Solar Radiation Measurements for Solar Energy Applications

KIPP & ZONEN
SINCE 1830

Precision Monitoring of **Solar Radiation** for **Photovoltaic** and **Thermal Concentrating Solar Energy Systems**

technology research • quality control • optimise locations • select system type • inform investment decisions • maximise operating efficiency • schedule maintenance • monitor performance • output forecasting

Why is Accurate Solar Radiation Measurement Critical for Solar Energy?

Good quality, reliable radiation data is extremely important for all activities in the solar energy sector. Photovoltaic (PV) and concentrating solar power (CSP) thermal systems may have slightly differing requirements, but they need accurate solar radiation information for the same reasons.

Technology research

Improvements in PV technologies are often 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 ideal laboratory simulation. However, this needs to be verified in the real world under varying weather and sky conditions compared to 'reference' quality solar radiation measurements.

Quality control

If a manufacturer or a supplier wishes to ensure that the performance of their PV cells or panels does not vary by more than (for example) 5 %, they need to measure the solar radiation significantly more accurately than this. To verify specifications the manufacturer, or independent test laboratory, needs reference quality measurements.

Optimise locations

Solar energy resource maps are widely available and a map for Europe is shown. Such maps are often used to derive the potential for solar electricity generation in a particular region. However, they are generated from satellite data, ground-based meteorological observations (often widely spaced and not very accurate) and interpolation. The map data is usually not of good enough quality, and the scale is too large, to provide a reliable basis on which to make technology and investment decisions. Due to micro-climate and topographical differences, changes in location of a few hundred kilometers can result in a change of hundreds of annual sunshine hours.

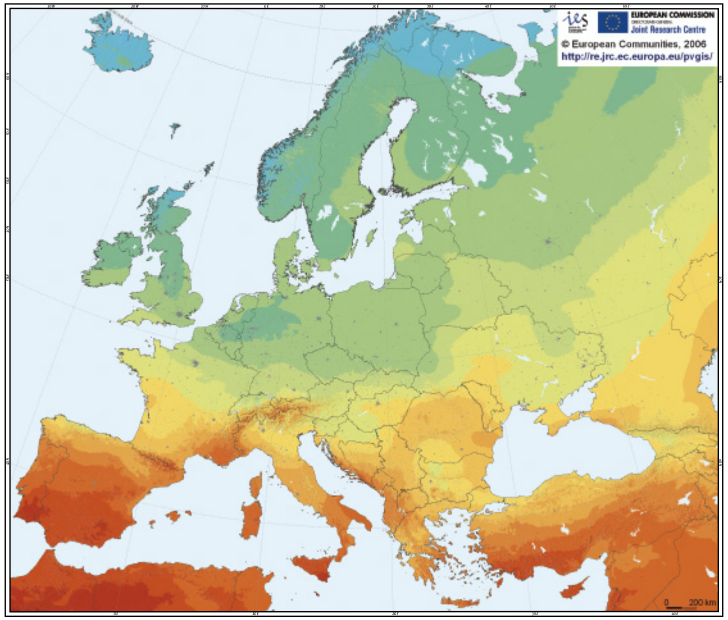
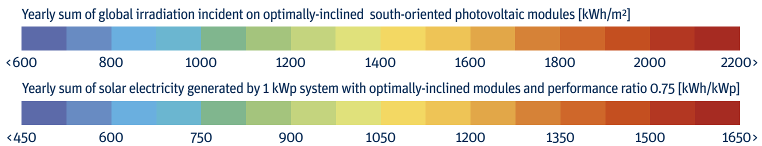


figure 1: energy resource map for Europe showing the annual amount of global solar radiation available

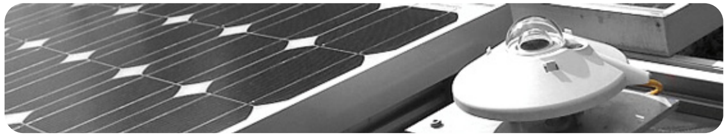


Šúri M., Huld T.A., Dunlop E.D. Ossenbrink H.A., 2007. Solar Energy, 81, 1295-1305, http://re.jrc.ec.europa.eu/pvgis

Having selected potential sites based on resource maps and other criteria (access, distance to grid, climate, etc.), these locations need to be evaluated by making high quality on-site measurements of the solar radiation (energy) over at least a full year. The temporal resolution must be sufficient to understand real-time variations on a daily basis (for example, a particular location may have a lot of sun, but if there is too much pollution or dust at certain times, the site may still be unsuitable).

Select system type
The on-site measurements need to be independent of the power generation technology so that the most appropriate type for the location can be assessed.

Inform investment decisions and improve bankability
Investors want the lowest uncertainty in the on-site solar resource data, equipment performance and reliability before making decisions on the locations for solar energy plants and on the most effective solar energy system types to use. Errors in the solar radiation measurements can significantly impact upon the return on investment. High quality solar radiation data is critical to the bankability of projects.



