GUIDELINES ON SOLAR RESOURCE ASSESSMENTS FOR CSP POWER PLANTS

PROJETO Energia Heliotérmica

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This study has been elaborated by the project DKTI-CSP which is working in the context of the German Climate Technology Initiative. The project is realized by close cooperation between the Brazilian Ministry of Science, Technology, Innovation and Communication (MCTIC) and the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. The project aims at the creation of the necessary prerequisites for the successful application and dissemination of Concentrating Solar Power (CSP) in Brazil.

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ACRONYM DEFINITION

CSP	Concentrating Solar Power (Solar Thermal Power)
DHI	Diffuse Horizontal Irradiance
DKTI	Deutsche Klimatechnologie Inititative (German Climate Technology Initiative)
DLR	German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt)
DNI	Direct Normal Irradiance
DSG	Direct steam generation
GHI	Global Horizontal Irradiance
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit, Germany
HTF	Heat Transfer Fluid
IEA	International Energy Agency
IEC	International Electrotechnical Commission
INPE	National Institute for Aeronautic Research (Instituto Nacional de Pesquisas Espaciais)
ISIS	Irradiance at Surface derived from ISCCP cloud data
KfW	Kreditanstalt für Wiederaufbau, Germany
NASA-SSE	National Aeronautics and Space Administration- Surface meteorology and Solar Energy
PV	Photovoltaic
RSI	Rotating Shadowband Irradiometer
SHC	Solar Heating and Cooling
SolarPACES	Solar Power And Chemical Energy Systems
SWERA	Solar and Wind Energy Resource Assessment
T	Temperature
UTC	Co-ordinated Universal Time
WMO	World Meteorological Organization

EXECUTIVE SUMMARY

Direct Normal Irradiance (DNI) is the dominant meteorological parameter for Concentrating Solar Power (CSP) plants. DNI is the sort of sunlight, which contrary to diffuse radiation can be focused on absorbers to reach high radiation fluxes. Global Horizontal Irradiance (GHI) as the combination of diffuse and direct has usually much lower variability in space and time compared to DNI. DNI is also more difficult to measure and to derive from satellite data. Thus, uncertainty of DNI resources is usually substantially higher than that of GHI.

Also other meteorological parameters like wind, ambient temperature, humidity etc. influence the efficiency of CSP plants as well as many technical parameters to consider for simulating the yields. From probabilistic modeling it is known that today the uncertainty of DNI remains the single most source of uncertainty, when it comes to estimation of potential yields of CSP plants.

To reach low uncertainty of long-term DNI it is recommended to calculate a long-term average from a combination of qualified measurements on site with overlapping satellite data, which for most locations in the world are now available over at least 10 years. For the selection of satellite-data, which have show good quality in the region it is recommended to check validation reports by independent experts.

To achieve good quality of measurements the following measures are recommended:

- Select station location representative for the site with unobstructed horizon – best on site of the planned plant, but at least within 10 km distances.

- Select suitable station type with instruments, whose maintenance demand reliably can be met by the available local station keeper work force: pyrheliometer can provide higher quality, if daily cleaning can be secured otherwise Rotating Shadowband Irradiometers (RSI) today are an established choice for qualification of CSP projects.

- Assure high quality and up to date calibration of the installed radiometers – reliable RSI requires long-term outdoor calibration against high quality thermopile instruments.

- Document proper installation by station description report including all relevant calibration documents, photos of installation details and horizon line.

- Force regular maintenance especially cleaning by regular reports to be sent by the station keepers.

- Collect recorded data regularly (typically daily) and apply automatic quality control.

- Backup original data on independent data carrier at different location than primary

- Prepare regular (typically monthly) reports with extended quality checks.

- Check stations and perhaps re-calibrate radiometers at least every second year, best every year.

The overlap of the measurements with the satellite-derived solar radiation time-series should be at least 1 year. But each additional year of good quality measurements will further reduce uncertainty of the long-term average, which represents the P50 value. The lower the remaining uncertainty the higher will be the P70 or P90 value of the long-term average DNI.

For simple financial calculations only a single year representing the long-term average P50 value is used in combination with a second annual data set representing either e.g. the P70 or alternatively the P90 value. Sophisticated financial calculations better ask for at least 10 actual measurement corrected years from satellite to better assess the risk arising from inter-annual volatility of DNI.

1. REQUIREMENTS FOR CSP-SPECIFIC SOLAR RESOURCE ASSESSMENTS SETS

All Concentrating Solar Power (CSP) technologies need to concentrate sunlight. As optical concentration cannot be achieved based on diffuse light coming from various directions, only the direct beam irradiance component is relevant for CSP. A CSP plant converts direct beam irradiance into thermal energy, and typically ultimately into electrical power. This is done by means of high temperatures and efficient heat-to-electricity conversion systems, such as steam turbines. Hence, direct sunlight or beam irradiance is the key resource for any concentrating solar system.

Beam irradiance has a significantly higher variability in space and time in comparison to global irradiance, and its measurement requires higher accuracy and attention. Therefore uncertainty of beam irradiance is higher and solar resources must be measured with great care. In order to get realistic long-term values, satellite-derived values are taken into account in addition to ground measurements to mitigate the high inter-annual variability. The short-term variability of beam irradiance in terms of fluctuations should be properly represented, as CSP systems are sensitive to transient conditions.

GIZ is supporting deployment of CSP worldwide in various ways. In Brasil GIZ was entrusted together with the Kreditanstalt für Wiederaufbau (KfW) the implementation of the project "Concentrated Solar Power for Electric Power Generation" (DKTI-CSP) which is part of the German Initiative for Climate Technologies (DKTI). Due to the excellent geographical location and high values of direct normal irradiance (DNI), large parts of the northeast of Brazil promise to have a great potential for the application of Concentrated Solar Power (CSP) technologies. Furthermore, the capabilities of the industry in the country, especially in the area of thermal power plants, provide good conditions for the integration of CSP technologies.

Suntrace GmbH is experienced with implementing, operating and controlling various kinds of such weather stations worldwide. They are involved in related standardization tasks of the International Energy Agency (IEA),and the International Electrotechnical Commission (IEC). As profound knowledge on meteorological data is crucial in the development of solar power plants, GIZ has contracted Suntrace to elaborate guidelines for solar resource assessments necessary for the development of commercial CSP power plants.

Acquiring information about typical solar irradiation available at potential plant sites is of high importance for planning of new solar plants. The climatological average annual solar irradiance is most important in planning process, but the characteristic frequency distribution also plays an important role as described in Chapter 5. Meteorological parameters like ambient temperature, relative humidity, wind speed and wind direction etc. are also required for site-specific engineering and are summarized in Chapter 2 on auxiliary meteorological parameters. Various types of sensors (instruments) to be used for measuring these meteorological parameters are described in Chapter 3, leading to recommendations on the type of meteorological station best suited for CSP project development. Chapter 4 focuses on the requirements for installation, operation and maintenance of CSP-specific meteorological stations. Once a meteorological station is set-up, data should be acquired, monitored and analyzed in details, which is described in Chapter 5. In addition, recommendations are given to carry out bankable solar resource assessments leading to expert opinions for CSP projects. Moreover, checklists are given in the annex: One on regular maintenance of meteorological stations and a second assists in checks of CSP-specific meteorological stations and their re-calibration. For both procedures Suntrace also provides interactive electronic tools.

2. DEFINITION OF THE RELEVANT METEOROLOGICAL TERMS AND POTENTIAL DATA SOURCES

The first and the most important step in the life of a solar thermal power plant is the decision to select a site where the power plant would be commissioned. Generally, such a decision is based on many criteria like: meteorological conditions at the site which include long-term annual average of Direct Normal Irradiance (DNI), average wind speed, ambient temperature; availability of land, proximity to grid, proper infrastructure, availability of water, probability of natural disasters and many others. One of the most important criteria amongst those mentioned above are meteorological conditions as performance of plant is strongly dependent on local meteorological parameters at the site. Generally evaluation of meteorological data for CSP projects is different for different stages of the project: from initial site selection to (pre) feasibility study to project development to due diligence. This process will be described more in detail in chapter 5. For a better comprehension of the terms used in solar resource assessments the following sub-chapters shall explain the relevant meteorological parameters. The last chapter is dedicated to potential sources for meteorological data sets, reaching from on-site measurements to satellite- and model-derived data sets.

2.1 METEOROLOGICAL PARAMETERS

As solar thermal power plants are very large installations and often exposed to harsh desert environments, meteorological parameters need to be analyzed for specific project locations. DNI is the fuel for any CSP plant and hence knowledge of DNI is of utmost importance for any planning, operation and maintenance of any CSP project. The influence of other meteorological parameters like ambient temperature, wind speed, relative humidity etc. is minor as long as the variations and absolute values are not too extreme. Therefore these parameters are termed as auxiliary. However, information about auxiliary meteorological parameters is often necessary for planning a CSP project and hence shall be obtained as well.

2.1.1 Solar radiation parameters

Extraterrestrial solar radiation changes significantly when passing through the Earth's atmosphere. The sunlight reaching the ground is affected by scattering, absorption and emission processes depending on the chemical composition of the atmosphere, the types of aerosols and most strongly on the presence of clouds. Even thin cirrus clouds scatter and reflect the direct sunbeam and lead to a disproportionately large reduction in the direct solar radiation. Thick clouds can almost entirely extinguish this component, which is most relevant for CSP plants since the mirrors only concentrate the direct normal radiation. In Figure 1 the different absorption and scattering processes in different atmospheric layers are shown. The numbers in this graph give estimates for the average attenuation due to atmospheric gases,

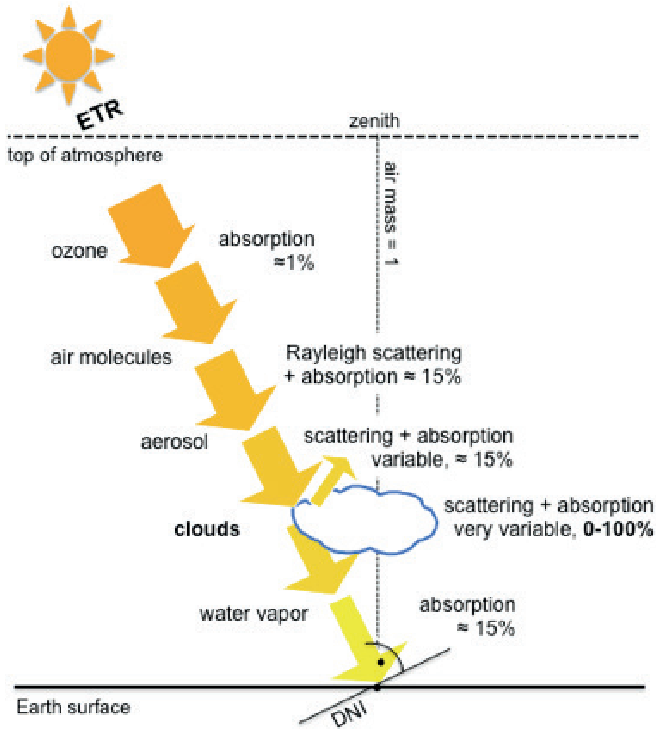

Figure 1: attenuation path of extraterrestrial radiation through the atmosphere.

aerosols and clouds. Clouds have the highest and most variable influence on the sun beam. Figure 2 displays the spectral irradiance finally reaching the ground depending on the wavelength (Sengupta et al. 2015).

In general, the irradiance reaching the ground can be split up in three components, the direct beam from the sun disk, DNI, only the scattered and reflected light referred to as diffuse horizontal irradiance (DHI), and both components added together resulting in the global horizontal irradiance (GHI). The relation in between those components can be expressed in a mathematical sense with the following formula with θ being the solar zenith angle:

$GHI=DNI*cos(\theta)+DHI$ **Equation 1**

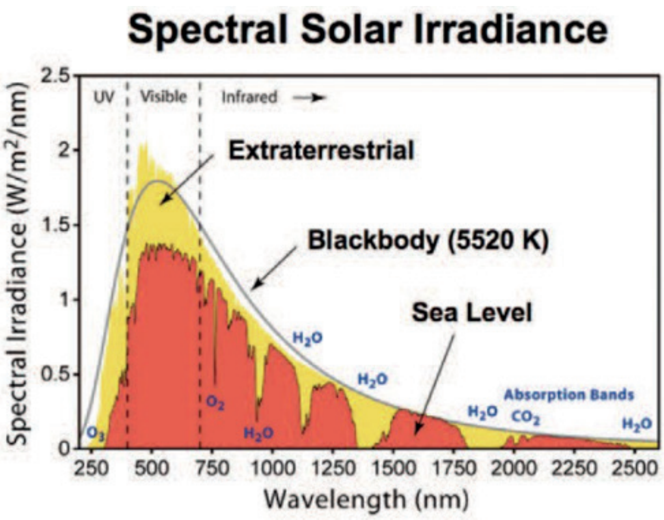

Figure 2: irradiance reaching the Earth's surface in the solar spectral region (red). The main absorption bands with their dominant absorbing gases are named. (Sengupta et al. 2015)

GHI is the simple sum of the direct horizontal and diffuse horizontal irradiance. However, for CSP plants only the direct normal part is relevant. Therefore, the direct horizontal part is converted to a normal plate by dividing it by the solar zenith angle to obtain DNI, the irradiance part that can be used by CSP technologies. Partly empirical models exist to calculate DNI values directly from GHI using empirical relations between different clearness indices. One example is the DIRINT model described in (Perez et al. 1990)

DNI

The meteorological parameter that has the strongest effect on the performance of a CSP plant is DNI. Generally the long-term average value of DNI expected at a site is one of the most important factors considered for site selection of a CSP project. This value is used to determine suitability of a site for a CSP project. Ho, Khalsa, and Kolb (2010) show that the uncertainty of available annual DNI compared to the uncertainty of technical parameters of a CSP plant is the input parameter that has the strongest impact on energy yields, which affects financing of CSP projects.

Moreover once a CSP project is realized, information on DNI measured at the plant site is necessary for its optimal operation especially under intermittent, broken cloud conditions. Hence, DNI should not only be determined before implementing a project but also during its operation.

GHI & DHI

For initial site selection, the knowledge of available global horizontal irradiance (GHI), also called total horizontal irradiance, and the diffuse horizontal irradiance (DHI) at a site is also useful in determining beam irradiance. Direct irradiance is simply the difference between GHI and DHI. If weighted with the sun zenith for each time step the normalized DNI is received (see Equation 1).

If GHI is much less than DNI at a site, this means the influence of atmospheric constituents on the beam irradiance is weak. Hence the site can be considered very sunny with high values of DNI. Similarly, if GHI is much higher than DNI, it means that the influence of atmospheric constituents on DNI is high. Then it must be expected that the site is moderately suitable for concentrating solar energy, while non-concentrating such as flat plate solar thermal collectors or PV can still be applied.

Later, after a measurement station is installed at the project site, the measured GHI and DHI values help to understand the occurrence pattern (frequency) of DNI and also allow to double-check through redundancy of measurements. Hence, GHI & DHI should not only be determined before implementing a project during development phase, but also later during operations.

2.1.2 Auxiliary meteorological parameters

The auxiliary meteorological parameters that affect the performance of CSP plants include amongst others ambient temperature, relative humidity and wind speed These parameters for example have influence on the cooling conditions and thus the efficiency of the steam turbine cooling system. Ambient temperature and wind speed also have an effect on thermal losses from receivers. During initial site selection phase, information on these parameters is not yet necessary, but during later stage of project development, these parameters become more relevant, so that early measurement is still of value.

Air temperature

The ambient temperature has two contrasting effects: one on the efficiency of solar field and other on the efficiency of power-block. The efficiency of solar field depends on the convective losses of the Heat Transfer fluid (HTF) and the collectors to the ambient air. These losses are dependent on ambient temperature. The lower the ambient temperature, the higher the losses and vice-versa. In addition, the efficiency of power block is indirectly a function of the ambient temperature. The overall efficiency of power block is dependent on the condenser efficiency. In case of wet cooling, the efficiency of the condensers increases with decreasing wet bulb temperature, which is a function of ambient temperature and relative humidity & vice-versa. Also the efficiency of dry cooling with air-cooled condensers is affected strongly by the air temperature.

Humidity

The efficiency of wet cooling system decreases with increasing relative humidity, which in turn results in reduced efficiency of power block. As a result, the overall energy yield of CSP plants is affected by changes in relative humidity.

Wind speed

At higher wind speeds, optical losses in the solar field increase because of distortion of the geometry of collectors and this reduces efficiency. Moreover, convective heat losses in the solar field also increase with increasing wind speed, which further reduce the efficiency. Too high wind speed conditions might also lead to plant shutdown in order to protect collectors or heliostats from being damaged, further reducing the performance. Thus, in general it is assumed that the energy yield decreases with increasing wind speed (Chhatbar and Meyer 2011).

Barometric pressure

Barometric pressure, together with ambient temperature and relative humidity values is used to calculate wet-bulb and dew point temperatures. These temperatures affect the cooling efficiency of turbines. Thus, knowledge of barometric pressure is important during operation of CSP plants.

Precipitation

It is necessary to know the historical average, minimum and maximum values of rainfall observed at the site of interest. Frequent and strong rain showers may lead to water logging at the site of a CSP plant. Hence information of precipitation is necessary to design water trenches at the CSP site.

ADDITIONAL RECOMMENDED PARAMETERS:

Visibility

If a solar tower power project is planned, then information on visibility at the site might also be useful. Solar tower power plants use large number of heliostats (mirrors) distributed in an array surrounding a tower that has a central receiver located at its top. Heliostats reflect DNI to the central receiver and the distance traveled by this reflected solar radiation can in some cases exceed 2 km. Under these conditions, reflected solar radiation gets attenuated on its way from the heliostat to the receiver due to scattering and absorption by atmospheric constituents. Scattering by dust or other aerosols usually is dominating. When humidity is high water vapor can cause significant absorption. At places where atmospheric turbidity is higher, this might lead to significant losses in solar radiation received at the central receiver. To understand the near-ground extinction conditions at a specific location, visibility sensors should be installed to measure visibility. This gives an insight into the extinction present at the site. At some places with relatively low average visibility this may lead to limitation of solar field size and may affect the design of heliostats and absorbers. In some cases it might lead to the decision for a line focusing CSP systems such as Parabolic Troughs or Linear Fresnel instead of a tower system. For line focusing systems, the path of sunlight through the atmosphere from the mirror to the receiver tube is very short and thus additional optical losses are negligible.

