GREBE

Generating Renewable Energy Business Enterprise

Resource Assessment Toolkit for Solar Energy

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www.grebeproject.eu

The GREBE Project

What is GREBE?

GREBE (Generating Renewable Energy Business Enterprise) is a €1.77m, 3-year (2015-2018) transnational project to support the renewable energy sector. It is co-funded by the EU's Northern Periphery & Arctic (NPA) Programme. It focuses on the challenges of peripheral and arctic regions as places for doing business, and helps develop renewable energy business opportunities in areas with extreme conditions.

The project partnership includes the eight partners from six countries, Western Development Commission (Ireland), Action Renewables (Northern Ireland), Fermanagh & Omagh District Council (Northern Ireland), Environmental Research Institute (Scotland), LUKE (Finland), Karelia University of Applied Sciences (Finland), Narvik Science Park (Norway) and Innovation Iceland (Iceland).

Why is GREBE happening?

Renewable Energy entrepreneurs working in the NPA area face challenges including a lack of critical mass, dispersed settlements, poor accessibility, vulnerability to climate change effects and limited networking opportunities.

GREBE will equip SMEs and start-ups with the skills and confidence to overcome these challenges and use place based natural assets for RE to best sustainable effect. The renewable energy sector contributes to sustainable regional and rural development and has potential for growth.

What does GREBE do?

GREBE supports renewable energy start-ups and SMEs:

- To grow their business, to provide local jobs, and meet energy demands of local communities.
- By supporting diversification of the technological capacity of SMEs and start-ups so that they can exploit the natural conditions of their locations.
- By providing RE tailored, expert guidance and mentoring to give SMEs and start-ups the knowledge and expertise to grow and expand their businesses.
- By providing a platform for transnational sharing of knowledge to demonstrate the full potential of the RE sector by showcasing innovations on RE technology and strengthening accessibility to expertise and business support available locally and in other NPA regions.
- To connect with other renewable energy businesses to develop new opportunities locally, regionally and transnationally through the Virtual Energy Ideas Hub.
- By conducting research on the processes operating in the sector to improve understanding of the sector's needs and make the case for public policy to support the sector.

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The Toolkit outlines best practice techniques for assessing solar resource potentials as a foundation for a solar resource assessment. Solar resource assessment is indispensable in estimating the solar potential in a given location, the social and environmental impacts accompanying the resources exploitation and the economic viability of solar utilization scenarios.

The scope of the Toolkit covers:

- Governing principles of solar energy
- Measuring Solar Irradiation
- Parameters for choice of optimal measurement station
- Data acquisition and quality control
- Solar radiation modelling – satellite-based models
- Applying solar resource data to solar energy projects
- Forecasting Solar Irradiation
- Best practices in on-site monitoring programmes

Governing principles of solar energy

Solar energy is obtainable in abundance in most parts of the world, even in the NPA remit. As seen in the solar irradiation map below, the NPA Region's average sum of solar irradiation is well below most parts of Europe. However, during the summer period, the countries based in the NPA region get around 17 to 19 hours of daylight and those in the Arctic Circle get 24 hours. Solar PV requires daylight (solar irradiation), rather than sunshine and high temperatures, which makes it a viable technology choice for businesses in the NPA region.

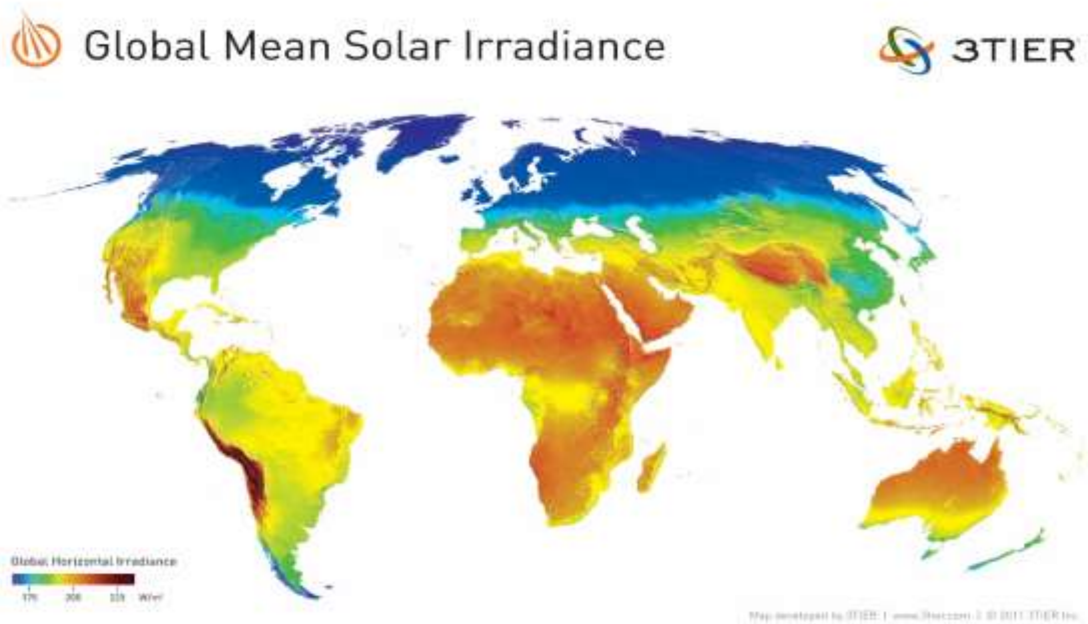

Figure 1. Global mean horizontal irradiation map [1]

The amount of solar energy incident on the earth's surface is approximately 1.5 x 1018 kWh/year, which is about 10,000 times the current annual energy consumption of the entire world. The density of power radiated from the sun (referred to as solar energy constant) is 1.373 kW/m2.[2] Like any generation source, understanding of the quality and future dependability of the fuel is vital for precise analyses of system performance and the financial feasibility of a project. With solar energy systems, the intermittence of the supply

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[1] https://cleantechnica.com/2013/08/19/germany-breaks-monthly-solar-generation-record/
[2] Resource Assessment Handbook, APCTT, 2009

of sunlight embodies the utmost uncertainty in a solar power plant's predicted performance.[3]

Solar Characteristics

Solar spectrum

Light of different wavelengths reaches different parts of the Earth's atmosphere. Visible light and infrared radiation reach the surface, warming the surface to liveable conditions. With an effective temperature of approximately 6,000 K, the sun emits radiation over a wide range of wavelengths, the solar spectral power distribution, or solar spectrum, commonly labelled from high-energy shorter wavelengths to lower energy longer wavelengths as gamma ray, x-ray, ultraviolet, visible, infrared, and radio waves. These are called spectral regions. Most (97%) solar radiation is in the wavelength range of 290 nm to 3,000 nm.

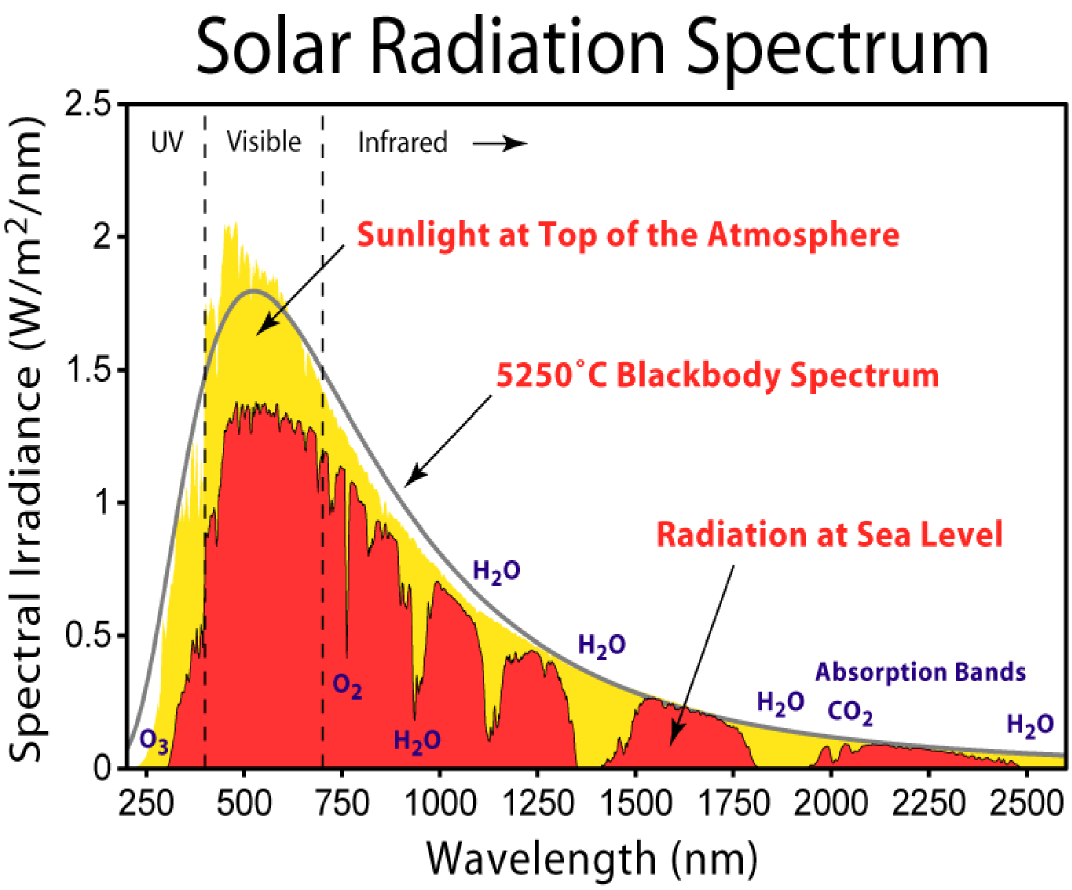


Figure 2 Solar radiation spectrums.

[3] Best Practices Handbook for the Collection and Use of Solar Resource Data, NREL,2015,

Solar Irradiance

Solar irradiance is the power per unit area received from the Sun in the form of electromagnetic radiation in the wavelength range of the measuring instrument. Irradiance varies according to the weather and the sun's location in the sky. This location continuously changes through the day due to changes in both the sun's altitude (or elevation) angle and its azimuth (or compass) angle. The figure below illustrates this.