Maximise operating efficiency
Reference solar monitoring instruments at a plant provide the data to the control room to assess the efficiency of the energy generation chain.

Schedule maintenance
Good quality solar radiation inputs to each inverter allow the efficiency to be continuously checked. Rapid changes may mean that a panel needs to be replaced, short-term decline usually means that cleaning is needed; longer term drift is probably due to ageing. Clearly, this requires solar radiation measurements different from, and better than, the panels.

Monitor performance
Using high quality solar radiation measurements at the plant, a database of performance can be built up, allowing more accurate forecasting of the future energy yield and financial returns.

Output forecasting
Current solar radiation and meteorological measurements, and a historical database, can be used in conjunction with satellite data and weather forecasts as inputs to now-casting/forecasting models for the output of the plant. This is of particular interest to grid operators, as other power generation sources cannot be switched in instantly when clouds pass over the solar energy plant.

Introduction to Solar Radiation

The sun provides 99.98 % of the energy for our planet (the rest is geothermal) and it is responsible, directly or indirectly, for the existence of life on Earth. The sun is a star that consists of 71 % Hydrogen, 27 % Helium and 2 % solid matter. Near the sun's core the temperature is approximately 16 million degrees and at its outer layer (the Photosphere) it is about 5,770 Kelvin. The energy emitted by the sun is approximately 63 MW for every m² of its surface, about 3.72 x 10^{20} MW in total.

The SI unit for the measure of irradiance (radiative flux) is Watts per square metre (W/m²). At the mean distance between Earth and sun of 150 million kilometres, the flux of the solar radiation reaching the Earth's atmosphere is 1,367 W/m² (World Meteorological Organisation, 1982). This quantity is named the Solar Constant. There are various processes inside the sun and at its surface, such as the sun spot cycle and solar flares, that cause fluctuations in the emitted radiation, but these are not more than 0.1 %.

The Earth's distance from the sun varies due to its elliptical orbit, so the 'extra-terrestrial' radiation at the top of the atmosphere is 6.6 % higher on January 4^{th} (Perihelion, closest approach) than it is on July 4^{th} (Aphelion). These dates are not the same as the Winter and Summer Solstices (shortest and longest days in the Northern Hemisphere) because the earth's axis of rotation is tilted by 23.5 ° relative to the orbital plane of the Earth around the sun (the ecliptic plane).

Due to the large distance between the sun and the Earth, the beam of radiation reaching the top of the atmosphere is almost parallel. This radiation ranges from high energy ultraviolet (UV) radiation through the 'visible' part of the spectrum, to the near infrared (NIR). The maximum intensities are found in the visible part of the spectrum, with wavelengths between 400 and 700 nm. The intensities in the UV and NIR regions of the spectrum are much lower. The sun does not emit far infrared radiation (FIR). However, when the Earth is heated by solar radiation, it does emit IR and FIR radiation, which is absorbed and re-radiated by gases, particles and clouds in the atmosphere.

When passing through the atmosphere some solar radiation reaches the Earth's surface undisturbed and some is scattered or absorbed by air molecules, aerosol particles, water droplets or ice crystals in clouds and ice in aircraft contrails. Gaseous molecules and aerosols cause most of the absorption. Scattering of solar radiation by water droplets and ice crystals takes place over the whole spectral range, whereas molecules predominantly scatter short wavelengths and aerosol particles mainly scatter longer wavelengths.