Aerosol Optical Depth

Aerosol is a suspension of fine solid particles or liquid droplets in a gas. Examples of aerosols in the atmosphere are air pollution constituents like smog and smoke suspended in the atmosphere and today are often of anthropogenic origin. Natural aerosols are pollen, or salt whirled by winds from the sea, or sand particles from desert land surfaces. Aerosols influence the energy balance by absorbing and scattering short wave solar radiation and emitting long wave radiation.

The attenuation of solar radiation by aerosols has several important influences on the atmosphere and environment. Aerosols reduce the visibility and alter the climate through the scattering and absorption of solar radiation. The key parameter needed to estimate the influence of aerosols on visibility is the extinction coefficient, which combines the aerosol scattering coefficient and absorption coefficient. From this the aerosol optical depth (AOD) can be calculated, which is defined as the integral over the vertical column of the aerosol light extinction coefficient.

Aerosols mainly cause scattering. Therefore DNI is much more affected than GHI. Aerosols increase the circumsolar ratio by scattering light in forward direction. The result is that DNI measured by the typical instruments is higher than what a CSP plant could utilize because the acceptance angle of CSP plants is usually smaller than those of DNI measuring instruments. Therefore, it helps for CSP plant qualification to make aerosol measurements on ground in addition to bulk DNI measurements.

Circumsolar Radiation

Direct Normal Irradiance strictly refers to the non-scattered solar radiation. This comes from the solar 'disk' only, which covers a solid angle of around 0.5°. Due to measurement reasons ISO 9448 (1999) allows an acceptance angle of up to 6° around the center of the sun's disk for measurement of DNI. Circumsolar radiation refers to the radiation that appears to originate from the region around the sun, beyond its center. It is often described as the sun aureole.

The radiation coming from the solar aureole and its angular distribution is important: overestimation of CSP yield occurs when the acceptance angle of solar concentrating system is lower than the acceptance angle of the DNI measuring instruments. Moreover, the angular distribution of the circumsolar radiation is needed to optimize the receiver aperture of a concentrating solar system. However, instruments for measuring/determining circumsolar ratio are yet in development phase and are difficult to operate. Hence, circumsolar radiation should be measured only if skilled personnel are available on site.

Summary of meteorological parameters

Once a meteorological station shall be set up to measure solar radiation, it is a minor additional effort to install additional basic equipment to measure the auxiliary parameters. Hence, meteorological parameters that should be considered for evaluating CSP projects include:

- Direct Normal Irradiance (DNI)
- Global Horizontal Irradiance (GHI)
- Diffuse Horizontal Irradiance (DHI)
- Wind Speed and Wind Direction
- Ambient Air Temperature
- Relative Humidity
- Barometric Pressure
- Precipitation
- Aerosol optical depth, circumsolar radiation and visibility for solar tower projects

2.2 DATA SOURCES FOR DNI

A general assumption in climatology is that when considering meteorological data spanning 30 years, weather conditions at the site are averaged out and hence they can be used to calculate the long-term average of meteorological conditions. Under the best possible condition, ground-measured meteorological data covering the above-mentioned period should be available. But in reality 30 years of measured data are available only for few scientifically monitored locations, but not for potential locations of commercial CSP plants. (Lohmann 2006) shows that for most sites in the Sunbelt, if data from at least 10 years are taken into account the maximum deviation of DNI-averages fall below ±5 % from the long-term average.

Thus, for site qualification and yield evaluation of potential construction sites for solar thermal power plants it is highly desirable to have reliable historical data of direct irradiation, ideally for at least 10 years. However for most potential plant locations only satellite- and model-derived data are available for such period. In cases where ground-based measurements are not available it is common to use satellite-derived solar radiation values.

Satellites measure reflected radiation from the earth's surface in several wavelengths bands. Albedo is a measure of the reflectivity of the earth's surface and is defined as the fraction of solar energy (shortwave radiation) reflected from the Earth back into space to incoming shortwave radiation. Known albedo values by location and complex models and algorithms are used to determine global, diffuse and direct beam irradiance components. To understand why satellite retrievals can come to very different results for the same location a short introduction shall be given.

Meteorological satellites are either geostationary, i.e. they view the same area on earth at all times, or polar orbiting satellites with a constant change in the area viewed on earth. Both have their advantages, the most obvious ones being a high temporal resolution for geostationary satellites images, whereas polar orbiting satellites are located on a lower orbit and therefore have a higher spatial resolution. Furthermore, most satellites are equipped with slightly different instruments or instrument versions. In a next step satellite images have to be converted to radiation values. Empirical models using correlations as well as physical models based on radiation transfer calculations can be used to derive GHI values. Continuing a second model is needed to calculate other radiation components like DNI.

Raw data are available from various satellite operators and these in turn are processed by several different organizations providing solar resource satellite data services. There are various data providers who can supply satellite-derived solar radiation values for different regions of the world. In some cases these are commercial services and in other cases, research or government. One of the most well known data set is provided by (NASA-SSE 2012). Table 1 lists the various satellite-derived data sources available as of date for different regions of the world. Some of the sources are available free of charge, while others are available on paid access basis.

Product	Provider	Temporal coverage	Spatial coverage	Temporal resolution	Spatial resolution	Access
		[-]	[-]	[min/h]	[km]	
Brazil specific dataset						
SWERA	UNERP/NREL/ INPE	1995-2005	Brazil	30 min	10 km	free
Brazil + World wide datasets						
3Tier	3Tier	1999->	world	15 min/30 min	3 km	paid
ISIS	DLR	1981-2004	world	3 h	280 km	free
Meteonorm	Meteotest	1981-2000	world	synthetic hourly/min	1 km	paid
NASA-SSE	NASA	1983-2005	world	average daily profile	100 km	free
SolarGIS	GeoModel	1994(99)->	world	15 min/ 30 min	3 km// 80 m	paid
Other datasets						
EnMetSol	University of Oldenburg, Germany	1995->	EU, MENA	15 min/ 1h	3-7 km// 1-3 km	paid
ESRA	Mines-Paris Tech	1981-1990	EU	average daily profile	10 km	paid
HelioClim	Mines-Paris Tech	1985->	EU, MENA	15 min/ 30 min	30 km// 1-3 km	free/ paid
IrSOLaV	IrSOLaV	1999->	EU, MENA, ASIA	15 min/ 30 min	1 km	paid
PVGIS	JRC	1981-1990	EU	average daily profile	1 km	free
Satel-light	ENTPE	1996-2001	EU	30 min	5-7 km	free
Solemi	DLR	1991->	EU, MENA, ASIA	1 h	1 km	paid

Table 1: List of satellite-derived solar radiation data providers with their general characteristics.

In addition to this there are data sources specifically available for Brazil like the SWERA dataset published by SWERA and INPE (Bueno Pereira and Greco Lima 2008) & (Martins, Pereira, and Abreu 2006). This dataset is available in terms of annual and seasonal maps and also as datasets containing radiation values from 1995 to 2005. Solar atlas of Brazil, 'Atlas Solarimétrico do Brasil' (Universidade Federal de Pernambuco 2001), have been previously developed using ground-based measurements. A similar atlas has been created using satellite data only (Ceballos, Bottino, and de Souza 2004).

All satellite data providers have different temporal and spatial coverage, different temporal & spatial resolution, use different algorithms and different inputs. As a result solar radiation values derived for a given place from various satellite providers can differ significantly. Under that situation, satellite data from multiple sources should be used following the procedure described in (Meyer et al. 2008). According to Meyer et al., 2008, the uncertainty of each data source should be calculated separately. This uncertainty should take into consideration both, uncertainty due to number of years and methodological uncertainty. Weights are assigned to each of the data sources considered as inverse of their corresponding uncertainty. Finally, all data sources are combined and weighted average is calculated from these sources to represent the best estimate of solar radiation at that site.

Such studies should be done for multiple sites. These sites should be ranked based on their best estimate and uncertainty values. Depending also on other site selection criteria, a preferred site should be selected. Once a site has been pre-selected, a meteorological measurement station should be installed.

3. DESCRIPTION OF RECOMMENDED METEOROLOGICAL MEASUREMENT INSTRUMENTATION

The meteorological parameters required for evaluation of large-scale CSP projects have been discussed in Chapter 2.1. The main purpose of a CSP-specific meteorological station is to measure solar radiation parameters (especially DNI) with high accuracy. Auxiliary meteorological parameters could be measured with sensors of moderate to good quality as their relevance is not that high compared to DNI and GHI. Various types of sensors are available in the market to measure these meteorological parameters. These sensors are specifically designed to match requirements for various applications. The accuracy requirements of these sensors vary from the type of application, ranging from moderate and good to very high quality of sensors. Different types of sensors that can be used for a CSP-specific meteorological station are discussed in following sections.

3.1.1 Solar radiation measurements

Measuring the sun's energy incident on the earth's surface is one of the most difficult field measurement exercises. The measurement technology applied today is based on an energy conversion process whereby electromagnetic radiant energy is converted into another form of energy, which can be detected by measurements. Preferred is the conversion into electric signal.

Solar radiation measuring instruments with a hemispherical (180°) field of view are called pyranometers. In contrast are pyrheliometers instruments using only a narrow field of view (typically 5°). These are designed to measure the radiation coming from the solar disc and the adjacent region around the sun (circumsolar). Consequently, pyrheliometer must be accurately tracking the sun to keep it properly oriented.

The sensor principles employed today either follow the thermoelectric or the photoelectric effect. Both have specific advantages and shortcomings.

3.1.1.1 Thermal sensors

With thermal solar radiation sensors, the radiant energy is initially converted into thermal energy by means of a black absorbing surface, and then into an electrical signal by a thermopile. This electrical output can be measured with a voltmeter.

As an example thermal pyrheliometers are shown in Figure 3 which are designed to measure DNI directly. Alternatively, as measured by pyranometers, DNI can be derived indirectly by simultaneous measurement of global horizontal irradiance and diffuse irradiance, with arithmetic deduction of values.

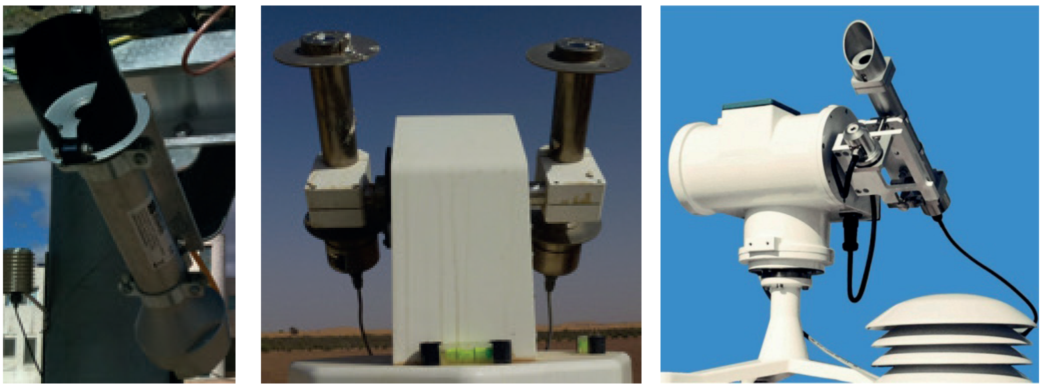

Figure 3: Thermopile pyrheliometer instrument (Left: Kipp & Zonen CHP1; center: Eppley solar tracker with two arms for pyrheliometers; right: EKO Tracker with Hukseflux DR02-T1). © Suntrace (2015)

Figure 4 shows examples of thermopile pyranometers designed to measure hemispherical irradiance. Ideally the black surface of thermopile instruments should absorb like a perfect black body, which is a body fully emitting and also absorbing radiation of all wavelengths. Such a photon trap converts all radiation into heat, allowing the conversion of solar radiation intensity into a temperature signal, which then can be measured for example through a thermopile element. Such thermopile element consists of a large number of thermocouple junction pairs electrically connected in series. A thermocouple consists of two dissimilar metals connected together. The absorption of thermal radiation by the active (or "hot") thermocouple junctions increases its temperature to T1 and the reference (or "cold") junction is kept at a fixed temperature T2. The differential temperature between the active junction and a reference ("cold") junction produces an electromotive force directly proportional to the differential temperature created. This effect is called the thermoelectric effect. The type of metal and the temperature difference between the hot and cold ends affects the magnitude and direction of the electromotive force. The relationship between the temperature difference and the output voltage of a thermocouple is nonlinear and is approximated by a polynomial interpolation.

Figure 4: Examples of thermopile pyranometers (Left: Kipp & Zonen CHP21, center: Eppley PSP, right: Hukseflux SR20-T1. © Suntrace (2015)

Due to the functional principle of thermopile radiometers, they are sensitive in a wide spectral range. The thermal detector absorbs around 97 % to 98 % of the total irradiance energy. The major disadvantages of thermopile pyranometers in comparison to photoelectric pyranometers are a higher price, frequent soiling of the glass dome and slower responsivity (Pape et al. 2009).

3.1.1.2 Photoelectric sensors

Photoelectric instruments convert the radiant energy directly into electrical energy by a photodiode. A photodiode is usually a silicon semiconductor with p-i-n structure or p-n junction. Photodiodes can be used under either reverse bias (photoconductive mode) or zero bias (photovoltaic mode).

In zero bias, solar radiation incident on the diode causes a current across the device, leading to forward bias, which in turn induces "dark current" in the opposite direction to the photocurrent. This is called the photovoltaic effect, which is the basis for solar cells.

Figure 5 shows the photoelectric pyranometer LI-200SZ by LI-COR. The responses of pyranometers, which measure irradiance with a photodiode, have a much narrower spectral sensitivity compared to that measured by thermopiles (see Figure 6). Its spectral response typically is in the range between 0.4 and 1.2 µm. Within this interval the spectral response is not uniform. Therefore, narrow-to-broadband corrections need to be applied to derive the full solar range. Ideally these consider the spectral effect of lower air masses and also that of various contents of atmospheric trace gases and aerosols. In addition, silicon photocells have a certain temperature dependence. In case of the LI-COR sensor it is in the order of 0.15 %/K. Both, cosine and temperature response of photoelectric pyranometers, as well as the spectral dependence need to be corrected. A detailed description of various correction methods can be found in the IEA Report on Best practice for Solar Irradiance Measurements with RSI (IEA, 2015).

DNI can be determined from a single photoelectric pyranometer, if it is assembled in an arrangement that periodically blocks the direct beam radiation and causes it to measure global irradiance and diffuse irradiance alternately.

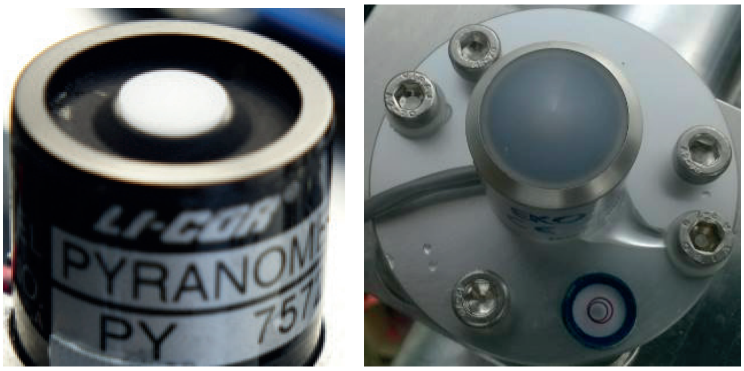

Figure 5: Photoelectric pyranometer, left: LI-COR LI-200SZ, right: EKO ML-01. © Suntrace (2015)

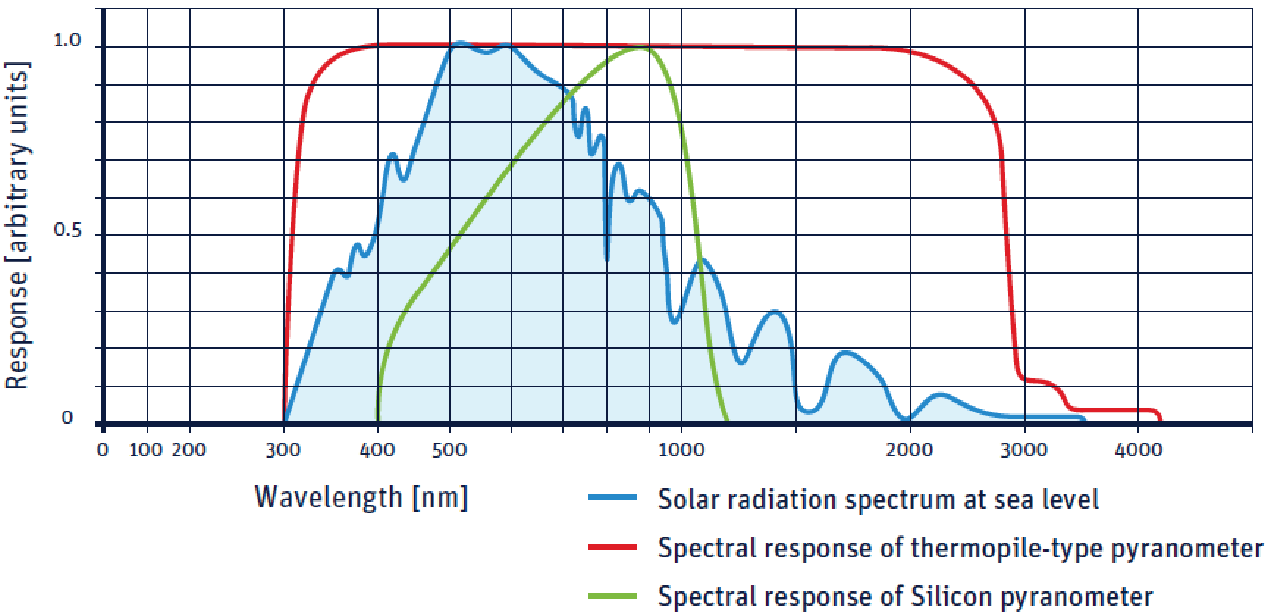

Figure 6: spectral response of thermopile (red line) versus photoelectric (green line) sersors (Image from Kipp & Zonen).

Rotating Shadow Band Irradiometers (RSIs) usually employ a photoelectric radiometer to measure incident solar radiation. As shown in Figure 7 the pyranometer is mounted on a "head unit" apparatus, which permits unobstructed measurement of global horizontal irradiance (GHI) and to measure horizontal diffuse irradiance (DHI) by means of a motor driven shadow band, which periodically blocks the direct beam component.