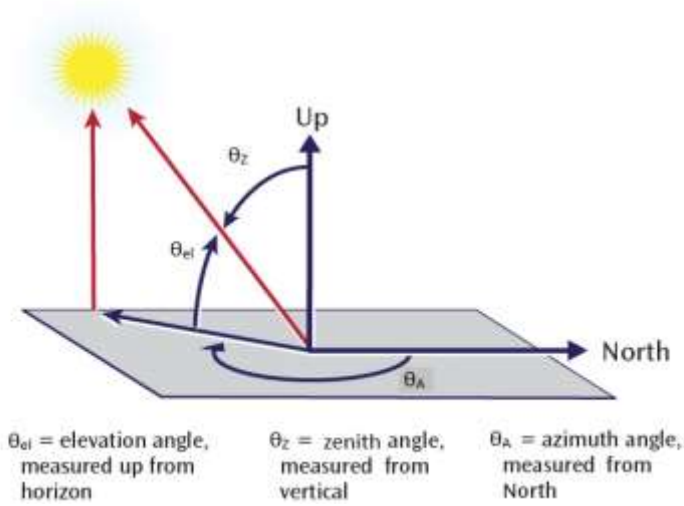
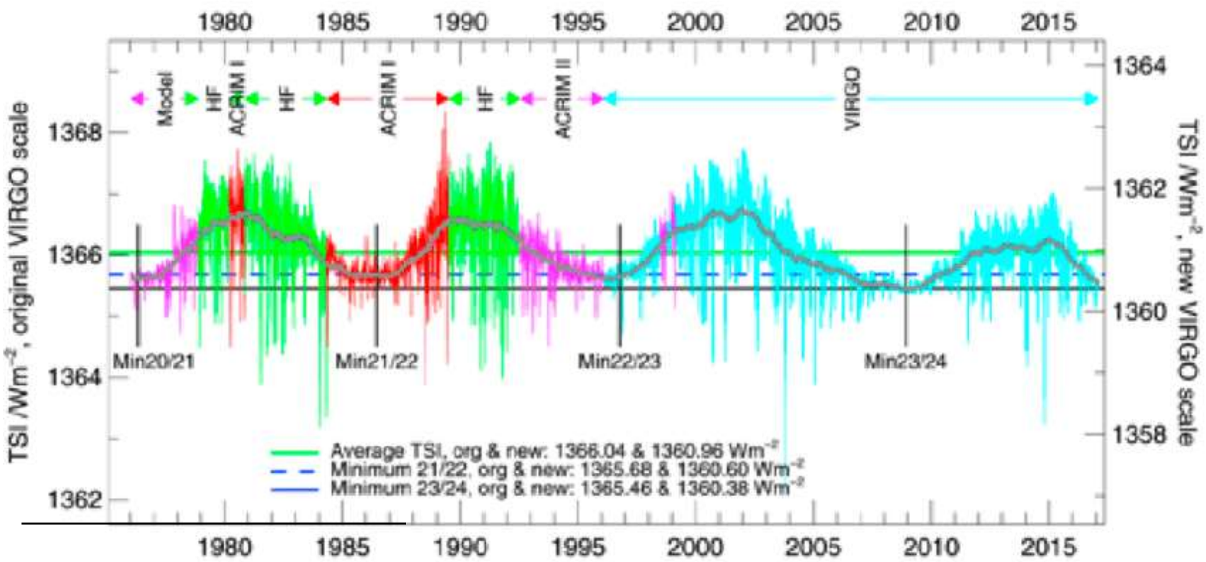


Figure 3 Altitude, zenith and azimuth angles. [4]

Total Solar Irradiance

The total radiant power from the sun is unusually constant. The solar output (radiant emittance) has commonly been called the solar constant, but the currently accepted term is total irradiance (TSI), to account for the actual variability with time. There are cycles in the number of sunspots (cooler, dark areas on the sun) and general solar activity of approximately 11 years.



4. https://pvpmc.sandia.gov/modeling-steps/1-weather-design-inputs/sun-position/

Figure 4 Four solar cycles show the temporal variations of TSI in composite measurements from satellite-based radiometers (colour coded) and model results produced by the World Radiation Center (WRC).

Relative Air Mass

The effective atmospheric depth will be affected by the apparent angle of the sun's rays with the ground (illustrated in Figure 3 above). The actual path length (Figure 4) through the atmosphere is described using the term 'relative air mass', AM. This value will depend on the height of the site above sea level and the solar altitude – at higher values of relative air mass, less solar radiation will reach the earth's surface and the higher frequencies (blue/green light) are increasingly scattered, so leading to light dominated by lower frequency red/orange.

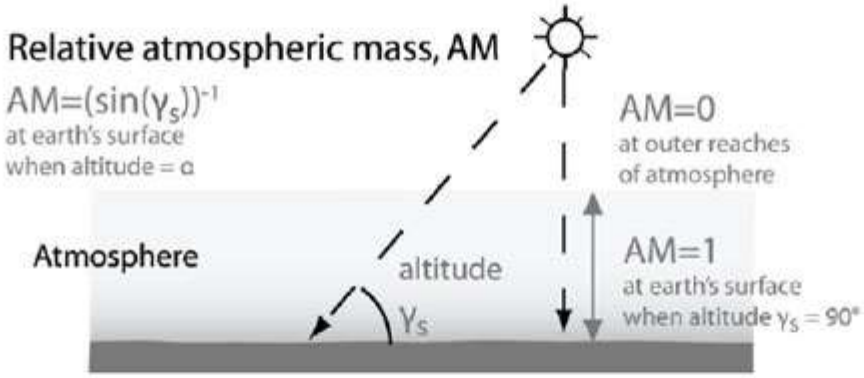


Figure 5. Relative atmospheric mass. [5]

Absorption converts part of the incoming solar radiation to heat and raises the temperature of the absorber. The longer the path length through the atmosphere, the more radiation is absorbed and scattered. Scattering redistributes the radiation in the hemisphere of the sky dome above the observer, including reflecting part of the radiation back into space. The probability of scattering increases as the path (AM) from the top of the atmosphere to the ground increases. To account for the effect of the climate and pollution at a particular location, the 'Linke Turbidity Factor', LTK, represents the multiple of clean dry atmospheres that would produce the equivalent solar attenuation to the actual atmospheric conditions at a particular location. This ranges from a value of 2 for very clean, cold air to 3 for warm air, and above 6 for a location with heavily polluted air.

Direct and diffused beam radiation

When the solar radiation reaches the earth's surface the direct component of the solar energy, known as the 'beam irradiance' (measured perpendicular to the direction of the sun) will be affected by the site elevation. The terrestrial solar radiation is divided into two components. To account for this, an altitude correction factor is applied to the basic beam

[5] Ibid 4

irradiance that will also be dependent on the sky clarity. This correction factor is shown in Figure 6 for a Linke Turbidity Factor of 3.5.

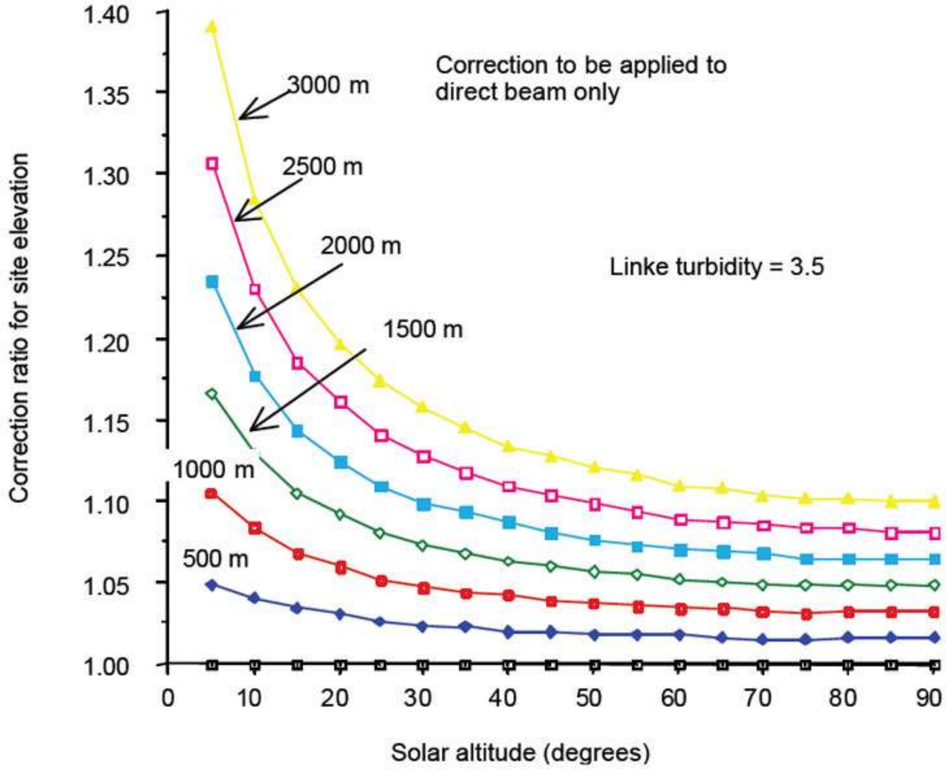


Figure 6 Effect of site elevation in metres on the predicted beam irradiance

After passing through the atmosphere, the normal beam irradiance has a maximum value of approximately 950 $W \cdot m^{-2}$. In addition to the direct irradiance, there is a diffuse component that – as the name suggests – is non-directional and will depend on the atmospheric (notably climatic) conditions, as well as the surrounding surfaces. As the Linke Turbidity Factor increases, the diffuse irradiance at a given solar altitude rises, see in Figure 7, since there is greater scattering of light.