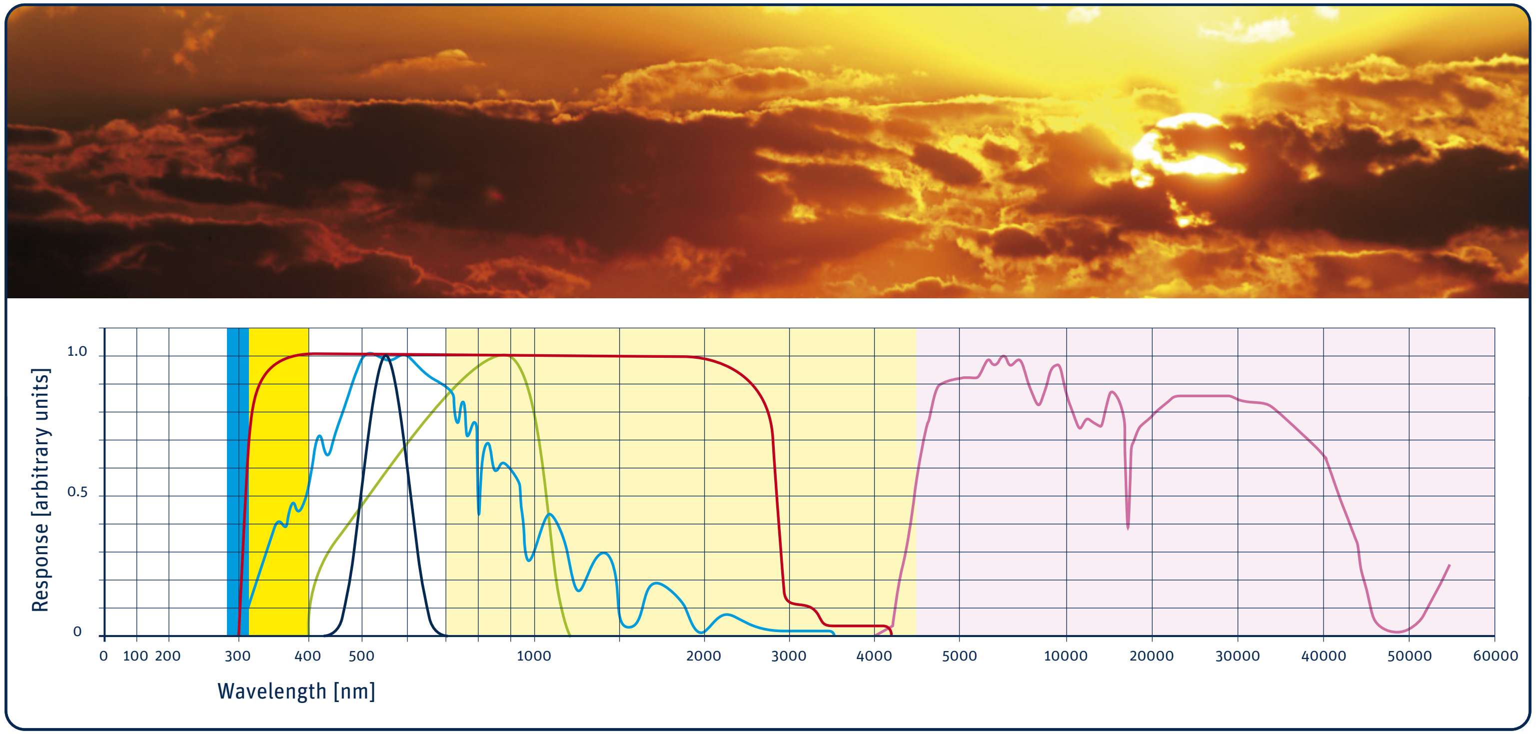


figure 2: the wavelength bands of radiation, where blue is UVB radiation, yellow is UVA, white is visible light, cream is near infrared (NIR), and pink is far infrared (FIR). The blue line represents the solar radiation at the Earth's surface, the black curve represents the sensitivity of the human eye, the green curve is the spectral sensitivity of a typical photovoltaic cell, the red curve represents the sensitivity of a thermopile pyranometer with glass domes, and the pink curve shows the sensitivity of a thermopile pyrgeometer. All are normalised to an arbitrary maximum of 1.0 unit for comparison purposes.

These processes significantly affect the spectrum of radiation that reaches the Earth's surface. When the sun is directly overhead the atmospheric depth/thickness is at a minimum, and is defined as having a Relative Air Mass of 1.0 for that location. As the sun moves down towards the horizon, the air mass increases to approximately 11 times larger and the effects of absorption and scattering are correspondingly greater.

Some of these processes are easily observed. Short wavelengths are scattered much more strongly by molecules in the atmosphere (Rayleigh scattering) than longer wavelengths, so when the sun is high the 'diffuse' sky appears blue. However, when the sun is near the horizon so much blue is scattered by the thick atmosphere that the skies in the morning and evening appear red.

On a day with a clear sky the irradiance reaching the Earth's surface is typically in the range from 700 to 1,300 W/m² at local solar noon; depending on the latitude, altitude and time of year.

For observations of radiation at the Earth's surface, two wavelength regions are defined; short-wave radiation, of wavelengths from 300 nm to 4,000 nm, and long-wave radiation from 4,500 nm (4.5 µm) to more than 40 µm. The short-wave radiation includes the ultraviolet, visible and near infrared wavelength bands.

The solar radiation reaching the Earth's surface is partly reflected and partly absorbed, depending on the reflectivity (albedo) of the surface. Snow and ice are good reflectors (high albedo), dark and/or rough surfaces in general reflect less efficiently (except

