sun–measure) consists of a collimation tube with an opening angle of 5° and slope angle of 1°, which blocks the light not coming from the direction of the sun, allowing a measurement of the solar beam (or DNI) when pointed at the sun.

Examples of these instruments measuring the different solar components are given in Figure 9, where it is shown that pyranometers can be used to measure GHI, POA, and DHI. For measuring DHI, both a shadow ring and a solar tracker with shading ball can be used. The shadow ring is a smaller investment but would have to be adjusted manually depending on the change of the sun elevation, which changes over the year. The solar tracker tracks the sun automatically without manual adjustment. For measuring the DNI also a solar tracker is used to point the pyrheliometer at the sun.

Solar irradiance measurement is important in many fields such as meteorology, climatology, building automation, and material research. However, the fastest growing application is in solar energy.

Solar energy applications are both in concentrated solar and in photovoltaic energy generation. For concentrated solar, the sunlight is concentrated to heat a small area, which generates electricity as a conventional power plant. The

Figure 9.
Measuring the components of solar irradiance: (a) GHI with pyranometer, (b) POA and POArear with a tilted pyranometer next to bifacial modules, (c) DHI with shadow ring and pyranometer, (d) DHI with shading ball on tracker, (e) DNI with pyrheliometer on a tracker, (f) SOLYS gear drive sun tracker with shading balls, pyrheliometer, and ventilated pyranometers [14].
measurements of importance for concentrated solar are the three solar components with an emphasis on the DNI.

For photovoltaic energy generation, the sunlight is used for direct conversion to electricity in the modules. The measurements of importance for photovoltaics are POA and POA_{rear} for the calculation of performance ratio. Additionally, other components can also be importance, such as GHI for comparison of data to local meteorological stations or satellite observations and also albedo measurements for bifacial plants.

2.1 Solar monitoring using IEC 61724-1

From the IEC 61724-1 [18], there are a number of classes of solar monitoring: class A and B (going from high to low accuracy). Requirements regarding the sampling and recording intervals for irradiance measurements are as follows:

<table>
<thead>
<tr>
<th></th>
<th>Class A</th>
<th>Class B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. sampling interval</td>
<td>5 s</td>
<td>1 min</td>
</tr>
<tr>
<td>Max. recording interval</td>
<td>5 min (1 min recommended)</td>
<td>15 min</td>
</tr>
</tbody>
</table>

The data have to be stored with a date and timestamp in either local or universal time.

The number of POA or GHI sensors recommended depends on the size of the power plant as well as the desired class of the monitoring system. For example, 5–40 MW would require two sensors and 500–700 MW six sensors.

Depending on the desired accuracy class, there are three possible choices of sensors: irradiance sensors such as thermopile or photodiode pyranometers, matched irradiance sensors such as reference cells.

Before using the measurement data in performance ratio calculations, a data quality check needs to be done where invalid data are identified and filtered out. Additionally, missing data will have to be treated in a certain way such as: taking the data from before and after the missing data, using a predefined method from a contract, or leaving the interval out of the analysis.

2.2 Application in photovoltaics

In photovoltaics, there are many applications for measuring solar irradiance with one of the first fields where measurements are important in the technology research (see Figure 10) [20].

![Figure 10](image-url)  
(a) GHI and (b) POA technology research using pyranometers and pyrheliometers.
Improvements in mass-produced PV technologies, such as crystalline silicon cells, are incremental; each step is small, but the total gain can be large. For example, two different solutions may show efficiencies of 20% and 22% (10% improvement) under controlled laboratory test conditions. However, the irradiance needs to be measured with an uncertainty of better than 2% to be sure that the efficiency improvement is genuine. Laboratory testing under indoor conditions is not enough. The performance of cells and modules needs to be verified in the real-world settings under varying meteorological and sky conditions compared with “reference” quality solar radiation measurements. Therefore, research institutes are equipped with scientific-level pyranometers, and in many cases, a complete solar monitoring station.