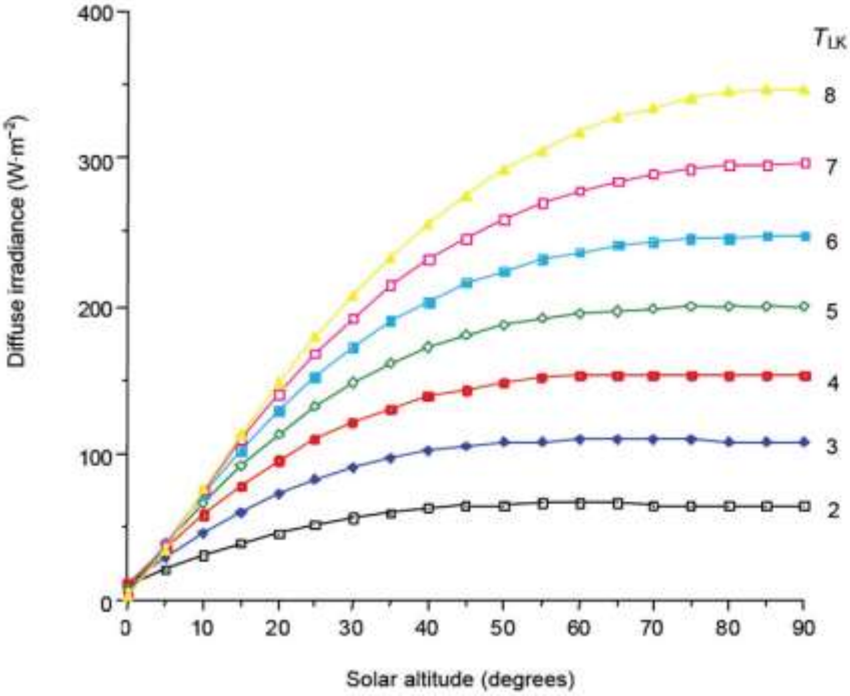


Figure 7.

The ground reflected irradiance is can be found by using the following equation:

$R_{gh} = \rho_g \cdot r_g \cdot G_c$ (W·m^{-2})

Where:

ρ_g - ground albedo

r_g - the ground slope factor

G_c - the clear sky global irradiance on a horizontal surface (W·m^{-2})

ground slope factor - $r_g = (1 – \cos(\beta)) / 2$

$r_g = 0.5$ for vertical surfaces

The figure below illustrates, the value of solar declination, d, is independent of location but related to the time of year (varying from +23.5° around 20 June to 0° at the vernal and spring equinox, and -23.5° around 22 December0. It can be determined by a simple sinusoidal function. Only locations in the 'tropics' (latitudes between 23.5°N and 23.5°S) can have the sun vertically above (at a solar altitude of 90°, zenith of 0°). When considering a particular location, the angular height of the sun above the horizon, the solar altitude, γ_s, and its angular position in the horizontal plane, the solar azimuth, α_s, may be calculated.

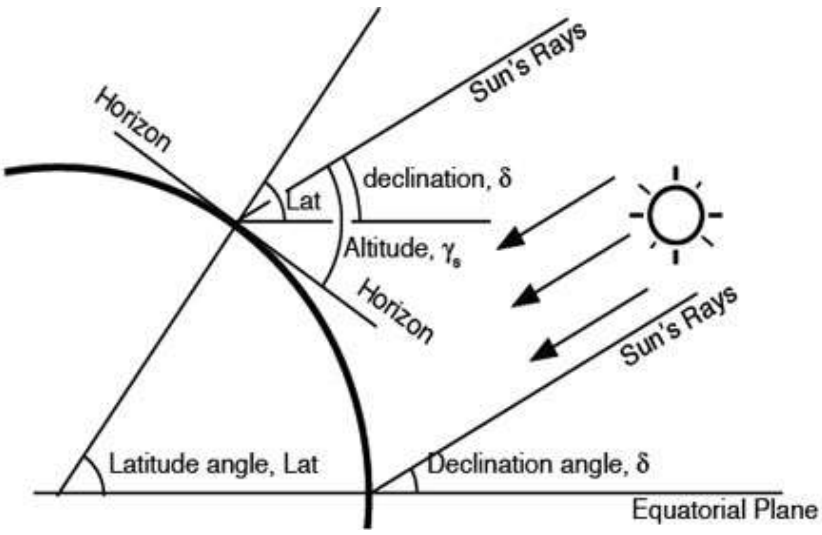


Figure 8 Solar geometry at a point on the earth's surface relative to the tangential visual horizon.[6]

$\sin(\gamma_s) = \sin(\delta)\cdot\sin(\Phi)+\cos(\delta)\cdot\cos(\Phi)\cdot\cos(\omega)$ and,

$\cos(\alpha_s) = (\sin(\gamma_s)\cdot\sin(\Phi) – \sin(\delta)) / (\cos(\Phi)\cdot\cos(\gamma_s))$

[6] https://www.cibsejournal.com/cpd/modules/2013-07/

$\sin(\alpha_s) = \cos(\delta)\cdot\sin(\omega) / \cos(\gamma_s)$

with the $\sin(\alpha_s)$ calculation being required to establish the quadrant where .s resides.

omega; = absolute value of the hour angle (e.g., noon = 0°, 2pm = 30°, 9am = 45°, etc.)

Φ = latitude

If $\sin \alpha_s < 0$, then $\alpha_s = -\cos^{-1}(\cos(\alpha_s))$; if $\sin \alpha_s > 0$, then $\alpha_s = \cos^{-1}(\cos(\alpha_s))$.[7]

Before continuing our discussion of solar radiation, it is important to understand a few basic radiometric terms, summarized in the table below.

Quantity	**Symbol**	**SI Unit**	**Abbreviation**	**Description**
Radiant energy	Q	joule	J	Energy
Radiant flux	Φ	watt	W	Radiant energy per unit of time
Radiant intensity	I	watt per steradian	W/sr	Power per unit of solar angle
Radiant emittance	M	watt per square meter	W/m2	Power emitted from a surface
Radiance	L	watt per steradian per square meter	W/sr/m2	Power per unit solid angle per unit of projected source
Irradiance	E, I	watt per square meter	W/m2	Power incident on a surface
Spectral irradiance	Eλ	watt per square meter per nanometre	W/m2/nm	Power incident on a surface per wavelength

[7] Ibid 6

Solar components[8]

Radiation can be transmitted, absorbed, or scattered by an intervening medium in variable amounts depending on the wavelength. Multifaceted interactions of the Earth's atmosphere with solar radiation result in three fundamental broadband components of interest to solar energy conversion technologies: direct normal irradiance (DNI), diffuse horizontal irradiance (DHI) and global horizontal irradiance (GHI).

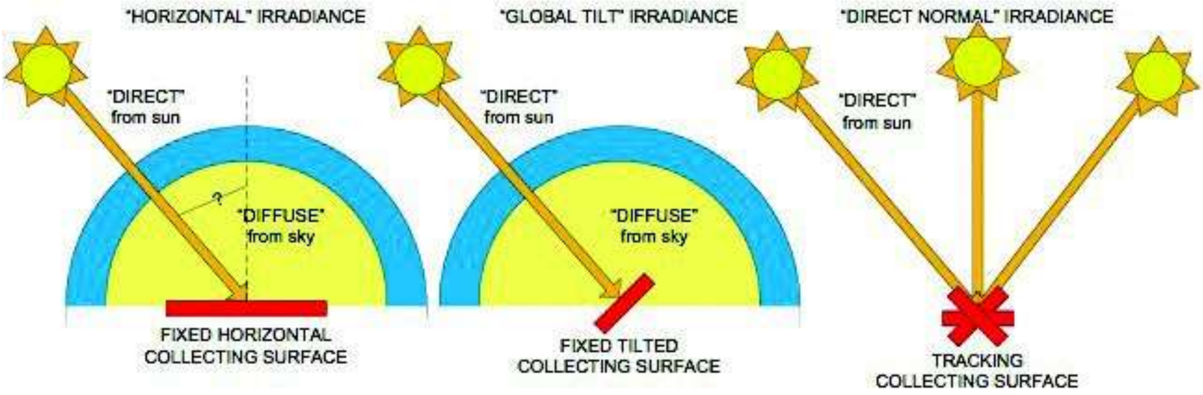


Figure 9 direct normal irradiance (DNI), diffuse horizontal irradiance (DHI) and global horizontal irradiance (GHI).[9]

Direct Normal Irradiance (DNI)

DNI is the amount of solar radiation received per unit area by a surface that is always held perpendicular (or normal) to the rays that come in a straight line from the direction of the sun at its current position in the sky. For solar resource assessment DNI is understood as the "radiation received from a small solid angle centred on the sun's disk". The size of this "small solid angle" for DNI measurements is recommended to be $5 \cdot 10^{-3}$ sr (corresponding to and approximate 2.5-degree half angle). This is because instruments for DNI measurements (pyrheliometers) have to track the sun all the way through its path of motion in the sky, and small tracking errors have to be expected. The large field of view (FOV) of pyrheliometers decreases the influence of such tracking faults.

Diffuse Horizontal Irradiance (DHI)

DHI is the amount of radiation received per unit area by a surface (not subject to any shade or shadow) that does not arrive on a direct path from the sun, but has been scattered by molecules and particles in the atmosphere and comes equally from all directions.

Global Horizontal Irradiance (GHI)

GHI is the total amount of shortwave radiation received from above by a surface horizontal to the ground. This value is of particular interest to photovoltaic installations and includes both DNI and DHI. The total hemispherical solar radiation on a horizontal surface is the sum

[88] Best Practices Handbook for the Collection and Use of Solar Resource Data, NREL,2015.
[9] https://firstgreenconsulting.wordpress.com/2012/04/26/differentiate-between-the-dni-dhi-and-ghi/

of the flux density resulting in the DNI at the given solar zenith angle SZA, and the additional DHI:

GHI = DNI · Cos (SZA) + DHI

This fundamental equation is the foundation of most solar radiation measurement system designs, data quality assessments, and atmospheric radiative transfer models addressing the needs for solar resource data.

Global Titled Irradiance

Solar conversion systems as flat-plate collectors or non-concentrating photovoltaics (PV) are tilted toward the sun. Estimating or modelling the irradiance incident upon these systems is essential to the performance and yield evaluation of these systems. The GTI can be measured directly by pyranometers that are tilted as the collector plane.

Estimating DHI from GHI

During clear and partly cloudy conditions, diffuse irradiance on a horizontal surface, DHI, is often a relatively small part (< 30%) of the GHI. During overcast conditions, the GHI and DHI should be alike. When DHI measurements are not accessible, evaluations of the diffuse may be needed in combination with GHI data to estimate DNI. DHI is also useful for daylighting applications. Generally empirical correlations between the global clearness index, Kt, and either the diffuse fraction, K (= DHI/GHI), or the diffuse clearness index, are used.

- Kt (Clearness index or global horizontal transmittance of the atmosphere) $= GHI/[TSI \cdot (r_0/r)^2 \cdot Cos(SZA)]$
- Kd (Diffuse transmittance of the atmosphere) $= DHI/[TSI \cdot (r_0/r)^2 \cdot Cos(SZA)]$

Estimating DNI from GHI

DNI can be assessed indirectly from the models of the previous section, once the global and diffuse components are known, or directly through other separation models that are not based on the diffuse fraction approach.