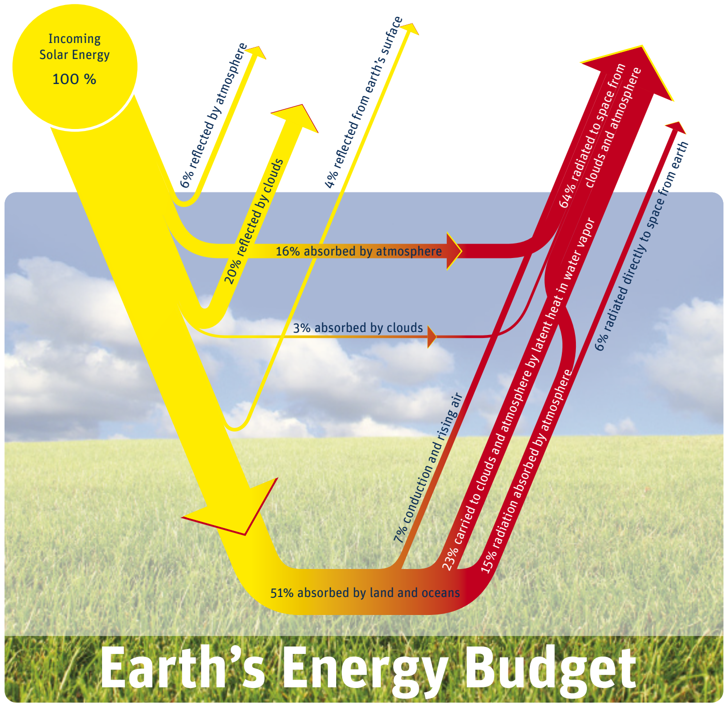


figure 3: schematic representation of the Earth's energy budget (or 'energy balance')

for specular reflections). A part of the radiation that is absorbed by the Earth's surface is radiated back into the atmosphere in the FIR wavelength range. Carbon Dioxide (CO_2), Methane (CH_4) and Water Vapour (H_2O) in the atmosphere can absorb this radiation, which in turn heats up the Earth's atmosphere. This is the well-known 'greenhouse effect'. In general there is an equilibrium, the Earth system receives as much solar radiation as it emits back into space, meaning that the Earth as a whole does not heat up or cool down.

How is Solar Radiation Measured?

High quality ground-based measurements of solar radiation are always made using radiometers with a flat spectral response over a wide spectral bandwidth. This is usually achieved using a 'thermopile' detector with a black coating that absorbs the incoming radiation, heats up, and converts the temperature rise into a small electrical signal.

The global horizontal irradiance (GHI) falling on to the Earth's surface consists of the diffuse horizontal irradiance (DHI) from the sky and the direct normal irradiance (DNI) from the sun. This is all short-wave radiation (UV, visible and near infrared). When the direct beam from the sun is falling obliquely onto the Earth's surface it is 'spread out' over a larger area than when it is directly overhead, so the energy per unit area is lower and this must be corrected by a cosine function.

The relationship of the components of solar radiation is:
$GHI = DHI + DNI*\cos(\theta)$ where θ is the solar zenith angle (vertically above the location is $0°$, horizontal is $90°$).

GHI is measured by a horizontally installed pyranometer. The thermopile detector is protected by one or two glass domes, which also determine the spectral response as shown by the red line in figure 2. Such instruments have been used for a long time in meteorological and climatology networks and in the solar energy research community.

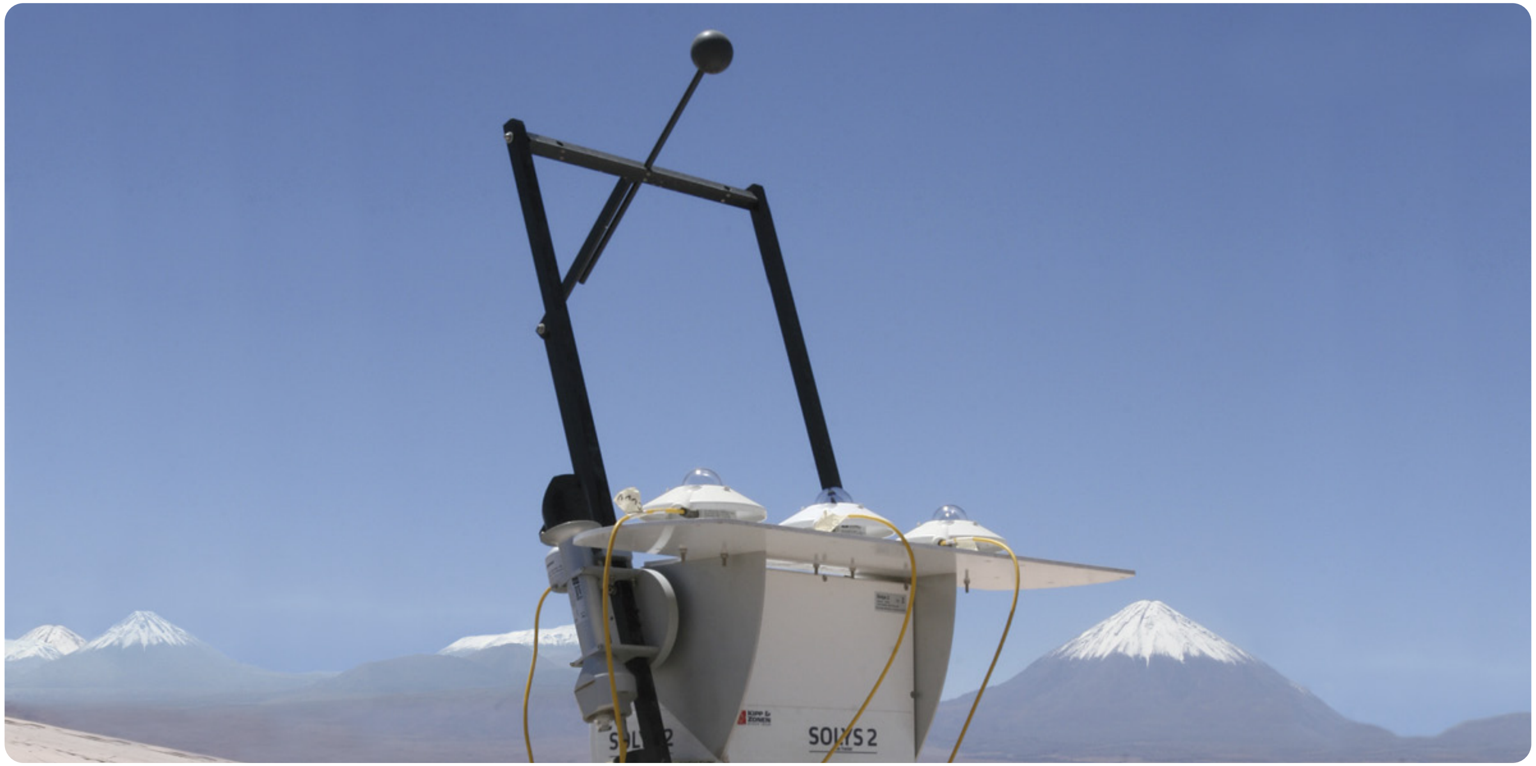
DNI is measured using a pyrheliometer. This is a thermopile type radiometer with a $5°$ field of view and a flat window. It follows that, in order to keep the radiometer pointed continuously at the centre of the sun, the instrument must be mounted on a high accuracy automatic sun tracker. The pyranometer for GHI may be conveniently mounted on top of the tracker.