Figure 7: RSI instruments (left RSR2 of Irradiance Inc.; right RSP4G of Reichert GmbH). © Suntrace (2015)

RSI operation is realized by a program, which drives a motor control module. The code is usually run by a datalogger, which also processes and stores the measured values.

Typically once every 30 seconds the shadow band rotates over the photodiode, taking approximately one second for this motion. During this period the photoelectric pyranometer signal is sampled about 1000 times and when the sensor is completely shaded from the sun by the shadow band the lowest pyranometer readings occur. During this short moment, the photoelectric pyranometer measures only the diffuse irradiance. The software detects the DHI from all values, finding the average of minimum values. Finally DNI is calculated from measurements of GHI and DHI, and using relation with the sun's zenith angle.

DNI measurements derived by RSIs are not reaching the exact same accuracy compared to pyrheliometer measurements, as long as the pyrheliometer tracking is accurate and the measurement device is maintained and properly cleaned.

3.1.1.3 Calibration of DNI sensors

Pyrheliometers are usually factory calibrated and come with a respective certificate. Additional field calibration is not required for new sensors. The calibration should then be renewed every 2 years.

RSI instruments are not factory calibrated, but have an individual characteristic error, which should be determined through a specific calibration procedure before they are installed in the field for measurement purpose. The calibration should generally be against a high precision measurement station, e.g. absolute cavity radiometer or high precision pyrheliometer traceable to a primary standard device. Ideally this calibration process shall be run for a minimum period of 4 weeks, but longer period will increase the calibration accuracy. Such calibration processes are currently offered at scientific reference measurement stations operated by NREL in Denver, USA and by DLR at the Plataforma de Almería in Spain.

3.1.1.4 Cleaning of sensors (soiling)

Soiling of measurement devices is often an issue with pyrheliometer, as these are easily affected by dust and dirt accumulation and need daily and careful cleaning. This has been confirmed in a test performed at Plataforma Solar de Almería, where properly cleaned and uncleaned sensors were operated for 30 days in parallel. The uncleaned pyrheliometer has lost 30% of data value due to soiling after 30 days, following an almost continuous degradation curve. The RSI on the opposite side has maintained accuracy at much higher levels.

In practice often the cleaning of pyrheliometers is not appropriate, also as this is difficult to realize in remote desert locations, typically preferred areas for CSP application. RSI type instruments on the opposite are less susceptible to soiling and thus require very little attendance and maintenance. They are also less expensive compared to a pyrheliometer station with a solar tracker. For maximum data reliability, solar monitoring stations with both sorts of instruments are typically configured with redundant sensors, which also allow comparison of both sensors regarding parallel measurement of the same DNI intensity.

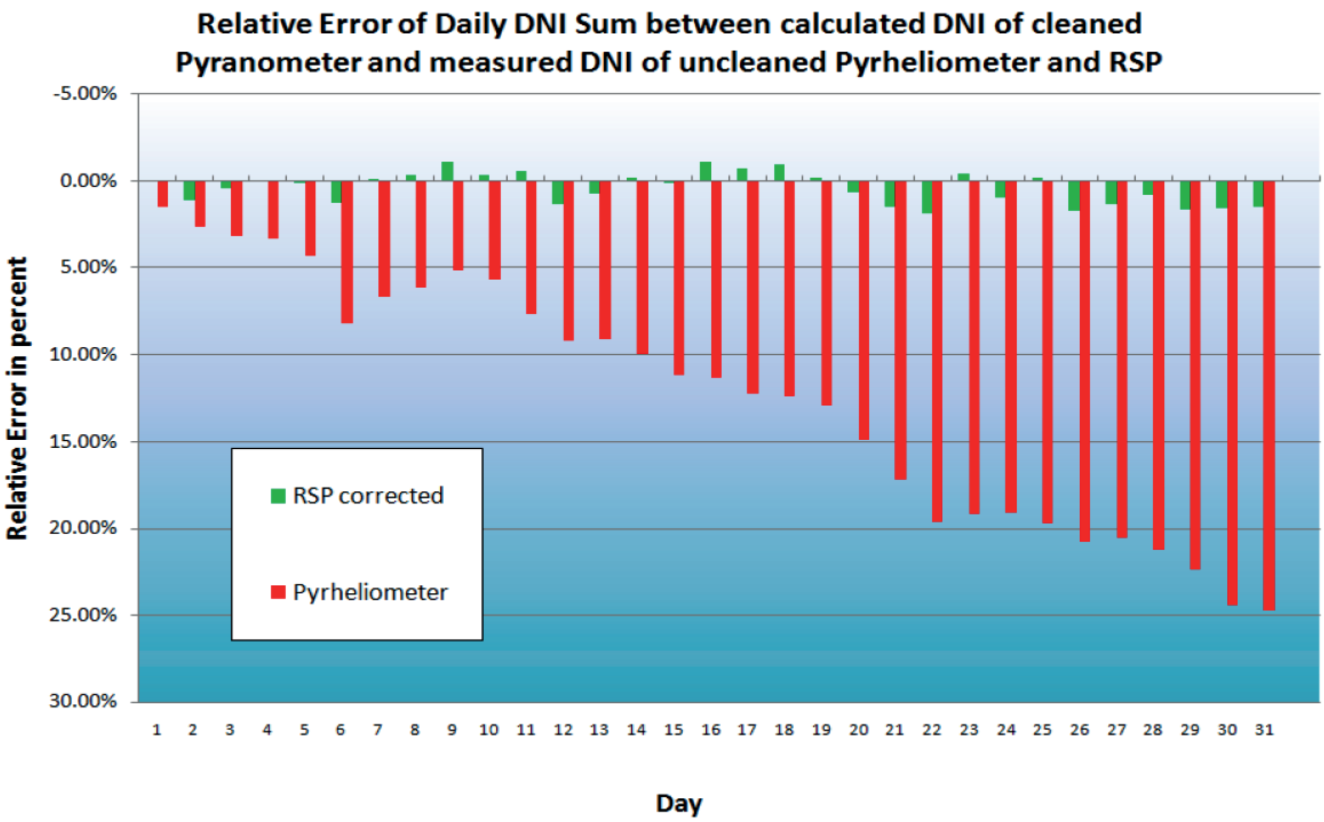

Figure 8: Effect of soiling on RSI and pyrheliometer compared to properly cleaned sensors (Pape et al. 2009).

3.1.1.5 Accuracy requirements:

For field instruments, (WMO 2008) recommends measuring DNI, GHI & DHI with requirements as mentioned in Table 2 below. A more detailed table with more characteristics is shown in Annex A.

For CSP-specific meteorological stations, it is also recommended to follow WMO standards, which meet either good quality or high quality requirements. Pyrheliometers are generally classified into primary standard and first class instruments (ISO 9059 1990). For CSP-specific meteorological stations, it is recommended to use first class pyrheliometers, for example Hukseflux DR01 or Hukseflux DR02, Kipp & Zonen CHP1, Eppley NIP, or EKO MS-56.

Instrument	Pyrheliometer		Pyranometer		
Characteristic WMO classification	High quality [a]	Good quality [b]	High quality [a]	Good quality [b]	Moderate quality [c]
response time (95 % value)	< 15 s	< 30 s	< 15 s	< 30 s	< 60 s
zero offset (response to 5 K/h change in ambient temperature)	2 W/m²	2 W/m²	2 W/m²	4 W/m²	8 W/m²
resolution (smallest detectable change in W/m2)	0.5 W/m²	1 W/m²	1 W/m²	5 W/m²	10 W/m²
stability (percentage of full scale, change per year)	0.1 %/a	0.5 %/a	0.8 %/a	1.5 %/a	3 %/a
1 min totals (%)	0.9 %	1.8 %	-	-	-
1 h totals (%)	0.7 %	1.5 %	3%	8%	20%
daily totals (%)	0.5 %	1 %	2%	5%	10%

a Near state of the art maintainable only at stations with special facilities and staff suitable for use as a working standard.

b acceptable for network operations.

c Suitable for low-cost networks where moderate to low performance is acceptable.

Table 2: Characteristics of different types of pyrheliometers and pyranometers as recommended by WMO.

Similarly, pyranometers are classified into primary standard, secondary standard, first class and second-class instruments. For CSP-specific meteorological stations, it is recommended to use secondary standard pyranometers, for example Kipp & Zonen CMP11/21/22, Eppley PSP, EKO MS-802 etc.

3.1.2 Auxiliary meteorological measurements

While solar radiation parameters can be measured by a couple of principles, auxiliary meteorological parameters can be measured by many principles using different techniques. As a result, recommendations are given with respect to the principle of measurement, range, minimum accuracy etc. with which these meteorological parameters should be measured.

Ambient temperature

Temperature is a measure of degree of hotness or coldness of a body or a system. Temperature can be measured using various principles like thermo-electric effect, expansion of metals, expansion of fluids, emission of electro-magnetic waves etc. There are various sensors available in the market, which measure temperature using one of the above-mentioned principles. However, for measuring ambient temperature on field a resistance-based sensor is generally employed.

According to (WMO 2008), ambient temperature sensor should have a range of -80°C to +60°C, a resolution of 0.1°C, a response time of 20 s and an accuracy of

0.3 °C for ≤ –40°C,

0.1 °C for > –40°C and ≤ +40°C and

0.3 °C for > +40°C

For a CSP-specific meteorological station the ambient temperature sensor should be able to measure temperatures in the range of -40°C to +60°C, have an accuracy of ±0.2°C or better with a resolution of 0.1°C. The response time of the sensor should be around 20 s. Ambient temperature sensors are very susceptible to solar radiation, cold breeze, rainfall etc., which affect the measurements. As a result, proper care must be taken to ensure that the ambient temperature sensor is properly shielded from exposure to solar radiation, rainfall and wind. To avoid this generally an external multi-plate shield is used, which houses the ambient temperature sensor.

Humidity

Relative humidity (RH) is defined in the ratio of the observed vapor pressure to the saturation vapor pressure with respect to water at the same temperature and pressure. Instruments for measuring humidity are called hygrometers. The requirements noted in WMO (2008) are quite ambitious goals for measuring temperatures and humidity, because ambient temperature sensors, humidity sensor may easily be influenced by solar radiation, wind speed and rainfall. Temperature and humidity sensors should be well housed within a 'radiation shield'. To reach the noted accuracies the radiation shield would be needed to be equipped with active ventilation. But such permanently ventilated 'huts' have relatively high power demand and maintenance needs.

For a CSP-specific meteorological station the hygrometer should be able to measure temperatures in the range from 0 % to 100 % RH. Often in field measurements combined sensors for ambient temperature and relative humidity are applied. As compared to meteorology and climatology the requirements for these measurements are much lower for solar energy purposes, passive ventilation is sufficient. The accuracy should be 5% or better with a resolution of ±1 %. As humidity changes in the atmosphere are relatively slow a response time of 60 s is sufficient for CSP applications. It is highly important that both sensors are shielded against direct sunlight to avoid significant measurement errors.

Wind speed and wind direction

Wind is considered mainly as a two-dimensional vector quantity specified by two numbers representing direction and speed. The extent to which wind is characterized by rapid fluctuations is referred to as gustiness. Single fluctuations are called gusts. Apart from mean wind speed and direction, many applications require standard deviations and extremes. Instruments measuring wind speed are called anemometers. There are mainly two principles to measure wind speed and direction: electro-mechanical and ultrasonic. Cup anemometers using electro-mechanical principle can measure wind speed and require wind vanes to measure wind direction. However, ultrasonic anemometers can measure both wind speed and wind direction.

There is a strong wind shear near the ground, which depends on the roughness of the terrain or vegetation. Thus it is highly important to measure wind at a height, where the shear effect is lower. Wind measurements at 3 m are not representative as their measurement is often disturbed by small scale structures such as the fence around a measurement station. It should also be considered, that a CSP structure will easily extend to elevations of 7-10 m, simply considering the aperture width of almost 6 m of a standard parabolic trough (e.g. Euro-Trough). New generations of parabolic trough collectors reach apertures of 8 m and big Heliostats can reach heights of 10 m when completely inclined.

Therefore it is recommended to measure wind at the WMO standard height of 10 m, where the wind flow is nearly in laminar state. It is more accurate to calculate wind speed at lower elevations from this height to the height of solar mirrors and other structures of a CSP plant affected by wind.

According to WMO (2008), accuracy for horizontal speed measurements should be 0.5 m/s if wind is less than 5 m/s and better than 10 % above 5 m/s is usually sufficient. Anemometers should be able to measure wind speed in the range of 0 to 75 m/s. The resolution recommended is 0.5 m/s or better.

Wind direction should be measured in an operating range of 0 to 360°, with a resolution of 1° and an accuracy of 5°. The required accuracy is easily obtained with modern instrumentation.

Wind load can occur in gusts with a short duration. Thus wind measurement data should be capable to record the 3-second wind gusts, which are relevant for design of structures for trough or heliostats. It has limited value to average out all gust related values to minute-averages, as then the design may underestimate wind loads.

Barometric pressure

The atmospheric pressure on a given surface is the force per unit area exerted by virtue of the weight of the atmosphere above. The pressure is thus equal to the weight of a vertical column of air above a horizontal projection of the surface, extending to the outer limit of the atmosphere. For meteorological purposes, atmospheric pressure is generally measured with electronic barometers, mercury barometers, aneroid barometers or hypsometers. The latter class of instruments depends on the relationship between the boiling point of a liquid and the atmospheric pressure.

The level of accuracy needed for pressure measurements to satisfy the requirements of various meteorological applications has been identified by the respective WMO commissions and is outlined as follows:

Measuring range:	*500 to 1080 hPa,*
required target uncertainty:	*0.1 hPa,*
resolution:	*0.1 hPa,*
sensor time constant:	*20 s,*
output averaging time:	*1 min.*

The above requirements should be considered achievable for new barometers in a strictly controlled environment, such as those available in a properly equipped laboratory. They provide appropriate target accuracy for barometers to meet before their installation in an operational environment.

Precipitation

Precipitation is defined as the liquid or solid products of the condensation of water vapor falling from clouds or deposited from air onto the ground. It includes rain, hail, snow, dew, rime, hoar frost and fog precipitation. The total amount of precipitation that reaches the ground in a stated period is expressed in terms of the vertical depth of water (or water equivalent in the case of solid forms) to which it would cover a horizontal projection of the Earth's surface. Precipitation measurements are particularly sensitive to exposure, wind and topography, and metadata describing the circumstances of the measurements are particularly important for users of the data. Precipitation gauges (or rain gauges if only liquid precipitation can be measured) are the most common instruments used to measure precipitation. Generally, an open receptacle with vertical sides is used, usually in the form of a right cylinder, with a funnel if its main purpose is to measure rain. Depending on the rain conditions on site, the catchment area of the rain gauge should be determined.

The requirements for accuracy, range and resolution for precipitation measurements are described below. The common observation times are hourly, three-hourly, and daily, for synoptic, climatological and hydrological purposes. For dimensioning of run-off systems at large solar plants it might help to log even precipitation sums over 10 min.

Measuring range: *0- 500 mm (daily)*

Target uncertainty: *0.1 mm for ≤ 5 mm & 2 % for > 5 mm*

Reporting resolution: *0.1 mm.*

3.2 SUMMARY OF ACCURACY REQUIREMENTS AND TEMPORAL RESOLUTION

Thus, different meteorological parameters should be measured with different temporal resolutions, different accuracy requirements and at different height. Table 3 summarizes these characteristics for all major meteorological parameters that should be measured by a CSP-specific meteorological station.

Parameter	response time	range of measurement	height of installation
global irradiance	< 10 s	0 to 2000 Wm^2	2 m ± 0.5 m
diffuse irradiance	< 10 s	0 to 2000 Wm^2	2 m ± 0.5 m
direct normal irradiance	< 10 s	0 to 1400 Wm^2	2 m ± 0.5 m
air temperature	< 60 s	-20º to +60ºC	2 m ± 0.5 m
Humidity	< 60 s	0 to 100 %	2 m ± 0.5 m
wind speed*	< 1 s	0 to 50 m/s	10 m ± 0.5 m
wind direction*	< 1 s	0 to 360º	10 m ± 0.5 m
atmospheric pressure	< 5 s	500 hPa to 1100 hPa	2 m ± 0.5 m
Precipitation	-	500 mm/d	2 m ± 0.5 m

Table 3: Summary of requirements for meteorological parameters to be measured for a CSP-specific meteorological station. Wind speed and direction should be measured at WMO standard height of 10 m to be more representative than sometimes realized wind measurements at 3 m.

4. REQUIREMENTS FOR CSP-SPECIFIC METEOROLOGICAL STATIONS

A CSP-specific meteorological station should be designed by keeping in mind the recommendations given by WMO & those mentioned in Chapter 3. However there are other aspects that should be taken care of before, during and after installation of CSP-specific meteorological stations. These include site-selection, location of measurement station, power-supply, maintenance and operation of CSP specific meteorological stations etc. The following sub-chapters cover these topics as described below.

4.1 PRE-INSTALLATION REQUIREMENTS

Generally CSP power plants are located in remote areas where land, water, grid, infrastructure etc. are easily available. Before a station is constructed, local planners should be consulted to determine whether or not future developments, either commercial or residential, would interfere with the observation site. In rural areas, care should be taken to ensure that significant land-use changes are not planned. While changes in the view of the horizon are less critical if they are small, potential changes should be considered before the location of a site is selected. Generally, sites will yield more representative data where the terrain is flat and free from obstruction. Moreover, the site should not be near areas that will adversely affect the radiation or ancillary measurements because of pollution sources, areas of unnatural reflectance or areas where the microclimate is altered by irrigation or other human modifications. In addition to this, the following requirements should be taken into consideration while installing a meteorological station.

4.1.1 Location

Meteorological stations are generally installed in an early phase of project-development. At this stage, only land plotting is done and the actual design and layout of CSP plant is not decided. CSP power plants are large installations occupying large areas, which can cover more than 10 km2. E.g. the diameter of Bright Source's Ivanpah plant is approaching 4 km. The meteorological station to qualify such plants should preferably be located within the proposed solar field. In case the region is flat and land use is relatively homogenous a station preferably in a 1 to 3 km distance is usually sufficient for qualification of a site. Far from coastlines, or other water bodies, and far from mountains, under extremely homogeneous conditions, and given there is approximately the same elevation ± 100 m even a station in a distance of approximately 10 km could be useful. However, then the assessment of the project needs to consider satellite data for both locations: the measurement station and the proposed project site: satellite-derived radiation time-series are required for both so that site-specific changes can be checked at least afterwards.