- Kt (Clearness index or global horizontal transmittance of the atmosphere) $= GHI/TSI \cdot (r_0/r)^2 \cdot Cos\ (SZA)$ *indirectly*
- Kn (Direct normal transmittance of the atmosphere) $= DNI/TSI \cdot (r_0/r)^2$

Where:

- TSI = Total solar irradiance (mean TSI, ~1366.7 Wm-2 ± 7 Wm-2)
- r_0 = mean Earth-sun distance (149,598 km)
- r = Earth-sun distance at the time of interest
- SZA = Solar zenith angle at the time of interest.

Spatial and temporal variability of solar resources

Spatial and temporal variability of solar resources entails the effects of the atmosphere, weather, climate, and geography on the variation of solar resources at the Earth's surface. Disparities in solar radiation from month to month, especially in the latitudes outside the tropics, follow an annual pattern, generally during the summer, with lower values during the winter. Inter-annual variability - the year-to-year variation in these patterns. The coefficient of variation (COV) is the ratio of the standard deviation to the mean of a set of given averages) can be used to quantify this variability.

Variations in weather and natural events such as forest fires, volcanic eruptions, dust clouds from drought regions, and agricultural activity all can contribute to inter-annual variations. Spatial variations in solar resources often come into question, especially if nearby or neighbouring measured data are obtainable for a site without measured data. Mountainous terrain or highly variable urban, agricultural, or other microclimate influences may contribute to high spatial variability of the solar resource. Prevailing winds and cloud motion patterns can also affect both spatial and temporal variability throughout distances from a few to hundreds of kilometres.

Measuring solar radiation

Precise quantities of the arriving irradiance are vital to solar power plant project design and implementation. Since irradiance data are comparatively multifarious, and hence costly compared to other meteorological measurements, they are obtainable for only a limited number of locations. Irradiance measurements are also used to develop and trial models for appraising irradiance and other solar irradiance components based on available surface meteorological observations or satellite remote sensing techniques. Irradiance measurements will also play a significant role in developing solar resource forecasting techniques. This section focuses on the instrument choice, installation, design, and O&M.

Instrumentation choice

Ahead of choosing instrumentation and committing to the associated costs, the developer has to assess the data accuracy or uncertainty levels that will fulfil the ultimate analyses based on the radiometric measurements. This will guarantee that the best value is attained after the accessible numerous measurement and instrumentation choices are considered.

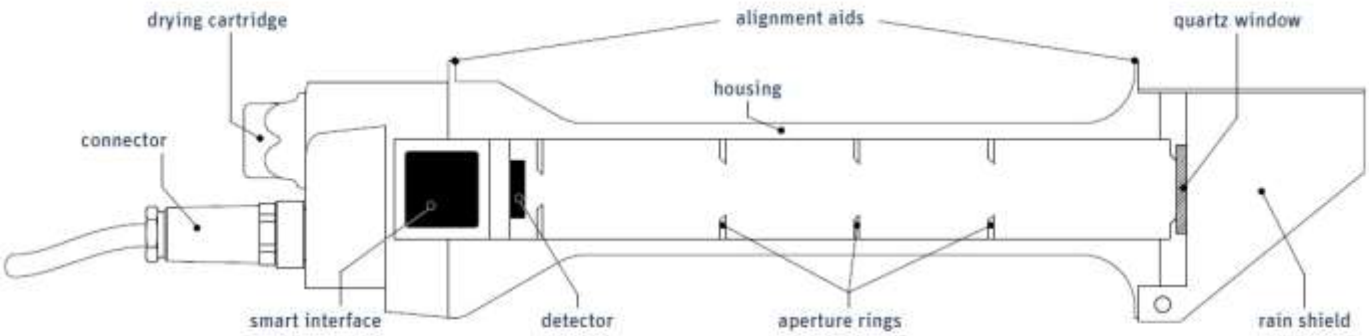
By instituting the project requirements for radiometric data accuracy first, the developer can consider instrument choice and the levels of effort necessary to operate and maintain the measurement system on an overall cost-performance determination. Redundant instrumentation is an additional key consideration to guarantee buoyancy in data quality. Multiple radiometers within the project location and/or providing for the measurement of all three solar irradiance components (GHI, DHI, and DNI) are recommended.

Instrument types

Instruments intended to measure any form of radiation are called radiometers. Here is a description of the types of radiometers most frequently used to measure solar radiation resources.

Pyrheliometer is used to measure direct beam radiation at normal incidence. Sunlight enters the instrument through a window and is directed onto a thermopile which converts heat to an electrical signal that can be recorded. Pyrheliometers are used to measure DNI. There are two types of Pyrheliometers:

- **SHP1:** it is a pyrheliometer device well equipped with an interface having both digitized RS 485 Modbus and an intensified analogue output. This pyrheliometer



offers a smart interface and is an advancement of the CPH 1 version. Moreover, the SHP1 also has a response period below 2 seconds. They individually measure temperature correction varies from negative 40°C to positive 70°C.

Figure 10 SHP1 Smart Pyrheliometer.[10]

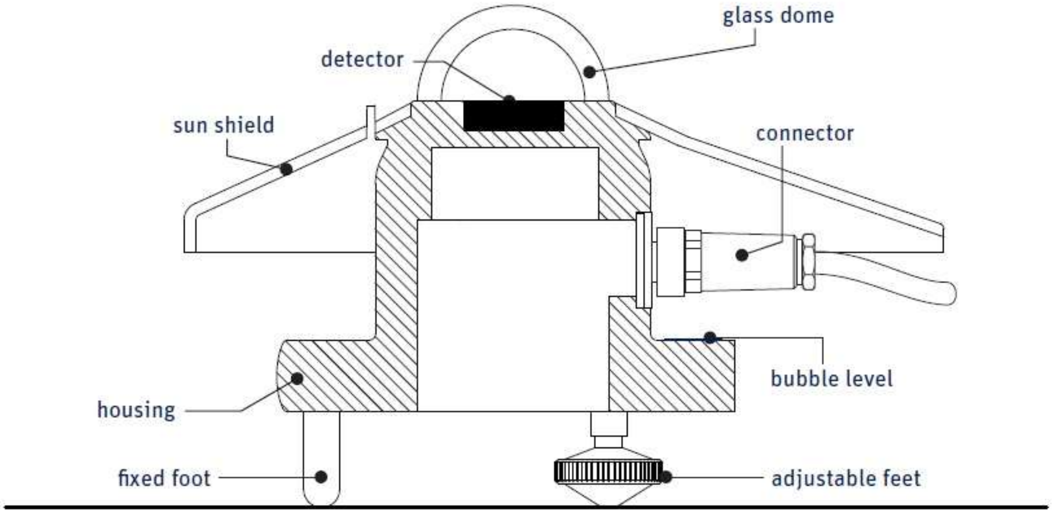
- **CHP 1:** This type of pyrheilometer completely complies with the latest standards set by International Standardization Organization (ISO) and World Meteorological Organization (WMO) regarding the criteria for First Class Normal Incidence Pyrheliometer. Each pyrheliometer is checked for manufacturing and supply standards with a traceable checking certificate issued by the World Radiometric Reference (WRD).

Pyrheliometers are mounted in automatic solar trackers to maintain the instrument's alignment with the solar disk and fully illuminate the detector from sunrise to sunset. Configuration of the pyrheliometer with the solar disk is governed by a simple dioptre, or a sighting device in which a small spot of light (the solar image) falls on a mark in the centre of a target located near the rear of the instrument. View-limiting apertures inside a pyrheliometer allow for the detection of radiation in a narrow annulus of sky around the sun to allow for small variations in tracker alignment.

Pyranometer is a type of actinometer used for calculating solar irradiance on a planar surface and it is intended to measure the solar radiation flux density (W/m^2) from the hemisphere above within a wavelength range 0.3 µm to 3 µm. This type of radiometer can be fixed on a horizontal platform to measure GHI. In this orientation, the pyranometer has a thorough view of the sky dome. Preferably, the mounting location for this instrument is free of natural or artificial obstructions on the horizon. Alternatively, the pyranometer can be mounted tilted to measure tilted irradiance,

[10] http://www.omniinstruments.co.uk/shp1-smart-pyrheliometer.html

vertical irradiance, or reflected irradiance. Pyranometer measures the solar energy that is coming into the system while power meter measures what electrical power it produces. Knowing these two values at all moments allows calculating the



performance ratio of a solar plant. PR is an important parameter that can indicate if the solar plant is operating well or if there are issues such as soiling, shading, short-circuits or module degradation. There are two types of pyranometers: thermopile pyranometers and semiconductor pyranometers.

Figure 11 CHP Pyrheliometer.[11]

- **Thermopile pyranometer** - measures the total amount of radiation on a surface. It has a thermopile detector (a device that converts thermal energy into electrical energy) with strong light-absorbing black paint that ingests all radiation from the sun equally. The thermopile pyranometer's black surface uniformly absorbs solar radiation across the solar spectrum. The solar spectrum is the range of wavelengths of light given off by the sun. Blue, white, yellow, and red stars each have different temperatures and therefore different solar spectrums. This produces a temperature variance between the black surface of the sensors and the body of the instrument and results in a small voltage at the sensor that can be measured and translated into W/m^2.