DHI can be measured by fitting a second pyranometer on top of the sun tracker and a shading assembly that moves with the tracker to always block the direct beam radiation from reaching the pyranometer

The types of pyranometers and pyrheliometers, performance specifications, calibration methods, etc., have been defined by the World Meteorological Organisation (WMO) and the International Standards Organisation (ISO). Instruments that comply with WMO and ISO classifications, provide accurate measurements of the solar radiation under all weather conditions. Since the meteorological world and the scientific community are using the same types of instruments, the data can be compared with measurements from weather and climate station networks and satellites, across various locations, and independent of the type of solar energy system.

This combination of instruments, for GHI, DNI and DHI makes a 'solar monitoring station', to which a horizontally mounted pyrgeometer may be added to measure the FIR long-wave radiation to WMO specifications. A pyrgeometer is similar in principle to a pyranometer but the spectral response, shown by the pink line in figure 2, is determined by a silicon window (or dome) that transmits far infrared radiation and has a special internal coating to block the short-wave radiation.

The low level millivolt analogue outputs from the radiometers are normally connected to a data logger that records and stores the readings. Data may be forwarded in real-time via telemetry or a wired connection or periodically downloaded for processing and analysis. The unique new generation of Smart radiometers from Kipp & Zonen can be interfaced directly to digital data acquisition systems.



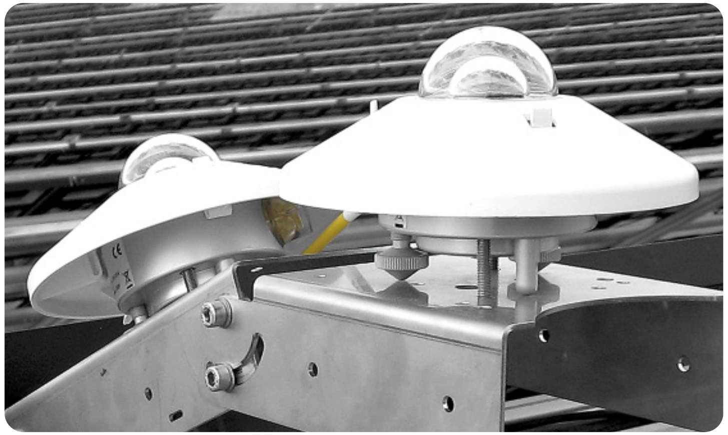
What Instruments are Needed for Research or Prospecting?

As previously described, measurements from WMO/ISO type pyranometers and WMO compliant pyrgeometers can be compared directly across sites anywhere in the world, with data from meteorological networks, with satellite information, and with solar radiation prediction algorithms. They are technology independent and can be used for any type of solar thermal energy or PV system and are therefore the ideal solution for solar energy research and site prospecting.

The basic requirement is always a horizontally mounted pyranometer to measure global horizontal irradiance (GHI) as a site reference. For research and site prospecting purposes high accuracy (low uncertainty) and reliable data is critical. This means pyranometers that meet, or exceed, ISO Secondary Standard classification. Kipp & Zonen CMP 11, CMP 21, CMP 22 and their corresponding 'Smart' models are capable of measuring the daily total of solar irradiance with a very low uncertainty of 1 to 2 %.