Apart from research, irradiance measurements are also used for quality control if a manufacturer or a supplier wants to know if the performance of their PV cells or modules does not vary by more than (for example) 5%, they need to test samples from production batches and measure the solar radiation with a significantly lower uncertainty. Verification of published specifications of equipment the manufacturer or an independent test laboratory, needs reference quality measurements.

2.3 Performance ratios

There are many stages in the development of a utility-scale solar power plant, and throughout its operational life and in all of them, the performance ratio (PR) is of key importance. In the early stages, this is an estimation or prediction but, in the later stages, it uses real plant monitoring data. PR is the ratio between the final (actual) yield of a solar power generating system and its reference (design) yield over a defined period of time. For PV systems, the actual yield of the generated AC power is easily measured accurately at the grid connection. The reference yield is the expected power produced by irradiance on the PV modules; the solar energy received by the panels multiplied by the efficiency of the conversion to electrical energy and which should include the inverter efficiency, cabling, and connection losses. Performance ratios (if defined and monitored in the same way) can be used to compare solar plants at any locations: a well-designed, -installed, and – maintained solar park in the northern latitudes could have a better PR than an averagely designed and installed solar park near the Equator (although the latter receives far more energy from the sun). How to calculate the performance ratio is defined in IEC 61724-1 [18] (of which a new version has come out in the summer of 2021):

\[
PR = \left( \frac{\sum_k P_{out,k} \times t_k}{\sum_k \frac{P_0 \times G_{i,k} \times t_k}{G_{i,ref}}} \right)
\]

Where \( P_{out} \) is the power out, \( t_k \) is the time period, \( P_0 \) is the power out under reference conditions, \( G_{i,k} \) is the in-plane irradiance (POA) during time period \( k \), and \( G_{i,ref} \) is the POA during reference conditions. For reduction of variation in this PR for the different seasons, a temperature-corrected formula is also provided in IEC-61724-1.

2.4 Site prospecting

A solar energy project starts with site prospecting—finding the optimal location for the plant. Solar energy resource maps are widely available and are often used to derive the potential for solar electricity in a particular region. These are usually
generated from models using up to 10 years of satellite data and ground-based meteorological observations (often widely spaced and not very accurate) and interpolation. However, the map data are not good enough quality, and the spatial scale too large, to provide a reliable basis on which to make technology and investment decisions for a power plant. Due to local climate and topographical differences, relatively small changes in location can result in a gain, or loss, of hundreds of annual sunshine hours per year, particularly in mountainous and coastal areas and for islands. Other meteorological factors also have to be taken into account such as cloud, fog, and rain that reduce the amount of energy produced. Local infrastructure issues also play an important part, site access for construction and maintenance, and proximity to a grid to feed in the generated power.

The information above would allow potential sites to be short-listed. However, in order to decide on which are the most economically attractive, and to select the optimum power generation technology for a site, high-quality ground-based irradiance measurements over at least a year are required. Meteorological measurements by an automatic weather station are also needed and allow comparison with historical data to ascertain if it is a typical year. The parameters are usually wind speed and direction, precipitation, air temperature, and relative humidity, GHI measurements by pyranometers can be used to validate and “train” for that specific location the GHI estimates derived from satellite data models. POA irradiance cannot be accurately derived with a model at a suitable level of uncertainty in order to make investment decisions, this needs local tilted pyranometers.

 Experienced investors want the lowest uncertainty of the on-site solar resource data, generating equipment performance and proven reliability, before making decisions on the locations for solar energy plants and on the most effective PV system types to use. Errors in the solar radiation measurements can significantly impact upon the difference between predicted and achieved return on investment.

 The estimated performance ratio indicates the potential profitability of a PV plant, and high-quality, reliable local solar radiation data are critical to the bankability of projects. See Figure 11 for an example of prospecting.