  The advantages of thermopile pyranometers relate to their extensive usage and accuracy. A thermopile pyranometer's black surface uniformly absorbs solar radiation across the short-wave solar spectrum from 0.285 to 2.800 µm. The uniform spectral response allows thermopile pyranometers to measure the following:

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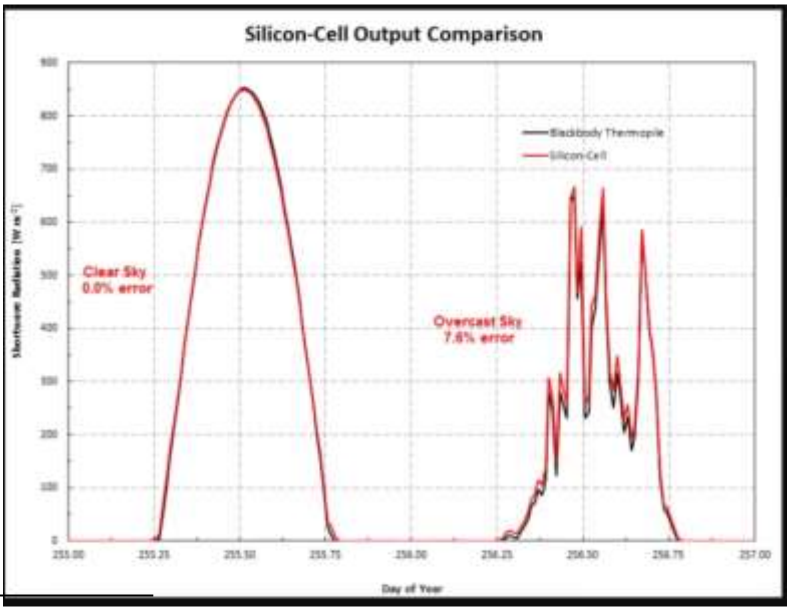
[11] http://www.omniinstruments.co.uk/cmp3-pyranometer.html

reflected solar radiation, radiation within canopies or greenhouses, and albedo (reflected: incident) when two are deployed as an up-facing/down-facing pair.[12]

- **Silicon photocell pyranometer** - produces a μA output current similar to how a solar panel converts the sun's energy into electricity. When the current passes through a shunt resistor, it is transformed to a voltage signal with a sensitivity of several μV/W/m^2. A plastic diffuser is used to provide a uniform cosine response at varying sun angles. The spectral response of silicon photocell pyranometers is restricted to just a portion of the solar spectrum from 0.4 to 1.1 μm. Although these pyranometers only sample a portion of the short-wave radiation, they are attuned to deliver an output similar to thermopile sensors under clear, sunny skies. Silicon photocell pyranometers are often used in all sky conditions, but measurement errors are higher when clouds are present. Silicon photocell pyranometers are typically several times less expensive than thermopile pyranometers. The disadvantage of the silicon pyranometer is that its spectral sensitivity is limited. These pyranometers perform best when they are used to measure global solar radiation under the same clear sky conditions used to calibrate them. They should not be used within vegetation canopies or greenhouses, or to measure reflected radiation.[13]

Figure 12 Comparison between the measured output of a silicon-cell pyranometer and a secondary-standard blackbody thermopile reference sensor on both sunny and overcast days.

The silicon-cell sensor is calibrated under sunny, clear-sky conditions; it closely equals the higher-end sensor in those environments, graph on the left. Conversely, because the silicon-cell sensor only subsamples solar short-wave radiation (0.4 to 1.1 μm), errors are introduced when the sky conditions change, the graph on the right. This specific sensor reported a positive 8% difference from the reference on an overcast day.



[12] https://www.solarpowerworldonline.com/2015/03/what-is-a-solar-pyranometer/
[13] https://www.campbellsci.eu/blog/pyranometers-need-to-know

The **ISO** and the **WMO** have established classifications and specifications for the measurement of solar irradiance (ISO 1990, WMO 2008). The table below demonstrates the WMO **pyrheliometer** categories.

WMO Characteristics of Operational Pyrheliometers for Measuring DNI[a]

Characteristic		High Quality[a]	Good Quality[a]
Response time (95% response)		< 15 s	< 30 s
Zero offset—response to 5-K/h change in ambient temperature		2 W/m^2	4 W/m^2
Resolution—smallest detectable change in W/m^2		0.51	1
Stability—change per year, percentage of full scale		0.1	0.5
Temperature response—percentage maximum error caused by any change of ambient temperature within an interval of 50 K		1	2
Nonlinearity—percentage deviation from the responsivity at 500 W/m^2 caused by any change of irradiance within the range from 100 W/m^2 to 1,100 W/m^2		0.2	0.5
Spectral sensitivity—percentage deviation of the product of spectral absorptance and spectral transmittance from the corresponding mean within the range from 300 nm to 3,000 nm		0.5	1.0
Tilt response—percentage deviation from the respon-sivity at 0 degrees tilt (horizontal) caused by a change in tilt from 0 degrees to 90 degrees at 1,000 W/m^2		0.2	0.5
Achievable uncertainty (95% confidence level):			
1-min totals	Percent	0.9	1.8
	kJ/m^2	0.56	1
	Wh/m^2	0.16	0.28
1-h totals	Percent	0.7	1.5
	kJ/m^2	21	54
	Wh/m^2	5.83	15.0
Daily totals	Percent	0.5	1
	kJ/m^2	200	400
	Wh/m^2		

[a] *High quality* means "near state of the art"; *good quality* refers to instruments for network operation.

Figure 13 WMO characteristic of operational pyrheliometers for measuring DNI.[14]

[14] Best Practices Handbook for the Collection and Use of Solar Resource Data, NREL,2015.

The table below demonstrates the ISO 960 specifications

ISO 9060 Specifications Summary for Pyrheliometers Used To Measure DNI

Pyrheliometer Specification List			
Specification	Class of Pyrheliometer		
	Secondary Standard Class	First Class	Second
Response time—95% response	< 15 s	< 20 s	< 30 s
Zero offset Response to 5-K h-1 change in ambient temperature	± 1 Wm^{-2}	± 3 Wm^{-2}	± 6 Wm^{-2}
Resolution—smallest detectable change in Wm^{-2}	± 0.5 Wm^{-2}	± 1 Wm^{-2}	± 5 Wm^{-2}
Stability—percentage of full scale, change/year	± 0.5%	± 1%	± 2%
Nonlinearity—percentage deviation from the responsivity at 500 W/m^2 because of change in irradiance between 100 Wm-2 and 1,000 Wm^{-2}	± 0.2%	± 0.5%	± 2%
Spectral selectivity—percentage deviation of the product of the spectral absorptance and the spectral transmittance from the corresponding mean between 0.35 µm and 1.5 µm	± 0.5%	± 1%	± 5%
Temperature response—total percentage deviation because of change in ambient temperature within an interval of 50 K	± 1%	± 2%	± 10%
Tilt response—percentage deviation from the responsitivity at 0 degrees tilt (horizontal) because of change in tilt from 0 degrees to 90 degrees at 1,000 W/m^{-2} irradiance	± 2%	± 0.5%	± 2%
Traceability—maintained by periodic comparison	With a primary standard pyrheliometer	With a secondary standard pyrheliometer	With a first-class pyrheliometer or better

Figure 14 ISO characteristic of operational pyrheliometers for measuring DNI.[15]

[15] Best Practices Handbook for the Collection and Use of Solar Resource Data, NREL,2015.

The table below demonstrates the WMO **pyranometers** categories.

WMO Characteristics of Operational Pyranometers for Measuring GHI or DHI

Characteristic	High Quality	Good Quality	Moderate Quality
Response time—95% response	< 15 s	< 30 s	< 60 s
Zero offset—Response to 200 W/m2 net thermal radiation (ventilated) Response to 5-K/h change in ambient temperature	7 W/m² 2 W/m²	7 W/m² 2 W/m²	7 W/m² 2 W/m²
Resolution—smallest detectable change	1 W/m²	5 W/m²	10 W/m²
Stability—change per year, percentage of full scale	0.8	1.5	3.0
Directional response for beam radiation—the range of errors caused by assuming that the normal incidence Rs is valid for all directions when measuring, from any direction, a beam radiation that has a normal incidence irradiance of 1,000 W/m²	10 W/m²	20 W/m²	30 W/m²
Temperature response—percentage maximum error caused by any change of ambient temperature within an interval of 50 K	2	4	8
Nonlinearity—percentage deviation from the Rs at 500 W/m² caused by any change of irradiance within the range from 100 W/m² to 1,000 W/m²	0.5	1	3
Spectral sensitivity—percentage deviation of the product of spectral absorptance and spectral transmittance from the corresponding mean within the range from 300 nm to 3,000 nm	2	5	10
Tilt response—percentage deviation from the Rs at 0 degree tilt (horizontal) caused by a change in tilt from 0 degree to 90 degrees at 1,000 W/m2	0.5	2	5
Achievable uncertainty—95% confidence level **Hourly totals** **Daily totals**	 **3%** **2%**	 **8%** **5%**	 **20%** **10%**

Figure 15 WMO characteristic of operational pyranometers for measuring GHI and DHI.[16]

[16] Best Practices Handbook for the Collection and Use of Solar Resource Data, NREL,2015.

The table below demonstrates the WMO **pyranometers** categories

ISO 9060 Specifications Summary for Pyranometers Used To Measure GHI and DHI

Pyrheliometer Specification List			
Specification	Class of Pyrheliometer[a]		
	Secondary Standard Class	First Class	Second
Response time—95% response	< 15 s	< 30 s	< 60 s
Zero offset Response to 200 Wm^{-2} net thermal radiation (ventilated) Response to 5-Kh^{-1} change in ambient temperature	± 7 Wm^{-2} ± 2 Wm^{-2}	± 15 Wm^{-2} ± 4 Wm^{-2}	± 30 Wm^{-2} ± 8 Wm^{-2}
Resolution—smallest detectable change	± 0.5%	± 1%	± 3%
Stability—percentage change in responsivity per year			
Nonlinearity—percentage deviation from the responsivity at 500 W/m^2 because of change in irradiance between 100 Wm-2 and 1,000 Wm^{-2}	± 10 Wm^{-2}	± 20 Wm^{-2}	± 30 Wm^{-2}
Directional response for beam radiation (the range of errors caused by assuming that the normal incidence responsivity is valid for all directions when measuring, from any direction, a beam radiation that has a normal incidence irradiance of 1,000 Wm^{-2}	± 3%	± 5%	± 10%
Spectral selectivity—percentage deviation of the product of the spectral absorptance and the spectral transmittance from the corresponding mean between 0.35 μm and 1.5 μm	2%	4%	8%
Temperature response—total percentage deviation because of change in ambient temperature within an interval of 50 K	± 0.5%	± 2%	± 5%
Tilt response—percentage deviation from the responsivity at 0 degrees tilt (horizontal) because of change in tilt from 0 degrees to 90 degrees at 1,000 W/m^{-2} irradiance			

[a] The highest category for pyranometers is the secondary standard, because the most accurate determination of GHI has been suggested to be the sum of the DNI as measured by an absolute cavity radiometer and the DHI as measured by a secondary standard pyranometer shaded from the DNI by a disk.