To avoid the failure of a measurement, an expert should check actual representativeness of a measurement site for a plant site before installation of a station. Best this is done during a site visit, because then additional features of the chosen location – like high dust content due to local soil characteristics or emissions from nearby industry – can be evaluated. The minimum requirement for site selection is to send proposed plant locations with a horizontal accuracy of at least ± 50 m. Then a measurement expert can evaluate suitability of a station from satellite data.

4.1.2 Free horizon

The ideal site for measurement of solar radiation for meteorological purposes is one that has a completely flat horizon. The WMO Guide to Meteorological Instruments and Methods of Observation (WMO No. 8) recommends that if possible no obstruction should be present, particularly within the azimuth range of sunrise and sunset over the year. This can be seen in in Figure 9 showing the sun path diagram for one year for the BSRN Station BRB close to Brasilia City (Latitude: -15.60, Longitude: -47.71). In cases where obstructions do occur, the instrument should be located where these subtend an elevation angle of less than 5° to minimize their effects.

While the distant horizon may be influenced by topography, the local horizon should be as clear as practically possible. A distance of 12 times the height of any object to the location of the sensor will ensure that the elevation of the object is less than 5° above the horizon. The site should be located such that all objects are to the poleward side of the installation and do not interfere with the direct beam radiation at any time during the year. The instruments should be removed, as far as is practical, from any highly reflective objects. Where a site is to be developed in a built-up area, the sensors can be located on the roof of a building to overcome problems with the local horizon. While antennas and other slender objects should be avoided, their effect is minimal and can be endured if they are less than 1° wide, and do not block the direct beam radiation during any time of the year.

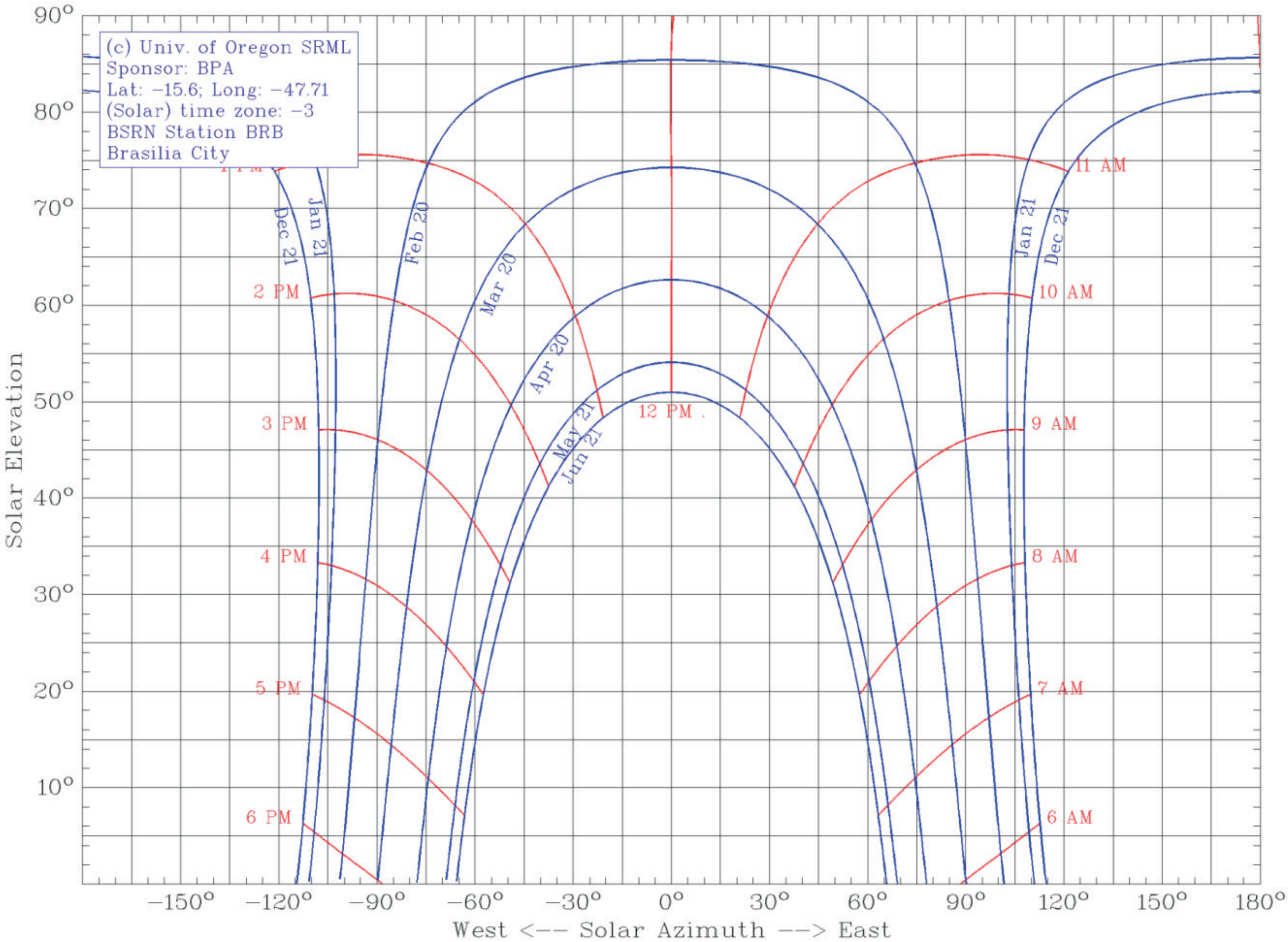

Figure 9: sun path over the year for BSRN station BRB, Brasilia City (Latitude: -15.60, Longitude: -47.71) from University of Oregon.

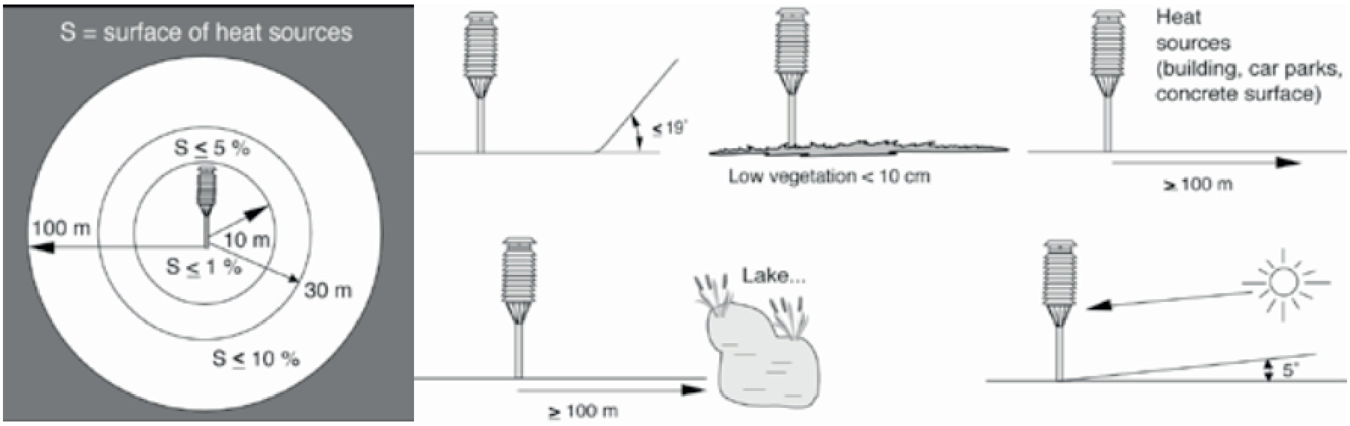

Figure 10: class 1 site classification according to the CIMO guide.

4.1.3 Datalogger requirements

Different types of datalogger are available in the market these days, which can generally support all types of instruments. The permitted operating temperature for such data logger is crucial, as a defective data logger would generally miss the highest and most desired DNI levels. Special care should also be taken while choosing the number of analog, digital channels, the number of switched excitation ports, the number of control ports and the number of power output ports offered by the datalogger. This becomes very important especially for the operation of RSI instruments. The accuracy, speed and reliability of datalogger are some of the important characteristics that should be kept in mind while deciding for a datalogger. Moreover, the capacity of datalogger to store measured data should be also taken into consideration. Depending on this, the scanning and averaging interval of different meteorological parameters should be decided. Table 4 lists exemplary the specifications of a suitable data logger. The number of required analog and digital inputs depend on the used instruments (analog or digital output) and the station configuration (number of sensor) itself.

Digital inputs	10
Analogue inputs	6 differential or 12 single ended
Additional inputs	Via RS485 and INPUT modules
Serial inputs	RS485, half-duplex, RS232 for Modem
Analogue measuring range	0 to 10 V
Resolution	16 Bit (0.2 to 0.01 mV depending on range)
Measuring interval	1 s to 24 h
Statistic interval	1 s to 24 h
Statistic functions	Mean value, standard deviation, max, min, sum
Data memory	256 MB (non-volatile ring buffer)
Data interface	RS232 interface, 1200 to 115200 baud, RS485 interface, half duplex, 1200 to 115200 baud
Remote data transfer	Ethernet interface (LAN), 10 MBit/s, GSM, GPRS, DSL, ISDN router
External power supply	15 to 30 VDC or solar panel
Power consumption	Typ. 600 mW (50 mA at 12 V)
Sensor excitation	12 VDC switched, max. 100 mA
Temperature range	–40 to +70 °C

Table 4: Specifications of a suitable data logger. © Suntrace (2015)

4.1.4 Telecommunication requirements

The intent of this section is to make the user aware of some of the possibilities available to transfer the collected measurements to the platform(s) on which the analyses occur. Whatever the means of communication selected, (Stamper 1989) provides an excellent set of criteria on which to base the decision. Each criterion should be considered, even though it may not be significant in the final selection process.

Cost: this includes the price of the medium selected, the installation of the necessary equipment (e.g., cable), software and hardware requirements (e.g., drivers and computer cards) specific to the medium and the ancillary cost of expansion, if and when needed.

Speed (capacity): this is broken into response time (the time required for each individual transaction) and aggregate data rate (the amount of information transmitted per unit time). An example of such is modem communication with a data logger every hour to download mean values of climate variables. The response time is the time it takes the modems to connect, while the aggregate time is the time it takes to download the data.

Availability: Is the medium available when there is a need to utilize it? For example, if using common carrier telephone lines, does one get a 'busy' signal at the times data is to be transferred, or is the telephone system so busy that lines are unavailable (e.g., during special holidays).

Expandability: Can the system be enlarged for increased demand? This can be an increase either in the number of stations using the communication system or in the amount of data being transmitted through the system. An example of the latter would be the upgrading of telephone modems to higher baud rates to handle increased amounts of data transfer over the same time period (increased aggregate data rate).

Errors: All means of data transmission are subject to signal distortion, which can produce errors in the data. To reduce this problem, data communication environments transmit redundant data to detect if such errors have occurred. The more complex the method used for detecting such errors, the slower the data throughput, but the higher the probability that the data will be error free. The number of copies of the data and how long each copy is maintained should in part be correlated to the frequency of data transmission errors. In turn this will dictate part of the overall cost of the system.

Security: The ease of access by outsiders increases the threat of breaches in security. This can vary from someone accidentally interrupting a data transfer to vandals physically or electronically destroying equipment.

The frequency at which data from the station is received (downloaded) to central data receiving system depends on the requirements of (near-real time) data and telecommunication system available to communicate with the station. For example, data measured by the station could be sent to the central data receiving system every 10 minutes, every hour or once every day. We recommend to receive (download) data once every day, preferred during night-time, because then the download does not disturb the measurement. Further data can be quality controlled every day and checked for any errors, which would give an alarm and allow for a timely rectification.

4.1.5 Site-preparation & evaluation

The preparation of the site before measurements begin consists of designing the installation to reduce interference of the sensors from buildings and other sensors, ensuring that the instrument platforms are appropriate for the climate and soil conditions, and designing a signal cable grid that is efficient and easy to maintain. While general principles can be applied to each of these aspects of the site, individual stations will require special adaptations to the following procedures.

Instrument siting

Care must be taken so that the instruments do not interfere with each other. Ideally, instruments should be far enough apart that they become insignificant objects in the field of view of adjacent instruments. Space limitations, however, often restrict the distance apart instruments can be placed. To reduce such interference, the instruments should be lined up in a poleward direction with slightly increasing elevation. In cases where the measurement of diffuse radiation and direct radiation are separate, the diffuse measurement should be the furthest poleward and slightly elevated, while the direct instrument should be closest to the equator and at the lowest height. The global instrument should be centered between these two instruments and higher than the direct instrument. The global and diffuse instruments should be at the same height, with only the shade portion of the diffuse apparatus extending above the height of the thermopile of the global instrument. In the case where the direct and diffuse instruments are set on the same tracking platform, the direct beam instrument(s) should not interfere with the horizon of the diffuse instruments.

For meteorological instrumentation, distant horizon problems are minimal but interference between instruments is significant. For the measurements of temperature and pressure, the Stevenson screen (or equivalent) should be at least twice the distance apart from the height of all significant objects. A Stevenson screen or instrument shelter is an enclosure to shield meteorological instruments against precipitation and direct heat radiation from outside sources, while still allowing air to circulate freely around them. These objects should be located poleward of the measurement site so that shading will not interfere with the instruments within the screen. Instruments used to measure precipitation should be located no closer to the nearest obstruction than four times the height of the obstruction.

An instrument for the measurement of wind should be at least 10 times the height of an object distant from that object. For example, if there is a 20-m tall tree, a meteorological measurement mast should be located in the distance of at least 10 times the height of the tree i.e. 200 m away from the tree. If the instrumentation cannot be located the prescribed distance from the obstruction, then the instrument should be located in a location where the obstruction least affects the data. In the case of a wind mast, the mast should be placed where the obstruction alters the wind field of non-prevailing winds. Distances from growing vegetation should be increased to account for any future growth.

Instrument platform

Instrument stands can be as simple as a vertical post or tripod holding a single pyranometer or as complex as a raised platform that can hold a large number of individual instruments and trackers. In all cases, the platform must be stable over long periods of time, resisting warping by changes in temperature and humidity, and be immovable in strong wind conditions (to within ±0.05°). In most climates, wooden platforms should not be used because of their tendency to warp with humidity and seasonal changes and because of attack by insects. In temperate climates platforms made of steel or aluminum provide both the necessary stability and durability required for radiation measurements. In hot climates though, these may be inappropriate because of extreme heating (both with respect to expansion and ease of access due to heating).

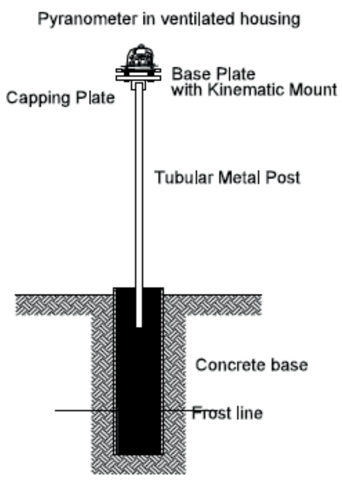

Figure 11: Illustrative diagram showing the foundation for mounting solar radiation instruments (WMO 2008). However such massive foundation is usually not required for CSP-stations.

Reinforced concrete, or concrete and steel structures, when expansion is considered, are probably the optimal materials for the construction of stands, whether they are simple posts or complex platforms.

The base of any post or platform either must be firmly attached to a building or dug into the ground. In the latter case, the base of the structure should be anchored at a depth below any material that may be subject to heaving due to frost or water. Figure 11 illustrates a typical post installation for a continental site in well-drained soil. These WMO recommendations refer to permanent weather stations, which should remain in the field basically forever.

CSP measurement stations however are often temporary. Therefore depending on the soil conditions it is possible to set up a station without concrete foundations only using e.g. tripods, which are well anchored, see Figure 12 showing a CSP-Tier 2 station with a Rotating Shadowband Pyranometer mounted on a tripod, which is fixed on concrete slabs.

Figure 12: CSP-Tier 2 station with Rotating Shadowband Pyranometer mounted on a tripod, which is fixed on concrete slabs. © Suntrace (2015)

Along with the structural integrity of the platform, the height of the platform above the surface must also be carefully considered. As previously mentioned, in built-up areas up-facing sensors can be located on the top of buildings to overcome local horizons. In more rural areas instruments can be located as close as 1.5 m above the surface. In the latter case, consideration must be given for terrain effects such as blowing or accumulating sand or snow. When instruments are placed higher than approximately 1.5 m, a means of accessing the instrument for cleaning must be provided. This can vary from a permanent deck structure to a simple stepladder, remembering that the easier the access to the instrument the more likely the instrument will be well maintained. If the instrument is to be mounted on the roof of a building care must be taken to guarantee that the instrument will not be blown off during high winds. Depending on the site, further measures may be required to ensure the stability of the pyranometer platform during high wind conditions. Extra guy-wires or bracketing may be added to keep the stand from oscillating.

Cables / Signal cables

Just as important as determining the best field of view for the instruments is the routing of the signal cable from the instrument to the data acquisition system. As most surface-based radiometers are thermopile instruments, the maximum signal is usually in-the-order of 10 mV for a 1000 W m-2 flux or 10 V W-1 m2. Such small signals can be affected easily by large line resistance, due to long cable lengths, and electrical interference from other sources, particularly AC power lines running parallel to the signal lines. Several suggestions follow to aid in the design of the measurement system.

- All signal cables should be twisted wire configured as a ground and signal pair sheathed in a foil wrap. The outer sheathing of the signal cable should be based upon the climatic regime of the station and the overall EMF to which the cable is to be subjected. It is recommended that cables be made of stranded copper for flexibility.

- Cable lengths should be kept as short as practically possible. The overall length of the cable is dependent upon the remoteness of the measurement platform and the type of data acquisition system being used to sample the signal.

- A number of data loggers are capable of withstanding harsh environments, including hot and cold temperatures and high relative humidity. All cables that run along the ground should be buried to a depth where they will not normally be disturbed by routine maintenance operations. Cables not specifically capable of withstanding burial should be placed in conduits. When effort is being expended to place cables underground, extra capacity for future expansion should be considered.

- Signal cables should be run through separate conduits from electrical power cables whenever possible. Cables should cross at right angles to reduce electrical interference. When such arrangements are impractical, specially shielded cables should be used.

- Cabling between the instrument and the data acquisition system should be carefully grounded and protected against lightning.