2.5 Plant design

Good solar plant design optimizes yield and reduces losses, resulting in a high PR [21]. The design and the equipment selected are heavily influenced by the environment surrounding a solar energy plant in terms of irradiation, sun elevation paths, shading (by mountains, trees, buildings, clouds), temperature ranges, precipitation, wind, pollutants, and soiling.

These environmental factors are important information retrieved during the site prospecting phase: most are naturally occurring and cannot be easily changed, and

![Figure 11](image.png)

*Figure 11.* Solar prospecting of GHI and tilted GHI or POA.
they influence the mechanical and electrical design but also the expected main-
tenance required during plant operation. Often, stakeholders have a preferred list of
suppliers; companies and products with good quality, performance, reliability, and
cost over the lifetime. Higher quality and performance instruments will in general
provide a more reliable long-term performance ratio, with lower uncertainty. By
using accurately measured solar irradiance and the back panel temperature-
corrected performance ratio, two critical environmental parameters for PV systems
are taken into account, both for the reference and final yields. A mean annual
temperature 2°C higher than the value used in the reference calculations can drop
the PR by 1%. Accurate local measurements also enable PR to be used over shorter
time periods, for instance, monthly.

2.6 Installation and commissioning

Following the design scheme as closely as possible during construction and
installation is key to reaching the projected reference PR. An initial period of
operation, from several weeks to months, is used to calculate the commissioning PR.
From this a target PR is derived. The contractually agreed target performance ratio
(sometimes called the guaranteed performance ratio) is often slightly lower than
the final PR, to allow O&M parties to correct faults and restore interrupted opera-
tion. A checklist for this is provided by the 2015 International Finance Corporation
showing a high performance ratio after the initial building, commissioning, and
operation time periods, EPCs can show their ability make well-performing PV
plants. Plants like these will generate a higher selling price on the secondary market
and reduce the future risk for the buyers. But, to do this requires suitably quality
irradiance data.

2.7 Plant operation

The monitoring of a solar power plant [20, 21] is a complex process with many
stages, from solar energy input to grid electrical power output. For all these stages,
separate instruments and associated software are available to monitor the process.
During the first few years, the final performance ratio of the plant is determined,
operating efficiency is maximized, and the true O&M costs can be assessed, leading
to an overview of the financial return on the investment. Of course, this includes
the quality of the solar irradiance data. By maintaining yield and availability at high
levels at modest costs, O&M parties can show their added value in optimized
operating and maintenance policies. A high performance ratio shows the quality of
their work. Gradual changes in efficiency compared with the local irradiance mea-
surements may indicate dirty panels, so cleaning actions can be scheduled. More
sudden changes may indicate a defective section, a cable and connection problem,
or an inverter issue, so further service actions are required to find the problem. See
Figure 12 for examples of operational monitoring.

2.7.1 Output forecasting

Using high-quality solar radiation monitoring at the plant, a dataset of perform-
ance can be built up, allowing more accurate forecasting of the future energy yield
and financial returns [22, 23]. Real-time measurements and a historical database can
be used in conjunction with satellite data and weather forecasts as inputs to now-
casting models for the output of the plant in the coming hours. This is of particular
interest to grid operators, as other power generation sources cannot be switched instantly when clouds pass over the solar energy plant.

2.7.2 Reinvestment

Over time, the plant PR will degrade and a business case for refurbishing can be made involving investment in new equipment: replacement panels, inverters, transformers, cabling, etc. Studies such as the Compendium of Photovoltaic Degradation Rates from NREL [24] show that the performance of PV panels commonly reduces by 0.5–1% per annum. A refurbishment might take place after 20 years of operation, or when a power plant is sold on, and the replacement will normally have better specifications and performance than the original equipment.