Figure 16 ISO characteristic of operational pyranometers for measuring GHI and DHI.[17]

[17] Best Practices Handbook for the Collection and Use of Solar Resource Data, NREL, 2015.

Solar radiation data delivered via pyrheliometric and pyranometric measurements may characterize time resolved information: e.g. irradiance (instantaneous measurements of solar energy flux), irradiation (integrated energy flux over time), or averaged irradiation. Depending on measurement setup, the data can be for horizontal or inclined surface. The data can characterize different types of radiation: beam, diffuse, or total. This is exemplified in the flow chart below.

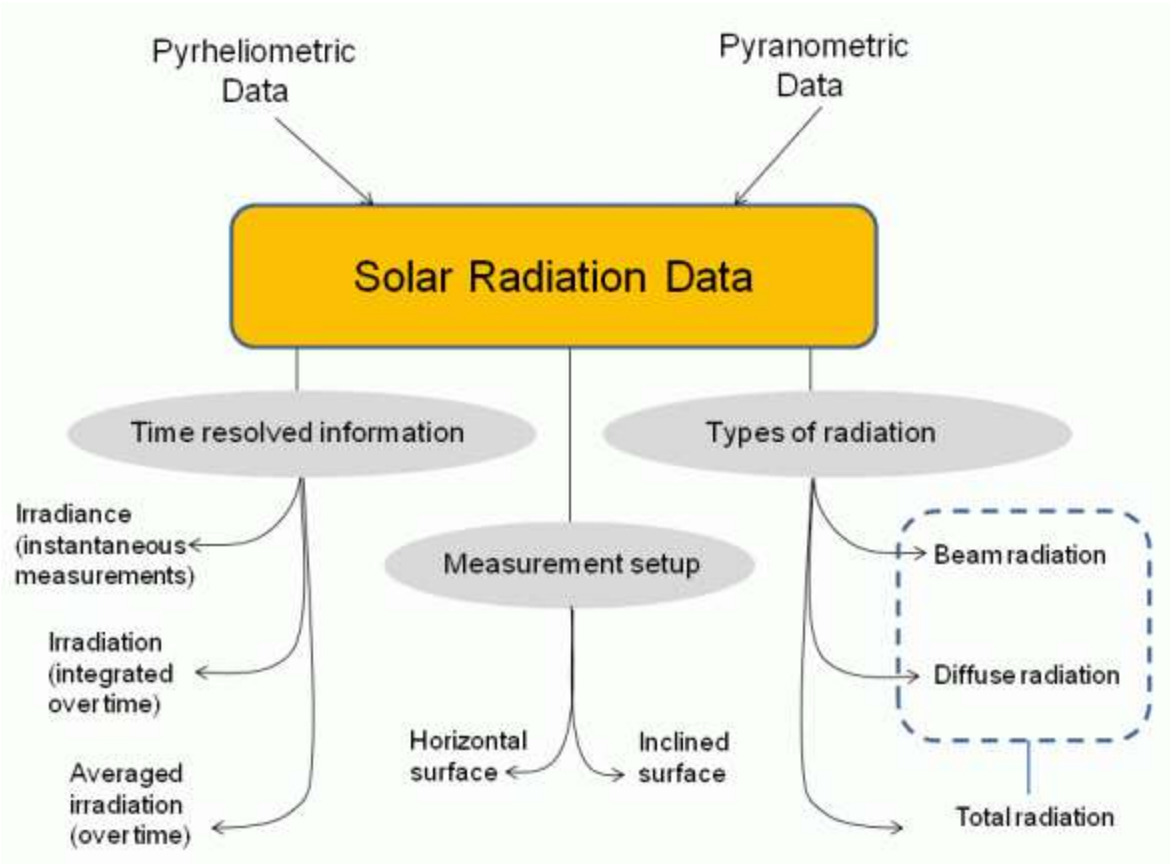


Figure 17. [18]

Other measurement tools

Some of the errors of pyrheliometers and pyranometers pointed out above can be reduced by correction of the solar zenith/cosine response. Similarly, particularly if the sensor temperature of pyranometers and pyrheliometers is measured using a temperature-dependent resistor near to the thermopile, a temperature correction can be applied too. Correction coefficients are supplied by the manufacturer. Measurements from only black pyranometers can be corrected for the thermal offset using additional measurements from pyrgeometers. A pyrgeometer is a device that measures near-surface infra-red radiation spectrum in the wavelength spectrum approximately from 4.5 µm to 100 µm.

It measures the resistance/voltage variations in a material that is sensitive to the net energy transfer by radiation that occurs between itself and its surroundings, by also measuring its

[18] https://www.e-education.psu.edu/eme812/node/644

own temperature and making some assumptions about the nature of its surroundings it can infer a temperature of the local atmosphere with which it is exchanging radiation. Alternatively, a less accurate correction can be made based on estimations of the thermal offset from the often negative measurements collected during the night.

Rotating Shadowband Irradiometer (RSI)

RSI sensors provide highquality solar irradiance measurements with a single device at lower cost. The RSI sensor comprises of two redundant horizontally leveled silicon photodiode radiation detectors, positioned in the center of a spherically curved shadowband (Fig. 1). While the shadowband is in its rest position below the sensor (Fig. 2), the photodiodes measure Global Horizontal Irradiance (GHI). In fixed intervals, the shadowband rotates around the radiation sensors (Fig. 3). During the rotation, the shadowband blocks the direct beam irradiation from the sun for a brief moment.

This causes a momentary drop of the photodiode signals (Fig. 4) and thus allows the determination of the Diffuse Horizontal Irradiance (DHI) and the subsequent calculation of the Direct Normal Irradiance (DNI) from GHI, DHI and the known solar incidence angle. The initially lower accuracy of RSIs compared to ISO 9060 first class pyrheliometers and secondary standard pyranometers are often compensated by some advantages as : low soiling susceptibility , low power demand, and comparatively lower cost (instrumentation and O&M). RSIs show significant advantages compared to thermal sensors when operated under the measurement conditions of remote weather stations.

Figure 18 Components of RSI. [19]

Then DNI is calculated using the following equation relating GHI, DHI, and DNI:

DNI = (GHI – DHI) Cos (SZA)

- **RSIs with continuous rotation** - rotation is performed with constant angular velocity and takes approximately 1 second, and the irradiance is measured with a high and constant sampling rate. This measurement is called burst or sweep. At the start of the rotation, the pyranometer measures GHI. In the moment when the center of the

[19]https://www.unioldenburg.de/fileadmin/user_upload/physik/ag/ehf/enmet/download/fachtagung_2016/poster/Poster_CSPS_Enmet_2016_Bremerhaven.pdf

shadow falls on the center of the sensor, it approximately detects DHI; however, the shadowband covers some portion of the sky so that the minimum of the burst is less than the DHI. An RSI with continuous rotation of the shadowband necessities a pyranometer with a fast response time (< 1 second, e.g., approximately 10 µs); therefore, thermal sensors as described in ISO 9060 cannot be used. Instead, semiconductor sensors are used. [20]

- **RSIs with discontinuous rotation** - do not measure the complete burst, but only four points of it. First, the GHI is measured while the shadowband is in the rest position. Then the shadowband rotates from the rest position toward the position at which it nearly shades the pyranometer, stops, and a measurement is taken. Then it continues the rotation toward the position at which the shadow lies centered on the pyranometer, and another measurement is taken. The last point is measured in a position at which the shadow just passed the pyranometer.
  RSIs with discontinuous rotation can use sufficiently long measurement times for each of the four points to allow the application of thermal pyranometers. The azimuth alignment of RSIs with discontinuous rotation is crucial for their accuracy. Also, the accuracy of the sensor's coordinates and the time is more important for the discontinuous rotation. The duration of the measurement with a discontinuous rotation increases the measurement uncertainty.[21]

Sunshine Recorders

The traditional standard instrument used to measure the "duration of sunshine" is the Campbell-Stokes sunshine recorder. This instrument consists of a glass sphere that focuses the direct solar radiation and burns a trace on a special pasteboard card. These recorders have been replaced in most installations by photo detector activated 'sunshine switches.' The major advantage of this type of recorder is its simplicity and ease of use. There are no moving parts and it thus requires very little maintenance. The unit can be used anywhere in the world with little or no modification to the design. The glass sphere – typically 10 cm (4 inches) in diameter – is designed to focus the rays from the sun onto a card mounted at the back and is set on a stand.

The card is held in place by grooves of which there are three overlapping sets, to allow for the altitude of the sun during different seasons of the year. The recording of each day goes onto one card. Each card is marked as to the hour, with local noon being in the centre, and is read in tenths. The single biggest problem is in the reading of the cards. On days when the sun is alternately covered and exposed by clouds, the amount of burn on the card may be the same for 30 seconds as for 5 minutes. Thus, the reading of the card may differ from one observer to another.

[20] Best Practices Handbook for the Collection and Use of Solar Resource Data, NREL, 2015.
[21] Ibid 20

Long-term data and typical metorological year (TMY) data

Understanding the long-term spatial and temporal variability of available solar resources is central to any assessment of solar energy potential. Information resultant from historical solar resource data can be used to choose optimum energy conversion technologies, design systems for specific locations, and operate and maintain installed solar energy conversion systems.

Long-term data can be representative of the climate if the period of record is at least 30 years. Climate “normals” are recomputed each decade to address temperature, pressure, precipitation, and other surface meteorological variables. Normal refers to the 30-year average of an observed parameter that is updated every 10 years . Thus, the averaging period shifts every 10 years.

TMY data is determined with various meteorological measurements made at hourly intervals over a number of years to build up a picture of the local climate. A simple average of the yearly data underestimates the amount of variability, so the month that is most representative of the location is selected. For each month, the average radiation over the whole measurement period is determined, together with the average radiation in each month during the measurement period. The data for the month that has the average radiation most closely equal to the monthly average over the whole measurement period is then chosen as the TMY data for that month. This process is then repeated for each month in the year. The months are added together to give a full year of hourly samples.[22]

A TMY data set provides designers and other users with a small sized annual data set that holds 8,760 hourly meteorological values that typify conditions at a specific location throughout a longer period, such as the 30-year climatic normal. Different types of TMYs exist. Twelve TMMs (typical meteorological months) selected on the basis of their similarity of individual cumulative frequency distributions for selected data elements comprise the TMY data set. The longer-term distributions are determined for that month using data from the full period of record. The TMM’s are then concatenated, essentially without modification, to form a single year with a serially complete data record.