Whenever a system is wired, care must be taken to accurately map both the physical location of the cables (especially if underground) and the connections running from the instruments through the junction boxes to the data acquisition system. Electricity should be available at the location of the sensors, both for the operation of the instruments and for use in the maintenance of the observation platform. Separate circuits for each set of instruments are desirable, but not always practical. Whenever redundant instrumentation is used, it should be operated on separate electrical circuits. All electrical wiring should meet or exceed local electrical codes. Just as in the case of the signal cables, all electrical cables should be buried or securely fastened to the instrument mounting platforms. Furthermore, for safety, switches or circuit breakers should be installed close to the equipment for easy servicing.

Environmental conditions

All instruments and additional equipment of a meteorological measurement station should be able to operate for at least a temperature range of -30 °C to 55 °C and withstand high wind speeds. Other natural stresses like earthquakes in tectonically active regions as well as lightning have to be taken into account. The station should be properly grounded to prevent damage from lightning. In addition the possibility for small birds and insects to build nests inside of station components should be minimized.

4.1.6 Power Supply

The power system should ensure an independent uninterrupted power supply to the meteorological station under all environmental conditions. The system to supply power to the meteorological sensors should be integrated within the station design and be kept independent of the external grid. This is mainly to avoid power failure to the meteorological station in events of brownouts, grid failure, high voltage conditions etc. This is usually provided by installing solar photovoltaic panel with a battery bank that can store energy. This energy can be used during cloudy days when electricity generated is less than that required for continuous operation of the meteorological station. Generally it is a practice in the industry to provide for at least two weeks of autonomy.

4.1.7 Security

Depending upon the location, security may be a significant consideration. Security is both for the protection of the site against vandalism and theft, and for the protection against harm of would-be intruders. At a minimum the measurement site should be well-fenced against intruders, both human and animal. Further security measures may include alarm systems, security lights (on buildings, but away from the instrumentation) and video camera systems. In some locales special security should be considered against burrowing and gnawing rodents.

4.1.8 Station information documentation

A detailed description of the measurement site and its surroundings is probably one of the most significant pieces of metadata provided to stakeholders, researchers etc. It is of utmost importance to describe the site and its surroundings, not only in terms of latitude, longitude and elevation, but also with respect to the topography and land use surrounding the measurement location. The latitude and longitude should be recorded in decimal degrees, North and East positive with both the South Pole and 180° W defined as zero. Example station information documentation is shown in Annex B.

General Description

- Information on whom the authority is for the site. Postal address, telephone, fax and E-mail if applicable.

- The site's location: latitude (N positive 0 - 90), longitude (East/West of Greenwich), Elevation above MSL, Local Time from GMT, Station Topography and Station Surface Type from the archive, and the date of the first data submitted.

- Topographic map showing the land within a 15 km radius. A topographic map with a scale of approximately 1:250000 provides the appropriate resolution. This gives users a sense of the homogeneity of the surrounding areas.

Site Description

- Site Surroundings: a written description indicating population centres, population density. Major sources of pollution. Large bodies of water or significant local topographic effects should be noted. If the site is located at an educational institution or on the top of a building.

- Climate characteristics: the general climate type (e.g., maritime, polar, etc.), climatic normals (min/mean/max summer/winter temperatures, mean rainfall etc.), significant climatic events (e.g., monsoons, hurricanes, tornadoes)

- A map of the local area around the station (approximately a 1 to 2 km radius). A recent topographic map or photomap with a scale of 1:50000 provides the necessary resolution.

Station Description

- A list of all the radiation fluxes being measured routinely at the station and the types of instruments being used. The type of data acquisition system(s) being used, the sampling rates of the data acquisition system and the outputs that are being archived. Information on the tracking and shading systems that are being used in obtaining the measurements is also required.

- A station map: a detailed map indicating the location of the individual sensors in relation with each other. This map is primarily for the radiation instrumentation locations and need not include the location of the meteorological station or upper air station. Such information would be on the station map if the distances were greater than approximately 20 m.

- A horizon view of the global radiation sensor indicating the major obstructions. This would be a figure utilizing the data supplied to the Archive running from North through South to North in a clockwise direction.

- Comments on the site. For example, comments would include the instrumentation and data acquisition systems that are used for the meteorological variables. If another individual is the responsible contact for the meteorological portion of the site, the name and address would be included in these comments. A brief description of the method and frequency of the calibration of the sensors would be included in this set of comments. If a particular set of research measurements were being made at the site, this should be noted and the name and address of the appropriate contact given.

- Photographs of the station and its surrounds. Up to 4 photographs with appropriate comments should be provided. These can convey useful information concerning the instrument set-up and the surrounding horizon if there are significant obstructions. For example, if a tower is found on the site, a photograph may be appropriate to show where the instruments are located, or four pictures of the cardinal points of the compass from the central instrument with a wide-angle camera.

The station description document should be updated regularly. If significant changes occur in the instrumentation, the horizon or the ancillary measurements, corrections should be made immediately. In a manner similar to the horizon survey, the site description should be updated every five years.

4.2 INSTALLATION REQUIREMENTS

4.2.1 General pre-installation checks and service

Before installing any solar irradiance sensor the instrument should be carefully inspected.

- If not provided by the manufacturer, the instrument should be calibrated against a proven and validated high precision measurement station, so that the following information is available:

  » the responsivity of the instrument to radiation

  » the spectral range of the instrument

  » the linearity of the instrument between 0 and 1500 W/m2

  » the directional responsivity of the instrument (cosine and azimuthal response of the instrument) for pyranometers

  » the deviation of the temperature compensation circuit of the instrument over the

  » temperature range (-10° to +40° C of range) or if not compensated, the required temperature correction of the instrument. In climates where the temperature range is greater than that specified, instrumentation should be selected to meet the temperature regime. For the most accurate measurements, the temperature of the thermopile should be monitored and the signal corrected for temperature variations. A number of instruments using non-thermopile sensors may be considered if they meet all other criteria.

  » the instrument has been radiometrically leveled. That is, the thermopile is horizontal when the bubble level indicates such (the bubble level should have an accuracy of ±0.1°).

  » the opening angle and the slope angle of the instrument

- Checks should be made of all wiring to ensure that there are neither nicks in the sheathing nor stress on the connections. The wire should be of a variety that will withstand the climatic regime of the area in which the instrument is to be installed.

- All O-rings should be lubricated lightly with very fine grease (e.g. Dow Corning Model 55 O-ring lubricant or Fischer Scientific Cello-Seal C-601).

- All threaded parts should be lubricated in a manner similar to the O-rings.

- The thermopile (or the signal transducer) should be visually inspected to ensure that the surface is uniform in colour and texture.

- The inner and outer domes should be checked for scratches or nicks. If found, the domes should be replaced. However, if the dome requires replacement due to damage, the instrument must be re-calibrated.

- The desiccant should be fully activated. It is recommended that the desiccating material be of the bead type (e.g. Trockenperlen, Kali-chemie AG) and not one which easily powders (e.g. Drierite, Hammond Drierite)

- All connectors must be waterproof and should be appropriate for the climatic conditions in which the sensor will be deployed.

4.2.2 Mechanical installation

- Ventilated housing: The recommended procedures for the measurement of global radiation require the use of a ventilated housing to improve the overall stability of pyranometer measurement by damping changes in the pyranometer body temperature due to solar loading and potentially reducing the thermal offset. In some climates, the use of a ventilator also improves the amount of recoverable data by eliminating dew and reducing the number of occurrences of frost and snow on the instrument domes. Measurements in other regions, however, have not shown a significant increase in accuracy or percent data recovered with the use of ventilated housings. As each ventilator adds extra cost and complexity to the installation and maintenance of a station a thorough analysis of its requirement should be made before installation. Locations where a ventilated housing are recommended are:

    » where dew, frost or snow is prevalent,

    » where natural ventilation is infrequent or variable,

    » where there is significant radiative cooling during portions of the year, a ventilated housing,

    » may reduce thermal-offset,

    » where the humidity is high during portions of the year a ventilator will reduce the possibility of water damage and reduce the frequency of desiccant changes.

- The instrument should be mounted with the direction of the connector facing poleward for fixed platforms and away from the solar disk when mounted on solar tracking devices.

- The instrument must be fastened to the platform (or ventilating device) so that it will not move in inclement weather. The bolts used should be lubricated before assembly for ease of disassembly. Initially, these bolts (normally two or three depending upon the instrument) should be not be tightened until the instrument is leveled according to its bubble level. Spring loaded bolting devices for mounting the instrument are also an excellent means of guaranteeing the instrument will remain fixed while providing the added ability of leveling the instrument without requiring the bolts being loosened.

- The instrument should be leveled using the supplied three leveling feet. By first adjusting the foot closest to the bubble, the instrument should be adjusted until the bubble is centered within the inner circle of the supplied bubble. When completely centered, and radiometrically leveled, the bubble level indicates that the thermopile is horizontal to within ±0.1° causing an azimuthal variation of ±1% at a solar elevation of 10°.

- Carefully tighten the retaining screws so that the instrument is immovable. To do so, gently tighten the bolts alternately until secure. Be careful not to over-tighten.

- Place and adjust the radiation shield or ventilated housing cover so that it is parallel to, and level with or below the thermopile surface.

- The mechanical installation of the pyrheliometer must ensure that the instruments are firmly attached to the tracker on which they are to be mounted. Care must be taken that the instrument will not shift position throughout the day as the center of gravity shifts with respect to the mounting brackets. When installed on a correctly pointing tracker, the combination tracker and instrument should work as an integrated unit with the sight of the instrument acting as the primary sight for the tracker. When using an active tracker, care must be taken to ensure that the pyrheliometer or active cavity radiometer sights are aligned with respect to the positioning of the active eye. Trackers that use a combination of active and algorithm tracking (an algorithm that calculates the location of the sun based on location and time) depending on solar intensity, must be set up in a manner that the tracker does not 'jump' to a different position when the solar intensity drops below the active-eye threshold.

- It should be noted that in aligning direct beam radiometers, the field of view of the sighting diopter is significantly smaller than the field of view of the instruments. Nominally, pyrheliometers have a field of view of approximately 5°, while the sighting optic subtends a maximum angle of between 1.4 and 2.0°.

- The tracker location must be known. The more precisely the location can be determined, the easier the setup of the tracker. With modern GPS receiver systems the position of the tracker can be determined (latitude and longitude) to within ±3 m.

- The base on which the tracker is to be placed must be stable. While active trackers and some passive trackers are able to correct for a non-level surface, all trackers perform better if they are mounted such that the instrument base is level. Trackers mounted on pedestals should be leveled such that the vertical axis of the tracker, and not just the pedestal post, is perpendicular to the horizon. A three-point base that allows easy adjustment is recommended. The use of spring tensioners, lock washers, or bolts that are tightened using double nuts, will reduce the problem of the connection between the mounting post and the tracker base loosening and causing the tracker to tilt from level. The tracker should be rotated about the vertical axis during the leveling process to ensure that the axis is vertical. A number of active tracking and computer-controlled passive tracking systems are capable of mathematically correcting for out-of-level conditions so that solar tracking is maintained.

- The tracker needs to be aligned in the north-south direction. Depending on the type of tracker the accuracy of this alignment varies. Equatorial trackers need to be precisely aligned, while most two-axes passive and active trackers have correction algorithms built into the software to allow alignment to be less precise. However, the greater the accuracy in aligning the tracker, the easier it will be to initiate accurate tracking.

4.2.3 Station commissioning

Station should be commissioned only after all the above-mentioned criteria have been fulfilled. In order to make sure that all the criteria have been fulfilled and for proper documentation, a station-commissioning sheet should be prepared.

Protocols should be developed for station commissioning tests and the instantaneous values of each meteorological parameters recorded by the station should be recorded in these commissioning sheets. The person in charge for commissioning of the station should fill in this sheet. An example of commissioning sheet for one of the instrument (RSR2) of a CSP-specific meteorological station is shown in Annex C. Such commissioning sheets can be created for all instruments used in the meteorological station. Moreover, station should be commissioned under proper weather conditions, that allows checking the functionality of different instruments.

4.3 POST-INSTALLATION REQUIREMENTS

High quality, consistent on-site maintenance is crucial if accurate long-term records are to be obtained. Not only does the individual have to care for the instruments, they must also carefully document any work that they do on those instruments. It is not good enough to assume that instruments are cleaned regularly; this activity must be properly documented. To help in this documentation, sample log sheets are reproduced in Annex D. Many national networks have developed their own methods of documentation and these can be used if they contain the appropriate information for the radiometers. All maintenance procedures, variations in instrument behavior and changes in instrumentation must be fully documented with respect to activity, time and date.

4.3.1 Daily Maintenance

The minimum daily requirements for maintaining a Baseline Surface Radiation Network (BSRN) radiation station are as follows:

- Cleaning Pyranometers and Pyrheliometers: The exterior of domes or optical surfaces of each instrument must be cleaned at least once per day. It is preferable that this cleaning is done before dawn. However, if this cannot be accomplished, the sensors should then be cleaned as early as possible during the day. If possible, the instruments should also be cleaned following the occurrence of any form of precipitation or atmospheric events that would cause degradation to the signal. Each time an instrument is cleaned, the time and duration of the cleaning should be recorded in the site documentation. All loose dust or particulate matter should be blown off gently (a camera brush is a useful tool) before the dome is wiped. Using a soft lint-free cloth the dome should then be wiped clean. Caution must be used so that the dome is not scratched, nor the instrument moved, during this procedure. Any film left from the cleaning material must be removed. Several methods may be used to remove frost or ice from the dome, depending upon the severity. Light deposits can be removed by lightly rubbing the surface using the lint-free cloth as in normal cleaning.

- The radiometer should be checked for any condensation on the inside surface of the outer dome. If this occurs, the outer dome must be removed in a clean, dry location, cleaned and the cause for the leak determined. The most probable cause is poor maintenance of the desiccant (see weekly maintenance). If the desiccant has been changed within a week, the probable cause is a poor 'O' ring seal. A replacement is required. If moisture is found on the inner surface of the inner dome, the instrument should be replaced with a spare instrument and the faulty instrument sent for service.

- The ventilator motors should be checked on a daily basis. If the motor is not operating properly, the problem should be corrected or the motor replaced. All procedures should be documented, including the start and end time of the work. If knowledge of when the ventilator began to malfunction is known (e.g., lightning strike) this should also be included in the log. On those ventilators where the cover acts as a radiation shield, the top of the cover must be situated below the receiver surface of the radiometer.

- The pointing of any instruments should be checked and, if necessary, corrected. The reasons for possible misalignment are partially dependent on the type of tracker being used. The sun must be shining to detect spot alignment for direct beam instruments; however, the checking of clock times and general system failures is independent of weather conditions.

- Shaded Instruments - Diffuse Irradiance: Each shaded instrument must be checked to ensure that the shading device completely covers the outer dome of the instrument. These checks are similar to those above for the direct beam instruments.

- Where possible, the site operator should be able to review the data from the previous day. This information will allow him/her to detect any significant changes that may have occurred during the day.

4.3.2 Weekly Maintenance

The minimum weekly requirements for maintaining a station are as follows (in addition to the daily maintenance):

- The level of each horizontally mounted instrument (e.g., pyranometers, pyrgeometers) should be checked and corrected as necessary. The bubble of the circular level should be completely within the inner circle. For most instruments, this indicates that the instrument is level to within ±0.1°.

- Operation and working of Rotating Shadowband Irradiometers (RSI) should be checked. The Shadowband should rotate once every 30 seconds from one end to another under relatively clear-sky conditions. Thus, it returns to its initial position every minute. Under cloudy conditions, it rotates even more, to capture the cloudy conditions. Shadowband should be checked for proper rotation, alignment and mechanical attachment to the motor. If Shadowband is found to be loose, it should be tightened.

4.3.3 Monthly maintenance

The minimum monthly requirements for maintaining a station are as follows (in addition to the daily and weekly maintenance):

- Rain gauge should be cleaned (if dirty) and any dirt/dust/foreign particles like tree leaves, insects, waste paper, plastic bags, etc. should be removed from the catchment area. In addition, the rain gauge should be checked for proper leveling and leveled properly in case required.

- Guy wires (if any) holding the masts securely should be checked for proper tightening. If not, they should be tightened properly so that the masts stand vertical.

- The station and its surroundings should be monitored for some unusual developments/ changes like growth of vegetation, missing fencing, missing parts, etc. If so, these changes should be documented.

4.3.4 Long-term maintenance

Semi-annual maintenance

Quarterly or semi-annual maintenance checks are recommended for CSP-met measurement stations. During such station visits the following tasks should be performed:

- Check the desiccant in each sensor. Desiccant should normally last several months, but is dependent upon atmospheric water vapor, the quality of radiometer seals, the size of the desiccant chamber and the quality of the desiccant. In drier climates checking the desiccant monthly may be sufficient while in areas where monsoon conditions occur, twice-weekly inspections should be made during the most humid season. Depending upon the type of sensor and the type of ventilated housing, the shield portion of the ventilator may require removal to check the desiccant. Once checked and replaced if necessary, the shield should be carefully replaced ensuring that the top of the shield is below the level of the instrument receiver surface. Whenever possible, desiccant should be changed during conditions of low relative humidity. If the desiccant is not a bright blue/purple, it should be changed. Desiccant can be recharged by drying. Therefore, no saving is gained by attempting to have the desiccant last another week. The material removed from any instruments should be saved and re-activated by placing in an oven at a low heat for several hours. The desiccant will return to its original color when dry. Desiccant should be stored in an airtight container.

- The color and the condition of the thermopile should be checked. If the color is fading or changing; or the thermopile surface appears rough, cracked or weathered; the instrument should be removed from service and replaced with a spare. On newer instruments this occurs rarely.

- The pyranometers used for the measurement of global and diffuse radiation should be swapped.

- The cabling leading from the instrument to the data acquisition system or junction box should be inspected for wear. Unless the cable is to be replaced, or must be untangled, the instrument should not be disconnected. All work on the cable should be appropriately documented. In cases where a cable is functional, but aging, a time should be set for its replacement during the station semiannual or annual maintenance (see below).

- Any wiring that has become cracked or brittle should be replaced. Any connectors that have begun to corrode should be replaced.

- A careful inspection of all instruments should be made to determine aging. If radiation shields etc. have begun to show signs of aging (brittleness, discoloration etc.) they should be replaced. Pyranometers should be checked for excessive weathering, O-rings checked and lubricated etc.