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. Depending on the location and cost/benefit decisions these panels may be installed in a fixed position at a fixed angle. In this case the only other instrument required is a second pyranometer. This is normally installed at the ideal angle for that location, to measure the 'tilted global irradiance' with the same view as a fixed panel.

To maximise use of the available solar energy PV panels are often installed on mountings that move to follow the sun during the day. Concentrating photovoltaic (CPV) and concentrating solar power (CSP) systems require the lenses or reflectors to be pointed at the sun with a high accuracy.



For these technologies it is necessary to measure the direct normal irradiance (DNI) with a pyrheliometer and an automatic sun tracker. The pyrheliometer should be ISO First Class, such as the Kipp & Zonen CHP 1 and 'Smart' SHP1, which can measure daily totals of solar irradiance with an uncertainty of 1 %. The sun tracker should have a pointing accuracy of 0.1 °, as with the Kipp & Zonen SOLYS 2 and 2AP models. Usually a pyranometer is installed on top of the Sun tracker to measure GHI. A second pyranometer with a shading assembly can be added to measure the diffuse horizontal irradiance (DHI). A third pyranometer can be mounted on the side of the sun tracker, pointing at the sun, to give the same moving 'tilted global' view as seen by a 2-axis PV panel.

Traditional photovoltaic (PV) semi-conductor materials are mainly sensitive in the visible and near-infrared parts of the spectrum, from approximately 400 to 1100 nm with a peak just beyond the visible radiation, as shown by the green line in figure 2. However, depending upon the sky conditions, there can be significant energy available from the ultraviolet radiation below 400 nm and also from near infrared radiation beyond 1100 nm. Therefore, materials development is pushing to make use of this resource. Increasingly, in PV research, a Kipp & Zonen CUV 5 'total UV' radiometer is being included to monitor the irradiance from 280 to 400 nm.

Concentrating solar power (CSP) systems typically use trough reflectors or tracking mirrors (heliostats) to focus the solar radiation onto a collector tube or tower, in which a liquid or gas is heated to very high temperatures (400 to 1,000 °C). The hot medium is usually used to generate steam that drives conventional turbines to generate electricity. Because of their reflective design, it is easy to understand that there is much less wavelength dependence for CSP's than for PV installations. They can focus all the available DNI UV, visible and NIR short-wave radiation from the sun and, on a cloudy day, the long-wave radiation from the atmosphere and clouds in the view of the reflectors and mirrors. For these systems a CGR 3 or CGR 4 pyrgeometer may be added to measure the long-wave radiation.

For solar site prospecting a simple automatic weather station is often added. This provides additional information to help with location decisions. PV cell efficiency is temperature dependent and high wind speeds may require very rugged panel mountings or be likely to cause damage. The sites are often remote and the prospecting system may need to operate from solar panels and batteries. Kipp & Zonen can supply solutions from a single pyranometer, to complete solar monitoring stations, including meteorological parameters, data acquisition and storage, telemetry solutions, and data visualisation.

Maintenance of Kipp & Zonen radiometers is simple; keep the domes and windows clean and periodically replace the desiccant that keeps the radiometers dry inside. Cleaning frequency can be reduced, and the uptime of good quality data increased, by using a ventilation unit such as the Kipp & Zonen CVF 3 that blows clean air over the pyranometer dome to help keep off dust and to remove raindrops and dew. The air flow can be heated to melt snow and frost.

Apart from the maintenance described, regular calibration is required to ensure that the radiometers operate within their specifications. Kipp & Zonen recommends recalibration of its radiometers at least every two years. All Kipp & Zonen calibration certificates are supplied with full uncertainty calculations and traceability to the standards at the World Radiation Centre in Davos, Switzerland.

What Instruments are Needed for Particular Solar Energy Plants?

Several types of solar radiation measurement instruments may be required within a single plant, depending upon the power generation technology in use and the purpose of the measurement within the plant operation and process flow.

One requirement is for 'reference' instruments that are used to quantify the solar energy available at the location. These are high quality, high accuracy instruments that can provide the data for comparison with other sites and other measurement sources, such as satellite data, and to build-up a historical, current, and trending data base for the site.