The resulting TMY data set contains measured and modeled time-series solar radiation and surface meteorological data, although some hourly records may contain filled or interpolated data for periods when original observations are missing from the data archive.. A TMY data set should not be used to predict solar resources for a particular period of time, nor to evaluate real-time energy production or the detailed power plant design. Rather, a TMY data set represents conditions judged to be typical throughout a long period, such as 30 years. Because it represents typical rather than extreme conditions, it is not suited for

[22] https://www.pveducation.org/pvcdrom/typical-meteorological-year-data-tmy

designing systems and their components to meet the worst-case weather conditions that could occur at a location.

Parameters for choice of optimal measurement station

To gather useful DNI resource data, the effective design and implementation of a solar resource measurement station necessitates careful consideration of few physical parameters.

Location - Availability of Land and Foundation needs

The principal determination of setting up a solar resource measurement station is to gather data that allows to precisely depict the solar irradiance and applicable meteorological parameters at a specific location. Preferably, the instruments would be allocated within the chosen analysis area, but in some cases separation distances may be accepted contingent on the complexities of local climate and terrain discrepancies. Lower variability in terrain and climate usually renders lower variability in the solar resource over larger spatial scales. These effects should be well understood before deciding the final location of a measurement station. Attentions should also be given to the possible influences of local sources of pollution or dust that could vitiate the measurements. The land must be plain and continuous. Non fertile, barren land should only be considered. Rocky terrain shall be preferred so that the cost of foundation will be cheaper.

Instrument choice is an essential factor, because measurements with greater precision will better reflect the actual resource. Instrument placement is also a significant matter. If nearby objects (trees or buildings) shade the instruments for some period of time during the day, the subsequent measurement will not accurately characterize the available solar resource. Distant objects, particularly mountains, may be real impediments, as the shadows they cast are likely to produce an effect beyond the area local to the instruments. Conversely, nearby objects can potentially reflect solar radiation onto the instruments, likewise resulting in measurements that do not represent the local natural environment. Such cases could include a nearby wall, window, or other highly reflective object. The best practice is to locate instruments away from any objects that are in view of the instrument detector.

The simplest way to define the quality of solar access is to scan the horizon for a full 360 degrees of azimuth and note the elevation of any objects protruding into the sky above the local horizon (buildings, trees, antennae, power poles, and power lines). Most locations will have some obstructions, but whether they will be substantial in the context of the necessary measurements must be determined. Generally, **pyranometers** are very insensitive to sky blockage within approximately 5 degrees elevation above the horizon. **Pyrheliometers**, however, are more sensitive, because objects can entirely block the DNI, contingent on the daily path of the sun through the year. To be a concern, the object must be in the area of the sun near sunrise or sunset, the time and azimuth of which vary throughout the year.

For most of the horizon, objects blocking the sky will not be a factor, because the sun rises in a limited range in the east and sets likewise in the west during sunset. However, the farther north in latitude the site is located, the greater the range of these sunrise and sunset areas of interest. A solar horizon map, or even a sketch of obstructions by elevation and azimuth, will help determine the areas where horizon objects will affect the measurement.

Considerations for locating a station should also include environmental concerns, such as wildlife habitat, migratory paths, drainage, and antiquities or archeological areas.[23]

Station security and acccessibility

The less visible and accessible the station is to the public, the less likely it will be the target of theft or vandalism. Security fences should be used if people or animals are likely to intrude. Fencing should be at least 6ft tall, and tailored with locking gates in high-profile areas, while less elaborate fencing may serve in areas that are largely secure and where only curiosity has to be discouraged. In remote venues with few human hazards, cattle fence paneling around 4ft high are sensible if large animals wander in the area. It may not be possible to keep smaller animals out of the station compound, and safeguards should be taken to guarantee that the equipment, cabling, supports, etc., can endure encounters with these animals.

Access to the equipment must also be part of a station construction plan. Since routine maintenance is a main aspect influencing data quality, provisions must be made for reasonable and easy access to the instruments. Factors here could include ease of access to cross-locked property, well-maintained all-weather roads, and roof access that might be controlled by other departments. Safety must also be a consideration. Locations that present hazardous conditions must be avoided.[24]

Power requirements

Constant measurements necessitate a dependable source of electrical power to reduce system stoppage from power outages. In some areas, power from the utility grid is dependable, and downtime is measured in minutes per year. In other areas, multiple daily

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[23] Best Practices Handbook for the Collection and Use of Solar Resource Data, NREL, 2015.
[24] Ibid 22

power interruptions are routine. Contingent on the tolerance to missing data of the required analysis, safety measures should be taken to guarantee that gaps in the data stream from power outages do not seriously affecting the results.

The most standard and economical measure for power outages is an uninterruptible power supply, which has internal storage batteries that are used as a source of power in the event of an alternating current (AC) power interruption. When the AC power is interrupted, internal circuitry makes an almost seamless switch from grid-connected AC power to AC provided through an inverter connected to the battery bank. When power is reinstated, the uninterruptible power supply recharges the internal battery from the AC line power. Power loss is identified rapidly, as is switching to battery, and it is measured in milliseconds or partial line cycles. Some equipment may be particularly susceptible to even millisecond power interruptions during switching and should be identified through trial and error to avert unexpected downtime despite use of the uninterruptible power supply.

The uninterruptible power supply is sized according to the operating capacity (amount of power in watts; it can continuously supply either on or off grid-connected AC power) and longevity of battery power (how long the battery can last under anticipated maximum load). Developers should evaluate the lengthiest conceivable power outage and size the uninterruptible power supply for the maximum load of attached devices and the maximum period of battery capacity. Batteries should be tested frequently to guarantee that the device can still function per design specifications. Internal battery test functions sometimes report errors only when batteries are close to complete failure and not when performance has degraded. A timed full-power-off test should be directed occasionally to certify that the uninterruptible power supply will deliver backup power for the time needed to avert measurement system failure.

In remote, peripheral locations where utility power is not accessible, local power generation should be created. Options for on-site electrical power generation include PV or small wind turbine systems (or both) and gasoline or diesel-fueled generators with battery storage. The renewable energy systems should be sized to deliver enough energy for the maximum continuous load and power through several days of cloudy weather when solar generation would be minimal. Some oversizing is required to accommodate degradation of PV panels and battery storage, and consideration should be given to ambient temperature, which affects the ability of a battery to deliver energy.

Equipment should be specified and tested for self-power-on ability in the event of a power outage. This ensures that when power is reestablished, the equipment will automatically resume measurements and logging without operator intervention. This is an important consideration for remote locations where considerable downtime might occur before personnel could be dispatched to restart a system.

Grounding and shielding

Station equipment should be secured against lightning strikes and safeguarded from radio frequency interference that could impair equipment or decrease the validity of the measurements. The following guidlines should be taken when designing and constructing a measurement station: [25]

- Use a single-point ground (e.g., a copper rod driven several feet into the ground) for all signal ground connections to avert ground loops that can introduce noise or biases in the measurements.
- Use twisted pair, shielded cables for low-voltage measurements connected as double- ended measurements at the data logger. Double-ended measurements require separate logger channels for + and – signal input conductors. These inputs do not share a mutual signal ground and hence considerably decrease the potentials for electrical noise introduced in the signal cable.
- Physically isolate low-voltage sensor cables from nearby sources of electrical noise, such as power cables. If a power cable must be near a signal cable, always position the two at right angles to each other. This limited contact will reduce the likelihood of induced voltages in the signal cable.
- Metal structures such as masts and tripods should be connected to the ground to provide an easy path to the ground in the event of a lightning strike. This will help protect sensitive instruments. Electronic equipment often has a special ground lug and associated internal protection to help protect against stray voltages from lighting strikes.

[25] Best Practices Handbook for the Collection and Use of Solar Resource Data, NREL, 2015.

Data acquisition and quality control

Data acquisition

Data logging tools must have performance conditions that do not reduce the potential measurement of the radiometer signals (e.g., analog-to-digital conversion of low-level direct current voltages, temperature response coefficients, and environmental limits of operation).

Most radiometers output a voltage/current/resistance that is measured by a voltmeter/ammeter/ohmmeter. The measured value is subsequently transformed to engineering units through a multiplier and/or an offset determined by calibration to a recognized measurement standard. Data loggers should be selected so that the measurement signal is coherent with the uncertainty of the sensor. The logger should also have a range that can measure the voltage or resistance at near full scale to best capture the resolution of the data. Most modern data loggers have several selections ranges, allowing the developer to enhance the match for each instrument. Because of the nature of solar radiation, radiometers can sometimes produce 200% or more of clear-sky readings under certain passing cloud conditions, and the logger range should be set to avoid over-ranging during unusual sky conditions.

The logging equipment should also have environmental provisions that are well-matched with the environment where the equipment will be used. Loggers mounted outside in an arctic environment will require more stringent environmental performance specifications. Equipment enclosures can create an internal environment several degrees above ambient air temperature because of solar heating, heat generated by electronic devices mounted inside, and lack of ventilation to help purge heat. Vent plugs are available to provide ventilation openings and avert insects and water from entering the enclosure.

The sampling incidence and time statistics of the solar resource data should be resolute from the anticipated data analysis necessities. For example, monthly means, daily totals, hourly, minute, or sub-1-minute data records can be useful. Data loggers can usually be designed to produce output of instantaneous or integrated values at any reasonable time period consistent with the radiometer time-response features. A high-temporal-resolution data-logging scheme can be down sampled or integrated to longer time periods than the other way around. Data logging equipment, data transfer mechanisms, and data storage can normally handle 1-minute data resolution, and this time realm should be considered the fundamental resolution in the data logger. Because most applications address the solar energy available over time, integrated data of sub-minute samples within the data logger is a common technique of data output irrespective of the final data resolution required by the analysis. If the size of a measured data set is a crucial issue (e.g., limited data communications throughput), the developer can determine the lowest temporal resolution needed for the application and optimize the data collection accordingly.[26]

Data communications

Stipulations should be made for transferring data from the data logger to a data processing facility. This is the foundation for effectively frequent data control. The manual transfer of data recorded on strip charts physically carried or shipped from the observing station to a data center has been replaced by advances in electronics and telecommunications that allow remote data collection from nearly any location (please see the RERA Wind Toolkit for more detailed information on data loggers).