- All-weather housings for cavity radiometers should be cleaned and any internal electrical connections checked and repaired as necessary. All weather-tight seals should be checked, lubricated or replaced as appropriate. Fans motors should be check and lubricated or replaced as necessary. Any other moving parts should be checked and lubricated according to the manufacturer's recommendations.

- Some trackers require semi-annual maintenance. Check with the manual provided with the tracking device to determine these requirements.

- All seals in weather-tight enclosures should be checked and lubricated or changed if necessary.

- Data acquisition/computer systems: The system collecting the data should be checked to ensure that it is operational.

- The power supply system (PV panel and battery) should be checked for proper functioning. If battery level is below the required levels, it should be replaced.

Annual maintenance

For annual maintenance the following task should be performed:

- All field support assemblies should be checked for level and structural integrity.

- All bolts should be loosened, lubricated and tightened. This preventative maintenance is especially important in areas of harsh climate where corrosion may occur.

- Fans used in ventilated housings should be lubricated or replaced (depending on the type of system in use).

- Station logbooks filled in by the station keeper should be reviewed for the status of cleaning and if major changes have been made to the station after commissioning.

- Semi-annual visit reports should be checked and the present state of the system should be compared based on the findings in the semi-annual report.

- Instruments should be checked for the validity of their calibration. If invalid, they should be re-calibrated either on field or sent to the laboratory.

- Pictures of the entire station should be taken including a horizon image (360° panoramic picture) from the view of solar irradiance sensors.

Ideally, such annual maintenance visits take only half a day on site. Depending on findings and requested level of detail of documentation may need additional days to complete.

Recommendations v/s achievable cleaning

While it is recommended to clean pyranometers and pyrheliometers daily, actual daily cleaning is difficult to achieve on field. Similarly, it is recommended to clean RSI instruments every week. However, in real life these recommendations for cleaning can be rarely fulfilled for CSP-specific meteorological stations due to their remote locations, unavailability of manpower, difficulty to access site, etc. Hence, minimum cleaning of these instruments is required according to Table 5.

Instrument	Recommended	Required
Pyrheliometer	Daily	Every 3 days
Pyranometer	Daily	Weekly
Rotating Shadowband Irradiometer	Weekly	Monthly
output averaging time:	1 min.	Monthly

Table 5: Table summarizing the recommended and required frequency for cleaning most important solar radiation instruments.

5. DESCRIPTION OF NECESSARY CSP SPECIFIC DATA ANALYSIS

Once CSP-specific meteorological stations are installed, measured data from the field stations should be received and stored at a central data receiving system. The incoming data should be checked with respect to their quality and used further. This is described in following sub-chapters. In addition, factors to be considered for data analysis leading towards bankability of CSP-projects are explained. In the end, recommended steps for performing solar resource assessment of CSP projects is described in brief.

5.1 CSP-SPECIFIC DATA ACQUISITION, MONITORING AND REPORTING

Data acquisition & storage

After installing a CSP-specific meteorological station on a site, raw data from the field should be received at a central data receiving system. This can be done in multiple ways: either the station (datalogger) should be programmed in such a way to send data to the central receiving system or the data from the station could be downloaded to central receiving system by connecting to the station. This kind of a system should be tested for functionality before installing a CSP-specific meteorological station.

This central data receiving system can be a simple computer, a server or a database installed on a computer. It should be designed in such a way that it should be able to receive data from not only one station but from multiple stations. Similarly, it should be designed in a way to receive data from field meteorological stations, which have different configurations. The central data receiving system is named as L1 system as it stores raw measured data. An example of this is shown in Figure 13.

The frequency at which data from the station is received (downloaded) to central data receiving system depends on the requirements of (near-real time) data and telecommunication system available to communicate with the station. For example, data measured by the station could be sent to the central data receiving system every 10 minutes, every hour or once every day. We recommend to receive (download) data every day because it can then be quality controlled and checked for any errors. In case an error is found the station keeper/supervisor can be informed about it so as to solve the problem.

Data backup

The L1 system should have some type of backup of the data in order to prevent data loss in event of failure of L1 system. Once the data is received in L1 system, it is recommended to take a backup of the entire L1 system and store it either at the same location or at a different location. The frequency at which data from L1 should be backed up depends on the communication between L1 and the mirror system of L1. We recommend backing up data once every day. Again, programming the system can automatize this backup task.

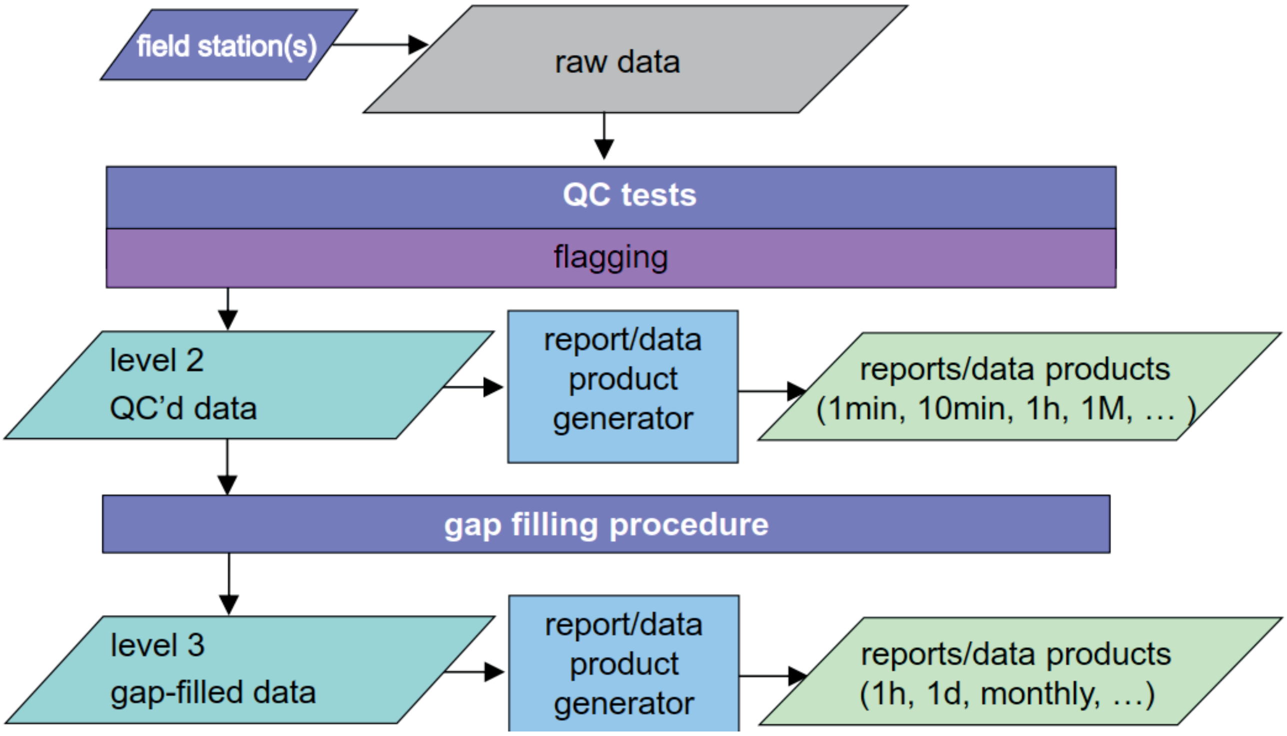

Figure 13: Proposed system architecture for data collection, quality control and reporting. © Suntrace (2015)

Quality control of data

As soon as data is available on L1 system, it should be checked for its quality. There are various quality control tests and algorithms using which the quality of data can be determined and possible errors identified. BSRN (World Radiation Monitoring Center 2011), MESOR (Hoyer-Klick et al. 2008), SERI QC (NREL 1993) are some of the examples of these quality control tests. The aim of such quality control algorithms is to determine if the data has passed quality control test or not. These algorithms mainly check data for plausibility tests (i.e. if measured data falls within physically possible minimum and maximum limits), test for clean and dry clear-sky condition (i.e. if the measured value exceeds values for clean and dry clear-sky condition), redundancy checks, tracking error, shading error, etc.

In any case corresponding flags should be assigned to all data so that it is easy to differentiate good data from bad data. At the same time, some quality control algorithms also detect the possible type of error. The choice of the quality control algorithms and the software depends on the user. The output of performing quality control test on data (namely data and their corresponding flags) should be stored in another system called L2 system. It is recommended to perform these quality control tests on L1 data as soon as latest data is available on L1 system. Again, this procedure of performing quality control tests on data can be automated.

Data monitoring

After performing quality control tests on L1 data, the processed (quality controlled) data should be monitored or checked for possible errors in the data. This process can be done either manually or it can also be automated. In case of errors detected by quality control tests, the data should be carefully investigated. If the error is created due to problem in an instrument, the station supervisor/keeper should be contacted to solve the problem. This part of data monitoring is very important, as it is the last step in quality control process and gives an idea about operational status of the station.

Data reporting

After determining quality of the data, it is recommended to prepare various kinds of reports to show the progress of measurements and also to have a continuous check on the operation of the station. These reports should include statistical parameters of all the measured parameters like mean, minimum, maximum, sum etc. over the period considered in creating the report. Graphs of various measured parameters can be included for easy visual-interpretation of the data. In addition these reports should include metadata of the station such as station ID, date of commissioning, location, geographical co-ordinates, etc.

Depending on internal reporting requirements of such reports may be created with different frequencies such as weekly, monthly, quarterly, or annually. We recommend creating these reports monthly by independent experts, who are familiar with the type of measurements.

In addition to creating these reports, quality controlled measured data can also be created in different time resolutions like 10 minutes, 15 minutes, 1 hour, 1 day etc. so as to cater to the needs of different parties associated with the CSP project.

5.2 DATA ANALYSIS FOR BANKABILITY OF CSP PROJECTS

Since DNI is the most important parameter that affects performance of CSP plants, most of the attention for evaluating bankability of CSP projects should be given to the knowledge of DNI. The following sub-chapters describe the characteristics of DNI, major statistical parameters that should be considered for analyzing DNI, conditions and methodology to combine ground-measured and satellite data. Typical Meteorological Year (TMY) creation is also explained along with procedure for risk assessment of CSP plants.

5.2.1 Characteristics of DNI

While evaluating bankability of CSP projects, following characteristics of DNI should be taken into consideration.

Long-term average value of DNI and associated uncertainty

Long-term average value of DNI should be generally determined from long-term ground-measured data at the site of interest as the inter-annual variability of DNI is very high. However, ground-measured data over long-term are scarcely available at most sites of interest for CSP-projects. Generally satellite-derived solar radiation data covering at least 10 years are easily available for most regions of the world. As a result long-term satellite-derived DNI values should be taken into consideration to consider the inter-annual variability, while determining the long-term average values.

However satellite-derived values are not accurate and hence have some associated uncertainty, which vary from one satellite data provider to another. Not only this, the long-term average values derived by different satellite data providers also vary significantly from each other for the same location. Chhatbar & Meyer (2011) have shown that for a given location the values from different satellite data providers can vary as much as ±9% from the long-term average value determined from ground-measurements. As a result, great care should be taken to determine the long-term average value of DNI at a given site as the bankability of CSP projects generally depends on this value.

In addition the uncertainty associated with the long-term average value of DNI should also be assessed properly as this is taken into consideration for risk assessment of CSP projects. (Meyer, Zuniga, and Westphal 2012) show that decrease in uncertainty of long-term average value of DNI by 1 % results in increase in 3 % increase in NPV of project and 1 % increase in equity IRR.

Annual cycle of DNI

Annual cycle of DNI is also an important metric while evaluating DNI expected at a given site. The distribution of DNI received at a site during summer and winter seasons plays an important role in the design of CSP plants. This should be considered because of variation in sun-positions throughout the year, which affects DNI_effective received at a given site. If DNI is distributed throughout the year more evenly, a CSP plant should be designed with a larger solar field than if more DNI is received during summer and less DNI during winter. An example of even distribution of DNI throughout the year is shown in Figure 14 by blue line representing a site in India (INBIK_DNI). While very high values during summer and low values during winter is depicted by the red line representing a site in Spain (ESPSA_DNI).

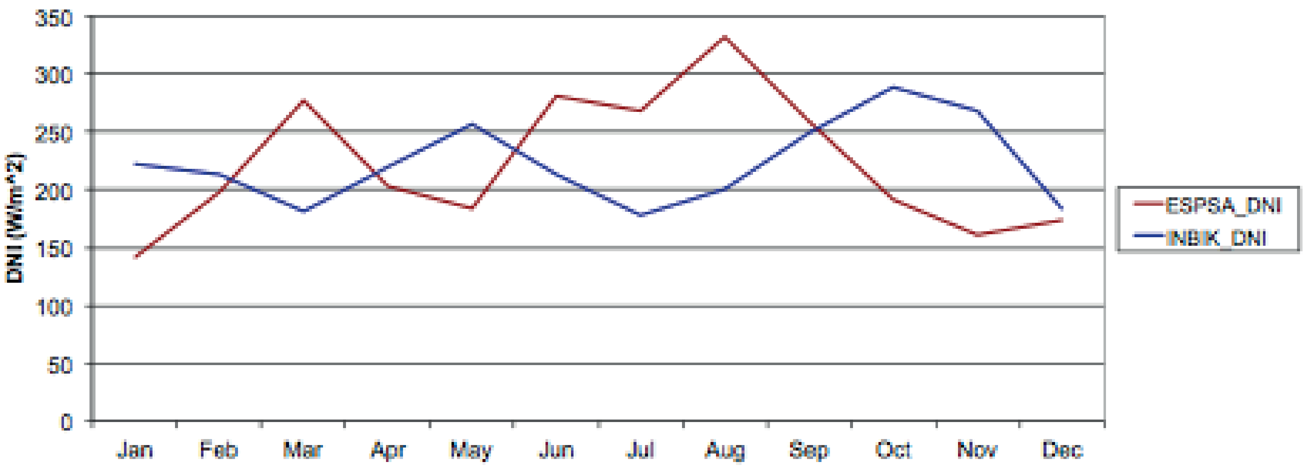

Figure 14: Annual cycle of DNI observed at a location in Spain (red) & India (blue). © Suntrace (2015)

Frequency distribution of DNI

The most important parameter that affects performance of solar thermal power plants is DNI. CSP plants are designed to operate within specific range of DNI values. If instantaneous DNI values are outside this range, the plant could not utilise such DNI values and hence energy incident is lost. The design range of DNI values within which a plant could operate are generally determined from long-term frequency distribution of DNI. Frequency distribution of DNI describes the expected number of occurrences of DNI values at a particular site.

It is assumed that at a certain location different years with same annual average of DNI might not have same energy yields because DNI frequency distribution might be different from one another. One year may have a very bright summer and a very deem winter leading to more values of high and low DNI and less values of moderate DNI. On the other hand other year may be relatively bright on average thus leading to more values of moderate DNI and less values of high & low DNI. Thus due to differences in the number of occurrences of DNI values, two given frequency distributions differ from one another. For a given value of design DNI, the year with more values of high and low DNI will have less energy yield when compared with the year with more values of moderate DNI.

DNI Frequency distribution for years with same DNI annual average may differ from one another due to various reasons such as:

- differences in annual cycle of DNI
- different environmental conditions. i.e. different atmospheric constitutions
- different locations leading to different sun positions during the year
- different sources of data. For ex: measured, satellite derived.

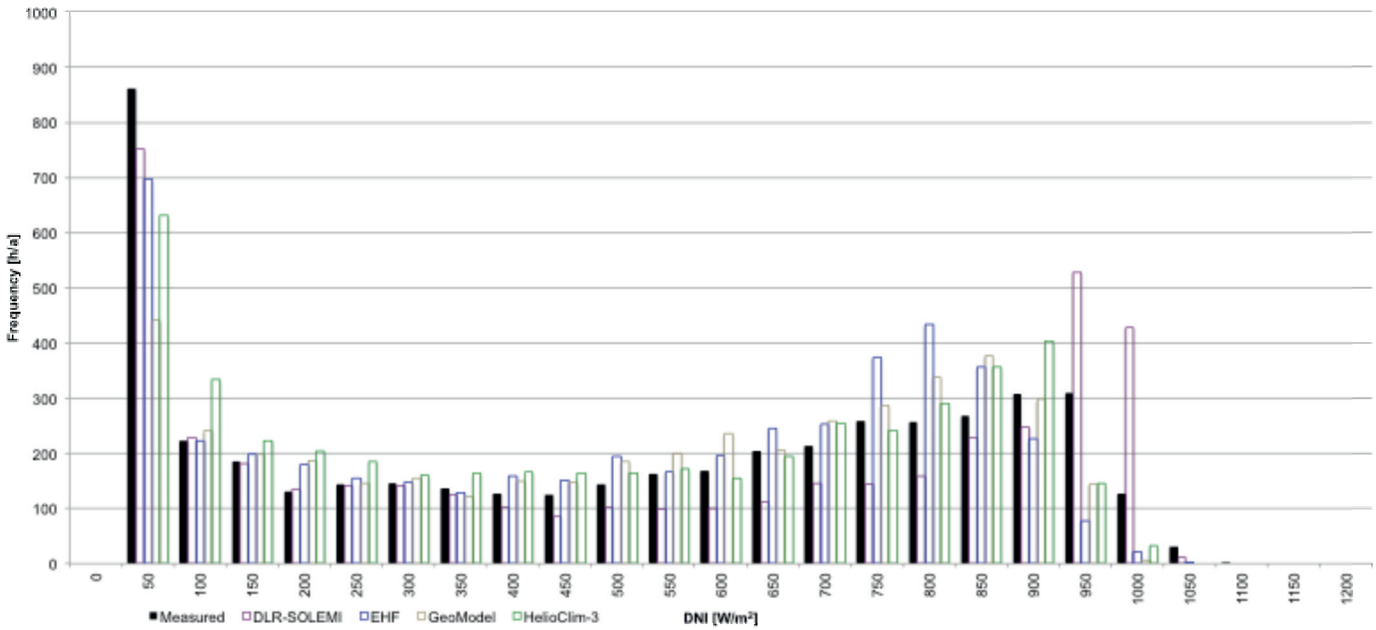

Figure 15: Comparison of DNI frequency distributions of TMYs created from different sources with that from ground-measured TMY at the site ESPSA. The black bars represent DNI frequency distribution from ground-measured TMY. © Suntrace (2015)

For years with same DNI annual average, Chhatbar & Meyer (2011) show that differences in energy yield of CSP plants due to differences in frequency distributions of DNI can be as high as ±9%.