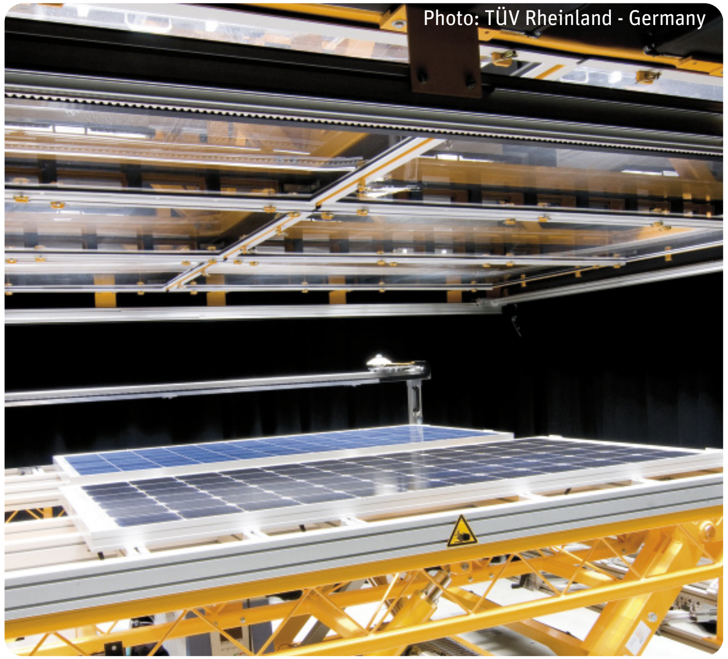


Photo: TÜV Rheinland - Germany

There is often a high quality automatic weather station that provides local historical and trending information that can be used with the solar radiation data as inputs to now-casting and forecasting models for the output of the plant. A large site may have two or more weather stations at the perimeter.

The radiometers for various solar power generation types are the same as those discussed in the previous section for research and site prospecting. In general, commercial power plants will have a complete solar monitoring station for GHI, DNI and DHI. Because these instruments are part of an industrial process there will usually be at least two systems, for redundancy and to provide backup when one set or radiometers is off-site being calibrated.

The other requirement is for pyranometers to check the efficiency of panels and arrays in PV plants. These could be fixed or tracking installations. Normally, each inverter has an input for a 'reference' pyranometer that is used to calculate the efficiency of the panels connected to that inverter. The pyranometer is usually mounted on one of the panel supports so that it has the same view as the PV panels. There may be a large number of these pyranometers on a plant, so instead of the ISO Secondary Standard Kipp & Zonen CMP 11, CMP 21, CMP 22 and 'Smart' SMP11 models, the ISO Second Class CMP 3 or 'Smart' SMP3 are used.

Pyranometers, such as the CMP 3 and SMP3, have largely replaced the 'reference cells' that were often used for the inverter inputs to calculate system efficiencies. There are several reasons for this.

PV modules are characterised under Standard Test Conditions using solar simulators that can seriously overestimate the module performance under operational conditions with varying temperatures, dirt accumulation, linearity effects, etc. A ‘reference’ cell of the same type will have the same problems, get dirty at the same rate and age at the same rate, therefore the efficiency will often show 100 %, which is unrealistic.

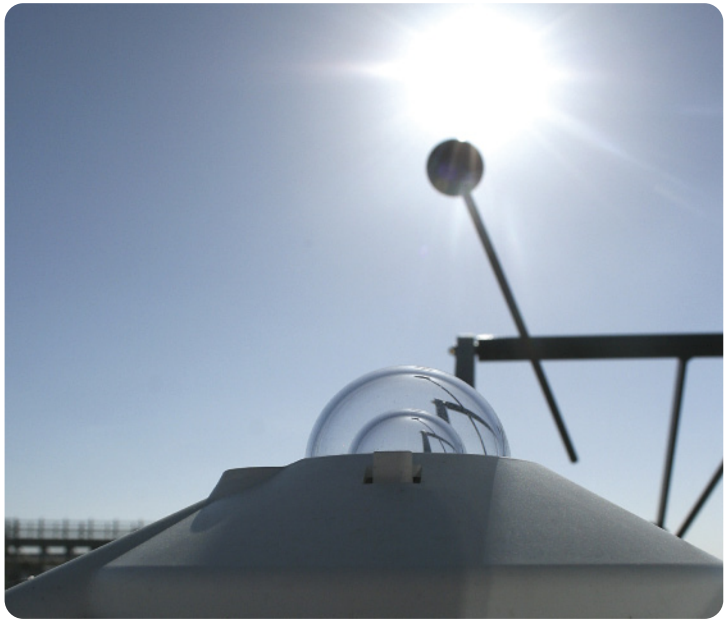
There are now many types of PV panels and reference cells, so it is difficult to compare one type with another, particularly when they have different (limited) spectral responses. This spectral mismatch can easily be 10 % and lead to calculated efficiencies of over 100 %! In fact reference cells and PV panels are themselves often calibrated against a Kipp & Zonen pyranometer at the test facility.

Because thermopile pyranometers have a broad and flat spectral response they measure all the solar irradiance available to the PV panel and it is easy to see how efficiently any panel of any type is using that energy, and meaningful comparisons can be made. The flat PV panels get dirty much more quickly than pyranometers with their dome construction. This means that it is possible to see when the panel efficiency is reducing in the short-term due to dirt, in the long-term due to ageing, or sudden changes that may be caused by panel or inverter failure.

Some International Standards, such as IEC 61724 “Photovoltaic system performance monitoring - Guidelines for measurement, data exchange and analysis”, specify that pyranometers must be used for the efficiency calculations.

Passion for Precision

Kipp & Zonen for all your Solar Radiation Measurements



Kipp & Zonen has been designing and manufacturing solar radiation measurement equipment since 1924 and has supplied its instruments for many decades to most of the leading meteorological, climatological and atmospheric science organisations, research institutes and energy companies around the globe.