PV panels have a wide field of view and must be positioned in such a way as to receive the maximum amount of solar radiation at the desired time of year. Depending on the local conditions, as well as the land price per area, a cost/benefit decision can be made whereby they are usually installed at a fixed angle. In this case, a pyranometer is required, tilted in the plane of array of the fixed panels to measure the solar radiation received by the modules. As this pyranometer is part of the plant performance monitoring system, a second POA unit is often fitted for redundancy and back-up in case of recalibration of one of the units. If the panels vary significantly in their azimuth and/or zenith angles, for example, where the plant is across a valley or an undulating hillside, additional pyranometers are needed. As the plant size increases, it takes time for clouds to move across, and some parts will be in shadow, and others will be in sunshine, requiring more irradiation measurement points. To maximize the use of the available solar energy, PV panels are often installed on mountings that move to follow the sun during the day, either by rocking about a single axis or on a two-axis sun tracker. POA pyranometers can then be mounted to the module frames (Figure 12).

3. Pyranometer measurement principles

Both instruments consist of a thermal element (either a thermopile or Peltier) built into a metal body [25, 26]. A thermopile consists of multiple thermocouples, consisting of two different metals connected at a “hot” and “cold” junction that generate a voltage when subjected to a temperature difference. Solar irradiance heats the black coating of the instrument, which also results in a temperature increase of the “hot” junctions of the thermopile. The “cold” junctions of the thermopile are in contact with the colder metal body. The resulting temperature difference between the hot and cold junctions generates a voltage through the
Seebeck effect. This effect is linear with the temperature difference and the magnitude determined by the Seebeck constant of the materials of the thermopile. With either an external datalogger or an onboard ADC for digital sensors (e.g., the Kipp & Zonen SMP pyranometers), the voltage is measured, and the irradiance can be obtained.

**Figure 13** shows the basis of a thermopile pyranometer with a thermocouple diagram (a) and the combination of multiple of these thermocouples to form a thermopile as shown in photograph (b). The physical effect that generates a voltage across the thermocouple (and thermopile) is the Seebeck effect:

\[ V_{\text{Seebeck}} = \alpha \cdot \Delta T \]  

(6)

Where \( V_{\text{Seebeck}} \) is the Seebeck voltage, \( \alpha \) the Seebeck coefficient, and \( \Delta T \) the temperature difference. How the thermopile functions within a pyranometer to measure solar irradiance is shown in **Figure 14**.

Where the sunlight is transmitted by the dome onto the black coating on top of the thermopile (or in some cases, a Peltier showing the same voltage effect). The black coating heats up as does the underlying thermopile hot side. The thermopile cold side is connected to the heat sink and remains at ambient temperature, and this generates a temperature gradient over the thermopile. Because of this temperature gradient, the Seebeck effect generates a voltage difference at the thermopile output.

**Figure 14.** Depiction of a pyranometer with the dome, black coating, thermopile, and heat sink, with sunlight incident on the pyranometer.
The measurement of the voltage allows for a measurement of the irradiance onto the pyranometer.

3.1 Pyranometer classification

Pyranometers are classified according to ISO 9060:2018 (in order of increasing quality: “class C,” “class B,” and “Class A”). The higher the instrument class, the better the time response, zero offsets, nonstability, nonlinearity, directional response, clear sky global horizontal irradiance spectral error, temperature response, tilt response, and additional signal processing errors. Two other additional

Figure 15.
(a) Kipp & Zonen thermopile pyranometer and silicon pyranometer spectral response plotted with the solar spectrum; (b) recalibration data of a CM22 Kipp & Zonen pyranometer located at NREL over 20 years [27]; and (c) nonlinearity of a class A pyranometer.
classifications are spectrally flat, for a constant spectral response from 350 nm to 1500 nm, and fast response, for a response time of less than 0.5 seconds.

The stability of a Kipp & Zonen CM22 pyranometer is shown in Figure 15b and shows a very stable instrument over nearly 20 years at NREL in Golden USA, based on publicly available data of recalibrations [27]. The nonlinearity of a class A Kipp & Zonen pyranometer is shown in Figure 15c and shows a nonlinearity very of approximately 0.13% at 1000 W/m².