5.2.2 Calculation of major statistical parameters

Once datasets are ready it is important to characterise them using various statistical parameters. Characterisation of datasets is important to determine the statistical behaviour and properties of various data sources. This helps in determining the differences between multiple data sources at a particular test site and also to determine the performance of a data source in general. Moreover, in addition to determining the quality of data sources, characterisation of data sets also helps in relating the results of performance simulation directly to the data sets. This kind of co-relation is necessary to draw conclusions on the influence of meteorological parameters on the energy yields. It should be noted that since DNI is the most important meteorological parameter for the operation of a CSP plant and the principal parameter for this guideline, characterisation of datasets is explained with respect to DNI values.

Various statistical parameters used for characterisation of DNI data are explained below:

Average/ Mean: It is calculated by taking average of the individual years from each data source, at each test site.

$$DNI_{average} = \frac{\sum_{i=1}^{n} DNI}{n}, n = number\ of\ years\ of\ record$$ **Equation 2**

Mean Bias (MB): The formula used to calculate Mean Bias is:

$$Mean\ Bias = DNI_{ground(i)} - DNI_{satellite(i)}, i = 1,2,3 \ldots n, n = number\ of\ parallel\ years$$ **Equation 3**

Ground-based measurements should be taken as reference to calculate mean bias. Since different data sources cover different time periods, mean bias should be calculated by taking into consideration only the years for which parallel data is available for the data source in question and ground-based measurements. Thus, mean bias of different data sources does not correspond to the difference between the overall annual averages.

Root Mean Square Error (RMSE): The following equation is used to calculate Root Mean Square Error.

$$RMSE = \sqrt{\frac{\sum_{i=}^{n} [(DNI]_{ground}^{2} - DNI_{satellite}^{2})}{n}}, n = number\ of parallel\ years\ of\ record$$ **Equation 4**

Average, Mean Bias and Root Mean Square Error give quantitative information of various properties. This helps in inter-comparison of data sources with respect to their properties. But at the same time these parameters fail to describe information about frequency distribution and variation of different properties. Thus, other parameters are used to provide information and to compare different frequency distributions as described below.

Kolmogorov-Smirnov test Integral (KSI): This parameter is very helpful in analysing and comparing DNI frequency distribution from different data sources. The KSI parameter (Kolmogorov–Smirnov test Integral) is defined as the integrated differences between the Cumulative Distribution Functions (CDFs) of the two data sets. The unit of this index is the same for the corresponding magnitude, the value of which depends on it (Espinar Bella et al. 2008). The KSI is defined as follows:

$$KSI = \int_{xmin}^{xmax} Dn\ dx\ ; Dn = |S(x) - R(x)|;$$ **Equation 5**

where x_{min} and x_{max} represent the range of the Cumulative Distribution Functions. S (x) & R (x) are the CDFs of the satellite and reference data respectively. KSI defined above can also be expressed in absolute units as defined below.

$$KSI = \frac{\int_{xmin}^{xmax} Dn \, dx}{a_{critical}} * 100\,\%$$ **Equation 6**

Critical area $a_{critical}$ is defined as

$$a_{critical} = V_c * (x_{max} - x_{min}); \; V_c = \frac{1.63}{\sqrt{N}}, N = number\ of\ points$$ **Equation 7**

V_c represents the critical value that acts as the threshold for calculating D_n. If the value of D_n is less than the value of V_c, KSI is calculated for that point. This is the limiting condition for Null Hypothesis to hold true. If this condition is met, it can be assumed that two frequency distributions are statistically similar. If not, another parameter named OVER is defined to consider such cases.

Thus, two different data sources can be inter-compared not only with respect to the average, mean bias and root mean square error values but also with respect to their frequency distribution. The advantage of using KSI is that it characterizes how closely two frequency distributions match each other. The smaller the value of KSI parameter, the better the match and vice versa.

OVER: As explained above, OVER is calculated for cases if the value of D_n is greater than V_c, and is defined as:

$$OVER = \int_{xmin}^{xmax} aux \, dx \;\; ; aux = Dn - V_c, if\ Dn \geq V_c, else\ aux = 0$$ **Equation 8**

While KSI indicates how well two frequency distributions match when Null Hypothesis holds true, OVER is used otherwise. OVER gives values of mismatch which are above the critical value V_c.

5.2.3 Combining ground-measured and satellite-derived data

As explained in Chapter2.2, most of the satellite-derived data sources have an inherent uncertainty associated with them. This uncertainty is due to many reasons like error in cloud detection, parallax effect, representativeness of atmospheric constituents used in models, uncertainty of the model used to calculate solar radiation values, etc. Because of these uncertainties satellite-derived solar radiation data do not match with ground-measured data for the same time-period, thus leading to differences between the two. Hence before using long-term satellite-derived solar radiation data to determine long-term averages and further create Typical Meteorological Year (TMY), they should be combined with ground-based measurements available at the particular site of interest.

Once quality control procedures have been applied to the ground-measured and satellite-derived solar radiation data, the next step is to combine available ground-measured data with satellite-derived data in order to reduce the uncertainty of satellite-derived data. In wind energy industry Measure Correlate Predict (MCP) methods are used very frequently to predict wind resources at any given site. Using MCP methods, wind resources at the site of interest are predicted by comparing short-term wind measurements at the site of interest with long-term data available at a near-by site.

In solar energy industry similar principle can be followed to determine solar resources at any given site. Carow introduced a parameter dependent modification as well as a so called feature transformation modification (Carow, 2008). The first method uses a defined combination of parameters, e.g. clear sky index and sun elevation angle and modifies additively or multiplicatively the original satellite time series. The additive modification efficiently reduces MBD and the RMSD on average. The second method, feature transformation, uses properties of the cumulative distribution function of high quality ground measurements and transfers those via look-up tables to the satellite-derived time series. The modification causes the distribution functions to move closer together. While this can be done in several ways, the method of (Schumann et al. 2011) is described here in brief.

Short-term solar radiation ground-measurements at the site of interest can be compared and correlated with satellite-derived solar radiation data for parallel periods of record. The main aim of this procedure is to reduce the mean bias and KSI between ground-measured and satellite-derived data, taking ground-measured data as reference. From this short-term comparison, satellite data can be adapted to ground-measured data so that satellite data have better characteristics that are similar to ground-measured data. This can be an iterative process and depending on the results of this initial comparison, long-term satellite data can then be adapted. Hence, long-term satellite-derived solar radiation data can be adapted to short-term site-specific ground-measurements in order to reduce the uncertainty of satellite data and better represent the solar resources at the site of interest.

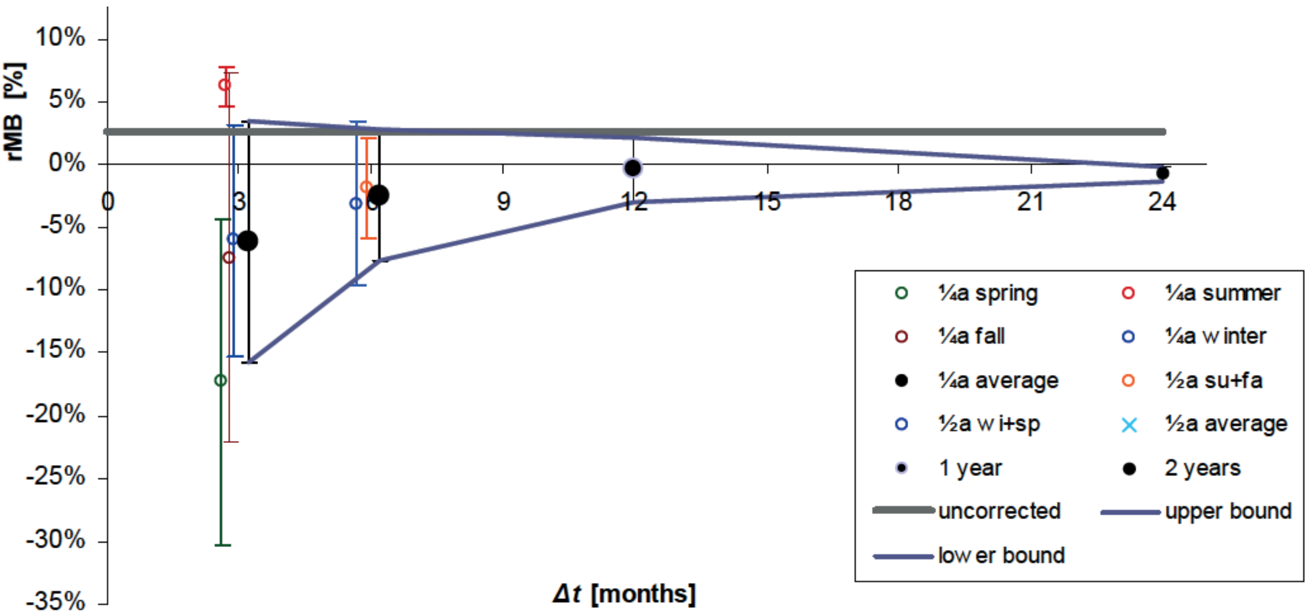

Figure 16: The effect of increasing overlap time on the relative mean bias of corrected satellite data in relation to the long-term average derived from long-term precise ground-based measurements. © Suntrace (2015)

The method of Schumann et al. (2011) presented shows improvement of systematic over- or underestimation: in one example it is shown, that if at least 3 months of parallel measurements are available at a site, even strong biases beyond 25 % can be reduced below 10 %.

But the quality of results applying only a quarter year of overlap for training is still quite variable. Applying half a year of data usually already gives significantly better results – at least if all sun angles are covered, by a start of measurements at summer or winter solstice. In most cases, a complete parallel year of measurements is sufficient to reach very good improvements at sites. From Figure 16 it can be seen that by considering at least two years (24 months) of overlapping data, the uncertainty of the corrected time-series can be improved significantly.

This study shows that improvements made by feature transformation strongly depend on the length of the overlap of satellite-derived irradiance data and ground-based measurements. It is recommended to take at least a whole year of measurements to develop the adaption algorithm.

Mieslinger et al. presented another method based on the assumption that lower irradiances are often overestimated with simultaneous underestimation of high irradiance levels so that a third degree polynomial is assumed for the data (Mieslinger et al., 2013). While the above described methods either improve mainly MB or KSI, this method is designed to minimize the bias while at the same time significantly reducing the KSI parameter as well. A polynomial with an additional weighting function obtained from one year overlapping time period is applied to the remaining satellite-derived solar radiation values. The method is tested at two sites for four satellite data providers. The results show a general improvement for most data sets. The bias on average is close to 0 % for most data providers and the frequency distributions of satellite-derived and ground-measured data usually move closer together. The KSI parameter improves between 30 % and 90 %.

While it is current state of the art to use satellite-derive imagery in conjunction with ground measurements methods evolve including also data from numerical weather prediction models (NWP). However, compared to satellite-derived DNI solar radiation data derived from NWP models are still of much lower quality, because solar radiation is mainly affected by clouds and realistic cloud parameters are highly uncertain in NWP.

Typical Meteorological Year (TMY) creation

Energy performance calculations to predict potential annual energy production of a CSP plant require a TMY as input. Therefore, TMYs need to cover a full year and shall provide the most relevant meteorological parameters for the technology to be evaluated. For CSP plants first of all this is Direct Normal Irradiance (DNI), ambient air temperature, relative humidity and wind speed among others. It should also well represent the characteristic meteorological conditions of average years at a site.

The average of the TMY shall closely meet the long-term average DNI. To derive these values an analysis of uncertainties has to be undertaken. This shall check the accuracy of the underlying data sets, the period of record and also needs to take into account the inter-annual variability of DNI. TMY shall represent the P50 case, which means that it will be exceeded in 50 % of all years. TMY shall also have realistic frequency distributions especially for DNI. This is prerequisite for reliable simulation of plant performance. Extreme weather conditions are filtered out for TMY. Hence, a TMY is not suitable as the only base for system or component design. There are mainly two methods to create Typical Meteorological Year (TMY), either by following NREL (Wilcox and Marion 2008) method or by method described in (Hoyer-Klick et al. 2009).

5.2.4 Risk assessment of CSP projects: Bankability

Finally, for bankable expert opinions on meteorological conditions for CSP, usually data with a lower probability are required to satisfy conservative approaches from banks and lenders. So that in addition to P50 TMY, other TMY's based on a more conservative approach are required to assess the risk of lower irradiance values. For this purpose typically either e.g. P70 or P90 data sets are derived. These represent the data of a typical year, whose values would be exceeded in 70 % or 90 % of all years respectively.

Alternatively risk assessments using performance simulation results based on several good and bad years could give sufficient comfort to the banks. These time series can be derived from satellites but should also be adapted to site-specific characteristics based on ground-measured data. This approach would allow a more detailed assessment of the influence of variable DNI conditions.

Also from processing of at least 10 years of data, P70 or P90 values could be derived, which usually are used as basis to calculate the financial base case for a project. Compared to the simpler approach of only using P70 or P90 years, the advantage of using multiple years is that on one side the effects of meteorological variability and uncertainty, and on the other hand the effect of uncertainties resulting from technical parameters (describing the plant or the uncertainty of the performance simulation models) can be assessed in more detail.

5.2.5 Example data set

In order to give an example of various terms like monthly averages, annual averages, long-term monthly averages and long-term annual averages, standard deviation etc. these values from a site are shown as an illustration in the table below.

Year/Month	January	February	March	April	May	June	July	August	September	October	November	December	Annual average		
Unit	[W/m²]												[W/m²]	[kWh/m²/a]	[kWh/m²/d]
1991	188	184	194	254	332	358	381	360	300	202	250	150	263	2301	6.30
1992	143	215	243	339	328	258	376	384	300	262	266	159	273	2389	6.55
1993	257	147	249	276	289	361	396	342	306	217	129	223	266	2331	6.39
1994	224	251	261	305	292	381	384	363	294	160	222	243	282	2467	6.76
1995	237	254	253	313	304	315	404	339	296	214	156	136	268	2352	6.44
1996	134	226	209	332	289	372	380	369	224	196	222	120	256	2244	6.15
1997	111	219	333	225	284	326	391	329	242	231	177	149	251	2202	6.03
1998	167	202	288	302	214	362	429	368	239	290	220	217	275	2408	6.60
1999	201	261	280	342	295	338	398	393	296	163	204	165	278	2434	6.67
2000	204	309	254	278	264	402	410	369	319	232	199	158	283	2481	6.80
2001	188	250	228	306	263	402	370	363	261	248	161	135	265	2319	6.35
2002	195	292	226	257	301	353	407	344	251	226	189	182	268	2350	6.44
2003	218	171	210	247	310	376	414	396	300	139	159	174	259	2272	6.23
2004	247	212	199	293	203	372	379	358	239	244	225	134	259	2266	6.21
2005	272	209	213	309	315	403	407	331	288	239	202	190	282	2467	6.76
Long-term monthly average [W/m²]	199	227	243	292	286	359	395	361	277	218	199	169	269	2352	6.44
Standard deviation [W/m²]	46	44	38	35	37	38	17	21	31	40	37	36	10	87	0.24
Relative standard deviation [%]	23%	19%	16%	12%	13%	11%	4%	6%	11%	19%	19%	21%	4%	4%	4%

Table 6: Table showing DNI monthly and annual average values for 15 years from 1991 to 2005 at a site in Spain. The monthly average values are shown in W/m², where as the annual average values are shown in the three major units used in solar energy industry.

The values shown in Table 6 above are based on 15 years of data from 1991 to 2005 at a site in Spain. The monthly average values for each month and each year are listed in the table in unit W/m_2. This is done on purpose to avoid differing number of days in each month and to avoid the effect of leap year. It should be noted that these values also consider the night hour values. From the monthly average values, annual average values are calculated for each year and shown in extreme right of the table. Taking an average (mean) of monthly average values over all months for gives annual average value for the particular year in question. Annual average values are expressed in three major units being used in solar energy industry for easy understanding of the user.

Long-term monthly average values of DNI can be calculated from monthly-average values for each month and each year. As shown in Table 6, for example the long-term average value expected in the month of January is 199 W/m^2, which is found by taking the average (mean) of January monthly-average values over all years. Similarly, the long-term annual average values can be calculated by taking an average (mean) over individual annual average values from 1991 to 2005 as shown in the table by 269 W/m2 or 2352 kWh/m^2/a or 6.44 kWh/m^2/d.

An additional parameter that can be calculated from this valuable information is the standard deviation or inter-annual variability of DNI values. This can be done for both, monthly and annual average values. From these 15 years of standard deviation (inter-annual variability) of DNI can be calculated as shown in the last three rows in the table.

5.3 RECOMMENDED STEPS FOR SOLAR RESOURCE ASSESSMENT OF CSP PROJECTS

Site-specific DNI data are difficult to obtain and often have a high uncertainty. Therefore special care should be addressed to solar resource assessment during project development. The long-term average of solar irradiation and its variability need to be analyzed for a reliable projection of their availability in the future. This must carefully take into consideration the uncertainties related to the derivation of solar irradiance data.

At present there is no standard procedure for processing solar radiation data or a set of procedures to be followed for solar resource assessments. As a result and due to pressing deadlines for projects on top, project developers do not always follow a strict approach for solar resource assessments. Majority of the decisions for site selection of CSP plants are still based on the usually rough and initial site assessments.

In such cases, the solar radiation conditions such as annual cycle of DNI, frequency distribution of DNI, inter-annual variability and the uncertainty have not been assessed in detail, and as a result the current knowledge of solar resources available at the site stays limited.

Based on practical experience and analysis of various data products and methods, best practices to achieve high quality assessments with reasonable effort are proposed. Following (Meyer 2010) the recommended procedure is the following:

- In the first place, when no detailed assessment of a project location has been made, multiple satellite-based sources based on average values, and if available, ground-measurements, should be taken into consideration. At this point, long-term average values of DNI from these sources may suffice

- Calculate a quality-weighted best average (Meyer et al. 2008) and determine the resulting uncertainty by Gaussian error propagation.

- Once a project site has been confirmed for further development of the CSP project, a suitable measurement station should be installed at the site in order to reach the 1-year of measurement data during the authorization process, which is on-going in parallel.

- Determine the long-term best estimate for the specific project site (in 1 km x 1 km resolution) and based on as many years of satellite data as available. For DNI as minimum 10 consecutive years should be considered, because inter-annual variability is much higher.
- Multiple Site-specific data sets from satellites and ground-based measurements, with overlapping time-periods can provide independent information and increase accuracy when combining these data sets. Only reliable data sets shall be considered. The uncertainty of the data is determined best individually for each data set.