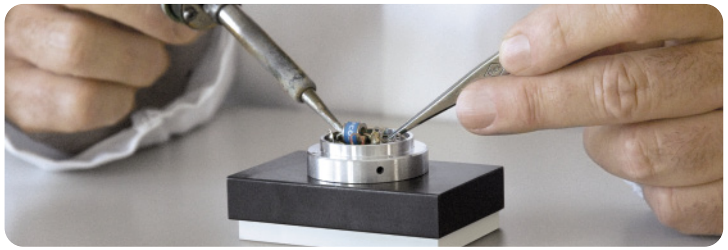
In addition to radiometers and sun trackers, Kipp & Zonen provides a wide range of accessories, data loggers and interfacing solutions. Our instrument calibrations are fully traceable to the World Radiometric Reference at the World Radiation Centre in Davos, Switzerland, and to relevant international standards.

The latest generation is the unique new range of 'Smart' radiometers that have integrated analogue-to-digital converters and micro-processors with digital signal processing. They provide polynomial temperature correction, faster response times and full two-way communication by RS-485 and Modbus® protocol to industrial digital data acquisition and control systems (SCADA, PLC, etc.). The radiometers are individually addressable so that many units can be linked together on a single multi-drop cable, saving on installation costs.

The 'Smart' radiometers also have built in digital-to-analogue converters to provide the enhanced performance as 0 to 1 V or 4 to 20 mA outputs. Both digital and analogue outputs have standardised ranges for simple installation and easy exchange during calibration.

Kipp & Zonen has a world-wide reputation for quality, reliability, expertise and support and all our products are provided with a two year warranty as standard. Extended warranties up to an additional 3 years are also available.

Please visit our website **www.kippzonen.com** for more information.



A Selection of Key Customers

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Pontificia Universidad Católica de Chile

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Akuo Energy
Bertín Technologies
CNR • Compagnie Nationale du Rhône
CSTB • Centre Scientifique et Technique du Bâtiment
EDF • Energies Nouvelles
Eole-Res
INES • Institut National de l'Energie Solaire
LE2P Université de la Réunion
Université de Corse
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Alfred-Wegener-Institute
CSP Services GmbH
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Forschungszentrum Jülich
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IBC Solar
ISE • Fraunhofer Institut für Solare Energiesysteme
Meteocontrol GmbH
Skytron Energy GmbH Berlin
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University Potsdam and others in Germany
ZSW • Zentrum für Sonnenenergie- und Wasserstoff-Forschung

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Netherlands
KNMI • Royal Netherlands Meteorological Institute

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Meteolabor AG
MeteoSwiss
Oerlikon Solar
University Basel

United Kingdom
Lightsource Renewable Energy Ltd

USA
Campbell Scientific
GroundWork
juwi solar inc.
Surya Design

System configurations

Basic Solar Monitoring
For fixed (tilted) panels
1 horizontal pyranometer for global radiation
1 tilted pyranometer for tilted global radiation

Recommended instruments:
CMP 3 | SMP3 | CMP 6 | CMP 11 | SMP11

Advanced Solar Monitoring
For concentrating and / or tracking systems
1 horizontal pyranometer for global radiation
1 pyrheliometer with sun tracker for direct radiation
1 tilted pyranometer fitted to sun tracker
1 horizontal pyrgeometer for infrared radiation (thermal systems)

Recommended instruments:
CMP 11 | SMP11 | CHP 1 | SHP1 | SOLYS 2 | CGR 4

Complete Solar Monitoring System
Includes global, direct, diffuse and global tilted measurement
1 horizontal pyranometer for global radiation
1 pyrheliometer with sun tracker for direct radiation
1 tilted pyranometer fitted to sun tracker
1 shaded pyranometer for diffuse radiation (shading assembly on sun tracker)
1 horizontal pyrgeometer for infrared radiation (thermal systems)

Recommended instruments:
CMP 11 | SMP11 | CMP 21 | CHP 1 | SHP1 | SOLYS 2 | CGR 4

Relevant IEC standards for PV panel testing

IEC 60904 (part1/10) Photovoltaic devices, measurements and requirements

IEC 61215 Design qualification and type approval, crystalline silicon

IEC 61646 Design qualification and type approval, thin film

IEC 61724 Photovoltaic system performance monitoring - Guidelines for measurement, data exchange and analysis

IEC 61853 Module performance testing

IEC 62108 Design qualification and type approval, concentrator photovoltaic (CPV) modules and assemblies

Relevant EN standard for thermal solar panels

EN 12975 Thermal solar system testing

Relevant ISO standards for pyranometers

ISO 9060 Specifications and classifications of instruments

ISO 9847 Calibration of field pyranometers

Traceability

All Kipp & Zonen solar radiation instruments are fully traceable to the World Radiometric Reference (WRR) in Davos, Switzerland, where Kipp & Zonen instruments form part of the World Standard Groups.

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