Both thermopile pyranometers and silicon pyranometers can be classified using the ISO 9060 standard. The most significant difference between the two is the spectral response as shown in Figure 15a, with the thermopile pyranometer having a spectral response, combined from measured black coating absorptance, glass transmission, and Fresnel reflections, that is very flat from 0.3 to 2.7 μm, encompassing 99.8% of the solar spectrum. The silicon pyranometer has a varying response over a smaller range of the solar spectrum, which results in a somewhat higher spectral error for clear sky global horizontal irradiance.

### 3.2 Pyranometer calibration and uncertainty

The pyranometers and pyrheliometers are calibrated to the World Radiometric Reference (WRR). This reference is recognized by SI as a conventional standard for solar radiation measurements and is maintained by the World Standard Group (WSG) consisting of absolute cavity pyrheliometers (Figure 16). At Kipp & Zonen, we use an absolute cavity pyrheliometer (PMO-6) and a pyrheliometer (CHP1) calibrated against the WSG at the International Pyrheliometer Comparisons (IPC) every 5 years and checked at the National Pyrheliometer Comparison (NPC) at the National Renewable Energy Laboratory (NREL) in Golden Colorado annually.

With these pyrheliometers, we calibrate the reference pyranometers according to the Alternating Sun Shade (ASS) in ISO 9846. The ASS method as compared with the Continuous Sun Shade (CSS) method has the advantage of a lower calibration uncertainty, as well as a lower influence during calibration by offsets varying with atmospheric conditions [29]. The setup for ASS, which alternatingly exposes and shades pyranometers and simultaneously measures the DNI with an absolute cavity pyrheliometer, is shown in Figure 17a. To transfer the calibration of the reference to the production instruments, the ISO 9847 is followed using the direct beam Kipp & Zonen method with a lamp as a light source (see Figure 17b).
The uncertainty of pyranometers in the field is a combination of the calibration uncertainty and the interaction of the pyranometer parameters with the site conditions.

The calibration uncertainty is stated on a calibration certificate and consists usually of a combination of the uncertainty of the reference pyranometer combined with the uncertainty of transferring the calibration from the reference to the pyranometer to be calibrated. Calibration uncertainties (with a coverage factor of $k = 2$, 95% confidence interval) of pyranometers can be as low as below 1% depending on the pyranometer parameters as well as the calibration process.

The uncertainty of a pyranometer in the field is dependent not only on the calibration uncertainty and instrument quality, but also on the site conditions such as location, time, sky conditions, and instrument maintenance. This can be calculated with the help of the Suncertainty app for different Kipp & Zonen pyranometers as a function of site conditions [30].

4. Alternative measurement methods

Alternative methods for measuring irradiance are reference cells or satellites. Reference cells, if completely identical to the PV panel, allow one to determine the energy the PV panel collects. However, to measure the broadband irradiance, their accuracy is less good than that of pyranometers. Furthermore, some research questions the stability of non-monocrystalline silicon reference cells [31]. Satellite-derived irradiance data have generally a lower accuracy, especially for short time frames, but can be complementary to ground measurement. Satellites perform better under clear sky conditions than cloudy conditions [32], and for longer time scales, the uncertainty is reduced [33].

5. Conclusions

Solar irradiance is of utmost importance for PV energy generation and can be affected in different ways. To a lesser extent, it is the variation of sunlight reaching the top of the atmosphere due to the sun cycle as well as the variation in sun-earth distance. To a larger extent, the atmosphere creates a variation by scattering at
particles or clouds. Additionally, the solar zenith angle, varying with season and solar time, is of large influence.

POA solar irradiance can be measured with pyranometers, silicon pyranometers, and reference cells. These measurements are necessary for PV site prospecting, design, and operation.

For solar energy applications, pyranometers have the lowest uncertainty for GHI and POA broadband irradiance measurements, and aside from absolute cavities, pyrheliometers are the most accurate way to measure DNI.

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Conflict of interest

The author declares a conflict of interest as he is working as a scientist at Kipp & Zonen, pyranometer manufacturer.

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