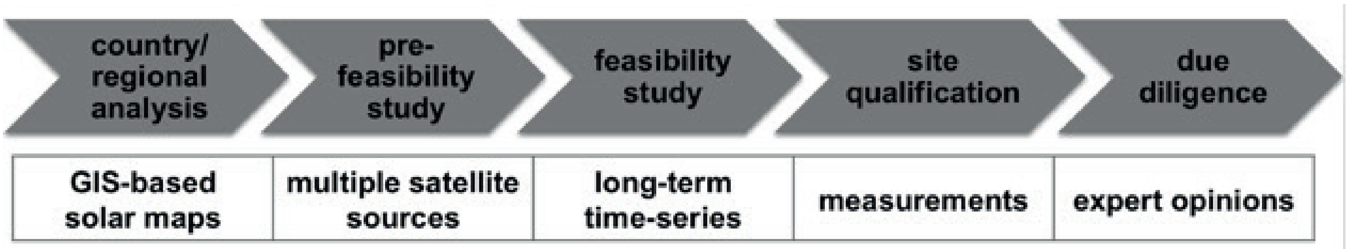

Figure 17: Recommended actions for solar resource assessment during project development of CSP plants. © Suntrace (2015)

Site-specific satellite data time series are required to reflect the long-term history of irradiation, and must be adapted based on overlapping time-periods between different satellite and measurement data sets. To be site-specific, at least a 10 km x 10 km spatial resolution is required; preferable should be 1 km x 1 km resolution.

The accuracy and reliability of the satellite data provider is important, as random and systematic error of data can be of poor quality. Satellite providers often have a regional focus, so that one provider not always is recommendable for all global regions. The current state of satellite-derived methods leaves room for improvement. Also ground-based measurements can be of poor quality, depending on the individual maintenance of the measurement station over the complete measurement period

Therefore, when a location is seriously considered during site qualification phase the satellite-derived time-series should be overlapping with and adapted to the ground-measured data e.g. by the procedure of (Schumann et al. 2011). From the long-term satellite data, which are corrected with the measurement data, the average DNI can be derived, representing the P50 value. P50 means, that the value should be exceeded in 50 % of all years. From the corrected satellite data also the climatological average of DNI can be derived.

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ANNEX A: DETAILED CHARACTERISTICS OF SOLAR IRRADIANCE MEASUREMENT EQUIPMENT

Instrument	Pyrheliometer		Pyranometer		
Characteristic WMO classification	**High quality a**	**Good quality b**	**High quality a**	**Good quality b**	**Moderate quality c**
Classification acc. To ISO 9060:1990	**Sec. Std.**	**First Class**	**Sec. Std.**	**First Class**	**Sec. Class**
response time (95 % value)	< 15 s	< 30 s	< 15 s	< 30 s	< 60 s
zero offset (response to 5 K/h change in ambient temperature)	2 W/m^2	2 W/m^2	2 W/m^2	4 W/m^2	8 W/m^2
resolution (smallest detectable change in W/m^2)	0.5 W/m^2	1 W/m^2	1 W/m^2	5 W/m^2	10 W/m^2
stability (percentage of full scale, change per year)	0.1 %/a	0.5 %/a	0.8 %/a	1.5 %/a	3 %/a
directional response for beam radiation	-	-	10	20	30
temperature response (rel. max. error due to change of ambient temperature within 50 K interval)	1 %	2 %	2 %	4 %	8 %
non-linearity (rel. deviation from the responsivity at 500 W/m^2 due to the change of irradiance within 100 W/m^2 to 1 100 W/m^2)	0.2 %	0.5 %	0.5 %	1 %	3 %
spectral sensitivity (rel. deviation of the product of spectral absorptance & spectral transmittance from the corresponding mean within the range 300 to 3 000 nm)	0.5 %	1 %	2 %	5 %	10 %
Tilt response (rel. deviation from the responsivity at 0° tilt (horizontal) due to change in tilt from 0° to 90° at 1 000 W/m^2)	0.2 %	0.5 %	0.5 %	2 %	5 %
1 min totals (%)	0.9 %	1.8 %	-	-	-
1 min totals (kJ m $^{-2}$)	0.56	1	-	-	-
1 h totals (%)	0.7 %	1.5 %	3%	8%	20%
1 h totals (kJ m $^{-2}$)	21	54	-	-	-
daily totals (%)	0.5 %	1 %	2%	5%	10%
daily totals (kJ m $^{-2}$)	200	400	-	-	-

a Near state of the art maintainable only at stations with special facilities and staff suitable for use as a working standard.

b acceptable for network operations.

c Suitable for low-cost networks where moderate to low performance is acceptable.

ANNEX B: EXAMPLE STATION INFORMATION DOCUMENTATION

Station Information Documentation for CSP-specific Meteorological Station

suntrace

Station Name	Station ID	latitude [°N]	longitude [°E]	elevation [m]	commissioned on

Contact details:

Station keeper	Station supervisor	Station supplier
Name	Name	Name
Address	Address	Address
Mobile:	Mobile:	Mobile:
Phone:	Phone:	Phone:
Mail:	Mail:	Mail:

List of instruments					
Sr.	Instrument	Manufacturer	Model No.	parameter measured	height of installation [m]
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					

Site description	
Item	Comments
Topography	
Land use	
Surrounding	
Climate type	

Weather extremes							
Parameter / Season		Summer			Winter		
	unit	min	max	average	min	max	average
Ambient temperature	[°C]						
Rainfall	[mm/d]						
Pressure	[hPa]						
Wind speed	[m/s]						

Station Information Documentation for CSP-specific Meteorological Station

Station Name	Station ID	latitude [°N]	longitude [°E]	elevation [m]	commissioned on

Station Picture

Picture 1

Picture 2

Picture 3

Picture 4

Horizon Image

Horizon Image (360° panoramic image from the view of solar irradiance sensors)

Control Sheet for Commissioning of Meteorological Measurement Station

HelioScale

site ID	station ID	latitude [°N]	longitude [°E]	elevation [m]	commis-sioned on

contact details:

station keeper	station supervisor	station supplier
Name	Name	Name Suntrace GmbH
Address	Address	Address Brandstwiete 46 20457 Hamburg Germany
Mobile:	Mobile:	Phone: +49 40 75 66 08 98
Phone:	Phone:	Fax: +49 40 75 66 08 99
Mail:	Mail:	Mail: meteo@suntrace.de

list of measurement instruments

	instrument / device	manufacturer	model no.	serial number	calibration constant	last calibra-tion	calibration valid for
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							

commissioning tests*

test no.	test	details
1	RSI	Ensure that the RSI sensor head is cleaned, horizontally leveled and aligned to the GEOGRAPHIC north for Northern Hemisphere or to the GEOGRAPHIC south for Southern Hemisphere. Check that the shadow band is moving.
2	pyranometer(s)	Check for any damage, condensation, check the glass surface for scratches/other damages, check ventilation motors (if any) are functioning properly. If any condensation and/or scratches on glass is/are found, replace or repair the instrument. Check the desiccant, replace if dehydrated. Write for each sensor type (reference cell/pyranometer) the quantity of installed instruments in comments.
3	pyrheliometer(s)	
4	reference cell(s)	
5	leveling/positioning of horizontal pyranometer	Check water levels for proper leveling. If instrument (cable) is aligned to GEOGRAPHIC North (Northern Hemisphere) or GEOGRAPHIC South (Southern Hemisphere). Correct if necessary. Check if any parts are misplaced or loose.
6	sun tracker	Check if tracker is well fixed at the foundation. Check for proper alignment of suntracker (GEOGRAPHIC North/South) by checking the spot created and/or the leveling of the tracker assembly. Spot should be created within the specified range. Check for proper mechanical functioning of the tracker.
7	air temp., rel.humidity probe	Check for correct installation, functionality and discernible external damage.
8	anemometer	
9	wind direction vane	
10	further sensors, instruments	Specify sensor(s)/instrument(s) in comments. Check for correct installation, functionality and discernible external
11	weather housing	Check that the weather housing of all sensors is proper and fixed, check the piping for visible damage. Replace if worn.
12	PV-panel	Check PV-panel.
13	loose parts	Check if any parts are misplaced or loose (sensors, antenna, in case: PV panel, wind mast wires, etc.).
14	cabling of all sensors	Check if the cabling of all sensors is done properly and fixed. Check the sensor cables for external discernible damages.
15	check power supply system	Check if the battery and the PV panel are correctly working and if the charge controller charges the battery.
16	sensor connections to data logger	Check if the sensors are properly connected to the data logger (right cables to the corresponding port). Compare with connection plan.
17	data logger sensor/communica-tion configuration	Check the measurement values and correct configuration of the sensors in the data logger (type, unit, slope, offset, etc.). Correct if necessary. Update communication configuration (e.g. e-mail address) if necessary.
18	check communication (modem)	It should be able to communicate with a remote server/computer properly.
19	real time measurements	Check real time measurements, compare them with observations and document them.
20	tripod, wind mast	Check if the mast(s) is/are steady and well fixed on the ground. Check bolts on the foundations of mast(s).
21	fence, door, lock	Check the fence and door including its lock.
22	horizon pictures	360° panorama picture from the view point of radiation sensors should be taken.
23	station pictures	Take photos of all sensors and instruments and also of the whole station. The serial numbers should be seen.
24	general view	Anything unusual?
25	Station Keeper training and	Training of Station Keeper. Check the station documentation such as: analogy of serial numbers, station logbook, etc.

* Ignore if instrument is not a part of station. Write "No part of station. Not installed" in comments in corresponding line.

ANNEX C: EXAMPLE STATION COMMISSIONING SHEET

Control Sheet for Commissioning of Meteorological Measurement Station

HelioScale

site ID	station ID	latitude [°N]	longitude [°E]	elevation [m]	commis-sioned on

date:		time (local):	

test results		
test no.	approved? Yes/No	comments*
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		
16		
17		
18		
19		
20		
21		
22		
23		
24		
25		

measurements			
time (UTC)	value	measurements	comments

signature consultant

signature station supervisor

signature station keeper

* Ignore if instrument is not a part of station. Write "No part of station. Not installed" in comments in corresponding line.

ANNEX D: EXAMPLE CHECKLIST FOR REGULAR MAINTENANCE

HelioScale
Solar Measurement Solutions

Control Sheet for Maintenance Visit of Meteorological Measurement Station

site ID	station ID	latitude [°N]	longitude [°E]	elevation [m]	commis-sioned on

contact details:

station keeper	station supervisor	station supplier
Name:	**Name:**	**Name:** **Suntrace GmbH**
Address:	**Address:**	**Address:** Brandstwiete 46 20457 Hamburg Germany
Mobile:	Mobile:	Phone: +49 40 767 96 38 0
Phone:	Phone:	Fax: +49 40 767 96 38 20
Mail:	Mail:	Mail: meteo@suntrace.de

list of measurement instruments

	instrument / device	manufacturer	model no.	serial number	calibration constant	last calibration	calibration valid for
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							

commissioning tests*

test no.	test	details
1	RSI	Ensure that the RSI sensor head is cleaned, horizontally leveled and aligned to the GEOGRAPHIC north for Northern Hemisphere or to the GEOGRAPHIC south for Southern Hemisphere. Check that the shadow band is moving.
2	pyranometer(s)	Check for any damage, condensation, check the glass surface for scratches/other damages, check ventilation motors (if any) are functioning properly. If any condensation and/or scratches on glass is/are found, replace or repair the instrument. Check the desiccant, replace if dehydrated. Write for each sensor type (reference cell/pyranometer) the quantity of installed instruments in comments.
3	pyrheliometer(s)	
4	reference cell(s)	
5	leveling/positioning of horizontal pyranometer	Check water levels for proper leveling, if instrument (cable) is aligned to GEOGRAPHIC North (Northern Hemisphere) or GEOGRAPHIC South (Southern Hemisphere). Correct if necessary. Check if any parts are misplaced or loose.
6	sun tracker	Check if tracker is well fixed at the foundation. Check for proper alignment of suntracker (GEOGRAPHIC North/South) by checking the spot created and/or the leveling of the tracker assembly. Spot should be created within the specified range. Check for proper mechanical functioning of the tracker.
7	air temp.,rel.humidity probe	Check for correct installation, functionality and discernible external damage.
8	anemometer	
9	wind direction vane	
10	further sensors, instruments	Specify sensor(s)/instrument(s) in comments. Check for correct installation, functionality and discernible damage.
11	weather housing	Check that weather housing of all sensors is proper and fixed, check the piping for visible damages. Replace if worn.
12	PV-panel	Check PV-panel.
13	loose parts	Check if any parts are misplaced or loose (sensors, antenna, in case: PV panel, wind mast wires, etc.).
14	cabling of all sensors	Check if the cabling of all sensors is done properly and fixed. Check the sensor cables for discernible damages.
15	check power supply system	Check if the battery and the PV panel are correctly working and if the charge controller charges the battery.
16	sensor connections to data logger	Check if the sensors are properly connected to the data logger (right cables to the corresponding port). Compare with connection plan.
17	data logger sensor/communication	Check the measurement values and correct configuration of the sensors in the data logger (type, unit, slope, offset, etc.). Correct if necessary. Update communication configuration (e.g. e-mail address) if necessary.
18	check communication (modem)	It should be possible to communicate with a remote server/computer properly.
19	real time measurements	Check real time measurements, compare them with observations and document them.
20	tripod, wind mast	Check if the mast(s) is/are steady and well fixed on the ground. Check bolts on the foundations of mast(s).
21	fence, door, lock	Check the fence and door including its lock.
22	horizon pictures	360° panorama picture from the view point of radiation sensors should be taken.
23	station pictures	Take photos of all sensors and instruments and also of the whole station. The serial numbers should be seen.
24	general view	Anything unusual?
25	station documentation	Check the station documentation such as: analogy of serial numbers, station logbook, etc.

* Ignore if instrument is not a part of station. Write "No part of station. Not installed" in comments in corresponding line.

HelioScale
Solar Measurement Solutions

Control Sheet for Maintenance Visit of Meteorological Measurement Station

site ID	station ID	latitude [°N]	longitude [°E]	elevation [m]	commis-sioned on

date:		time (local):	

test results		
test no.	approved? Yes/No	comments*
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		
16		
17		
18		
19		
20		
21		
22		
23		
24		
25		

measurements			
time (UTC)	value	measurements	comments

signature consultant | signature station supervisor | signature station keeper

* Ignore if instrument is not a part of station. Write "No part of station. Not installed" in comments in corresponding line.

ANNEX E: EXAMPLE CONTROL SHEET FOR CLEANING AND INSPECTION

Control Sheet for Cleaning/Inspection of HelioScale
Meteorological Measurement Station

site ID	station ID	latitude [°N]	longitude [°E]	elevation [m]	commis-sioned on

contact details:

station keeper	station supervisor	station supplier
Name	Name	Name Suntrace GmbH
Address	Address	Address Brandstwiete 46 20457 Hamburg Germany
Mobile:	Mobile:	Phone: +49 40 75 66 08 98
Phone:	Phone:	Fax: +49 40 75 66 08 99
Mail:	Mail:	Mail: meteo@suntrace.de

list of measurement instruments

	instrument / device	manufacturer	model no.	serial number	calibration constant	last calibra-tion	calibration valid for
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							

tasks*

task no.	instrument	installed*	details
1	press cleaning button		Press the cleaning button to start cleaning sequence in data logger.
2	RSI		Clean RSI sensor head during **EVERY station visit**. Check that the shadow band is moving. If not, inform station supervisor and make a note of observation.
3	pyranometer 1		Clean instrument during **EVERY station visit**. Check for any damage, misplaced or loose parts. Check the glass surface for condensation, scratches or other damages. Check ventilation unit (if any) for proper functioning. Check the desiccant (should be clear in colour). If any problems are found, inform station supervisor and make a note of observation.
4	pyranometer 2		
5	pyranometer 3		
6	pyrheliometer 1		
7	reference cell 1		
8	ref. cell 2 - Clean in intervals!		**Clean instrument only in given intervals!!!** Check for any damages or scratches. In case inform station supervisor and make a note of observation.
9	press cleaning button		Press the cleaning button to end cleaning sequence in data logger.
10	PV-panel		Clean and Check PV-panel. In case of problems inform station supervisor and make a note of observation.
11	ref. cell 3 - Don't clean!		**DON'T CLEAN ISTRUMENT!!!** Check for any damages or scratches. In case inform station supervisor and make a note of observation.
12	sun tracker		Check for proper alignment: Pyrheliometer should be aligned to sun ("sun spot" within the specified range). Shadow ball should completely shadow pyranometer measuring diffuse (if installed). If not inform station supervisor and make a note of observation.
13	anemometer		Check for any visible external damage. Check if moving when windy. If any problems are found, inform station supervisor and make a note of observation.
14	wind direction vane		
15	air temp./hum. probe		Check for any visible external damage. If any problems are found, inform station supervisor and make a note of observation.
16	further instruments		
17	external damages, loose cables, parts.		Check if any cables, antenna or other parts are misplaced or loose. In case inform station supervisor and make a note of observation.
18	tripod, wind mast		Check if the mast(s) is/are steady and well fixed on the ground. In case of problems inform station supervisor and make a note of observation.
19	additional tasks**		

* Write "Yes" if instrument is a part of station and task is to be done. Otherwise write "No".

** Specify here additional task if any.

Control Sheet for Cleaning/Inspection of Meteorological Measurement Station

site ID	station ID	latitude [°N]	longitude [°E]	elevation [m]	commissioned on

		1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.	17.	18.	19.		
		CLEANING										rough visual inspection										
frequency		each station visit							every 12 weeks*	each station visit		each station visit, at least weekly										
task		press cleaning button	RSI	pyranometer 1	pyranometer 2	pyranometer 3	pyrheliometer 1	reference cell 1	ref. cell 2 - Clean in intervals!	press cleaning button	PV-panel	ref. cell 3 - Don't clean!	sun tracker	anemometer	wind direction vane	air temp./hum. probe	further instruments	stations damage, loose cables, parts	tripod, wind mast	additional tasks		
installed? insert "✓" or "-"																						
date	local time																				comments	name / signature

Don't leave any fields empty.
If no comments or instrument not installed insert "–".

Complete blue fields always with:
✓ task done or – task not done

*) cleaning frequ. RC2 maybe changed, insert new:______

1/12

cooperação alemã
DEUTSCHE ZUSAMMENARBEIT

Por meio da:

giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

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