A telephone modem link that uses conventional dial-up phone lines to connect stations to data centers can now be substituted with cellular telephone technology, removing the requirement for a physical connection between logger and phone line. The cell phone network is designed to deliver virtual Internet links between a measurement station and the data center. Satellite up and downlinks are also available for data transfers in areas that are not served by either wire or cell-based phone service. Within the area of an observing station, short-distance wireless communications such as Wi-Fi connectivity may be useful to minimize the need for long cables between radiometers and data loggers.[27]

Operation and maintenance (O&M)[28]

Correct O&M procedures are vital for obtaining precise solar resource measurements. Numerous components in a chain form a quality system and collectively, they deliver correct and consistent solar resource data. Suitable O&M requires long-term uniformity, attention to detail, and an in-depth appreciation for the significance of pre-emptive and remedial maintenance of sensitive equipment.

Calibrations are performed with clean instrument optics and a carefully aligned detector. To properly apply the calibration factor, the instrument should be kept in the same condition during field measurements. To maintain the calibration relationship between irradiance and radiometer output, proper cleaning and other routine maintenance is necessary. The maintenance process includes:

- **Checking the alignment of the detector** - **pyrheliometers** must be accurately aligned with the solar disk for accurate DNI measurements. **Pyranometer** detectors must be horizontal for GHI and DHI measurements and accurately aligned with a flat-plate

[26] Best Practices Handbook for the Collection and Use of Solar Resource Data, NREL, 2015.
[27] Ibid25
[28] Ibid 25

collector for plane of aray measurements. The radiometer orientation should be checked occasionally.

- **Cleaning the instrument optics** - to measure accurately the solar intensity, no contaminant should block or reduce the amount of sunshine falling on the detector. The outdoor environment provides many sources of such contamination, such as dust, precipitation, dew, plant matter, insects, and bird droppings. The sensors should be cleaned frequently to reduce the influence of contaminants on the measurements. Depending on the local conditions, this can call for daily maintenance of unventilated or otherwise protected radiometers. Radiometer designs based on optical diffusers are less vulnerable to dust contamination than are instruments with clear optics. Soiling of the windowed or domed radiometers can quickly affect the measurement and increase by many-fold the measurement uncertainty. This is especially relevant for pyrheliometers.
- **Documenting the condition of the radiometer** - for analysts to comprehend limitations of the data, conditions that affect the measurement must be documented. This consists of substandard measurement conditions, but it is just as important to document proper operations to add credibility to the data set. Observations and notes provide a critical record of conditions that positively and negatively affect data quality. Radiometers should be carefully cleaned at each inspection, even if soiling appears minimal. With such a practice in place, the analyst can be sure that the instruments were kept clean according to the documented schedule.
- **Documenting the environment** - a consistency check, note the sky and weather conditions at the time of maintenance when interpreting data from the radiometer, including measurements with unusual values.
- **Documenting the infrastructure** - the measurement station as a whole should be examined for general robustness. Any defects should be noted and corrected.
- **Remote sites** - if a site will be challenging to maintain for extended periods, a higher class windowed instrument might not be optimal, despite its prospective for better measurements. The cost of maintenance for a remote site may direct the projected cost of setting up and operating a station. This aspect should be anticipated when planning a measurement campaign. Maintenance at remote measurement sites will necessitate a qualified person nearby who can perform the essential maintenance responsibilities.
- **Maintenance schedule** - a robust maintenance schedule will support the credibility of the measurement data set and provide the analyst a base of justification when assigning confidence intervals for the data. Daily inspection should be scheduled for instruments with clear optics, and twice monthly inspections should be scheduled for diffuser instruments. More frequent spot inspections should be conducted after

significant weather events (dust storms, heavy rainfall, rainfall during periods with high optical depth, and storms).

- **Documented** - all O&M should be carefully documented with log sheets, preferably with electronic databases that contain enough information to reveal problems and solutions or to assert that the instruments were in good form when inspected. The exact times of the maintenance events should be noted, not estimations.

Data quality control, correction, assessment, and metadata [29]

The data quality is generally established when the measurement is taken as little can be done after the fact to improve fundamental quality. In order to avoid a situation where, for example, a station is poorly maintained and producing data with presumed/apparent errors there is a need for data quality control. The magnitude of the errors is not likely to be discernable until days or weeks later and there is no way to systematically diminish the uncertainty of such a measurement. Data quality control involves a well-defined supervisory process by which station operators are confident that, when a measurement is taken with unattended instruments, the instruments are in a state that produces data of known quality. It also includes a critical inspection or assessment of the data to help detect problems not evident from physical inspection of the instruments.

Data quality assessment is a method by which data quality can be judged based on criteria for a particular application. Several particular errors of meteorological data can be detected by automatic screening algorithms. Data can be compared to certain physical limits that have been determined to be sensible, with redundant measurements, or with physical or empirical models, all of which will provide some degree of independent measure for a quality judgment. However, the stricter the screening parameters and their corresponding values, too many or too few events may be identified. Furthermore, the values of some parameters are site dependent according to corresponding weather conditions; therefore, the results of the automatic screening always demand a manually check of an expert to ensure their validity.

The interpretation and application of solar resource measurements is contingent greatly on the efforts to record and include metadata relevant to the observations. This includes site location; local horizon survey; data acquisition system(s); input signal channel assignments; radiometer types, models, serial numbers, calibration histories, and installation schemes; information on eventual post processing of the data and maintenance records. For example, effects that have to be documented may include damaged or misaligned sensors, maintenance works on the instruments, detection of soiled sensors and subsequent sensor cleaning, obstructed sensors, and temporarily erroneous calibration constants in the program code. These events are frequently not detected automatically or sometimes not even detectable by automatic quality-control screening tools. Hence, manual checks are essential.

The three-component coupling test – all three components (DNI, GHI, and DHI) are measured. Measurement redundancy is apparent, because any one component can be

[29] Best Practices Handbook for the Collection and Use of Solar Resource Data, NREL, 2015.

derived from the other two. This technique helps quantify the relative error among the three components, although it does not essentially define strictly which measurement/s is/are in error. However, operational knowledge of the instruments and trackers can provide valuable insight into likely errors.

An effective quality-control process necessitates elements of quality assessment and feedback. The figure below illustrates a quality-assurance cycle that couples data acquisition with quality assessment and feedback.

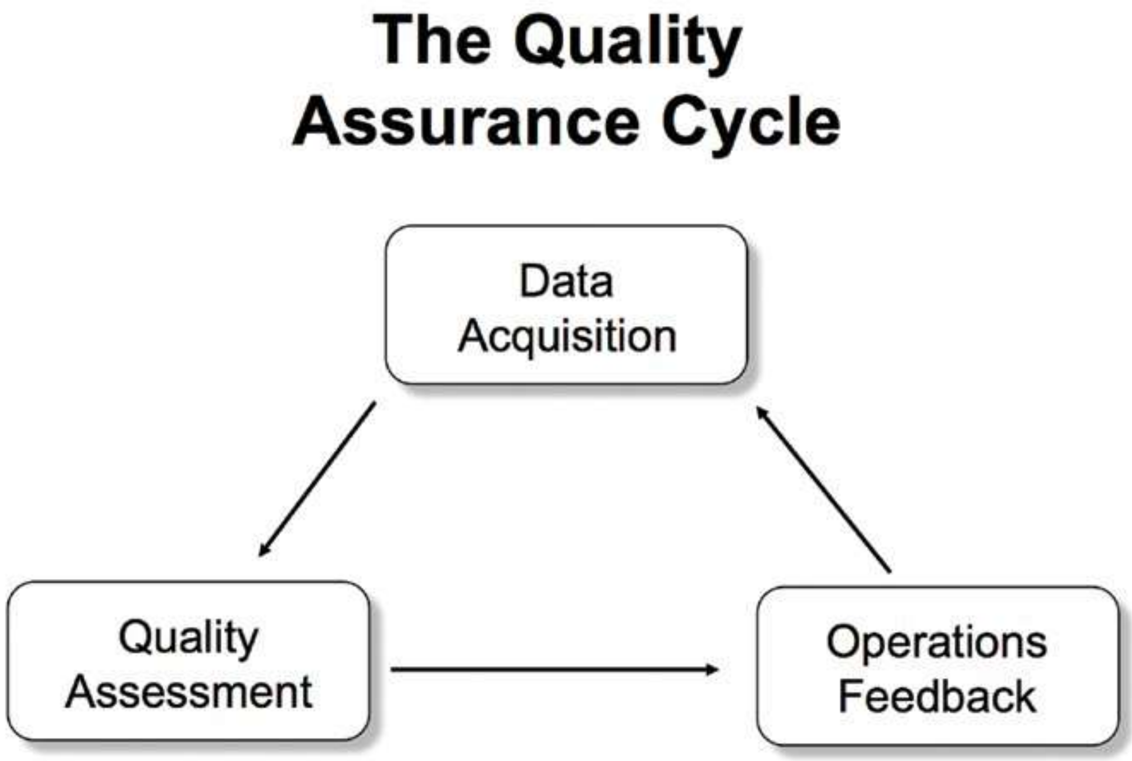


Figure 20 quality assurance cyle. [30]

The cycle starts with data acquisition, where some criteria are used to establish data quality, then the results of the quality assessment are analyzed and formed into feedback that goes back to the data acquisition module. The activities in the boxes can take several forms. For example, quality assessment could be the daily site inspection, and the analysis and feedback could be a simple procedure that corrects equipment malfunctions. Or the quality assessment could be a weekly summary of data flags, and the analysis provides a determination of specific instrument error that is transmitted back to maintenance personnel with instructions to correct deficiencies or further troubleshoot problems. The faster the cycle runs, the sooner errors will be spotted, and the fewer bad data will be collected. One practical aspect of this cycle is the importance of positive feedback—a

[30] Best Practices Handbook for the Collection and Use of Solar Resource Data, NREL, 2015.

regular report back to site personnel of error conditions and of high-quality operations or data sets exceeding quality thresholds.

The quality-assurance cycle is a deliberate part of the quality-control process, and it should be well defined and funded to maintain a consistency of data quality over time.

Solar radiation modelling – satellite based models

GHI and DNI are the magnitudes of interest for resource assessment and characterization at a particular location. High-quality solar resource assessment fast-tracks technology deployment and reduces doubt in investment decisions. Surface-based measurements of DNI and GHI can be made only on a comparatively scarce area, bearing in mind the costs of O&M. However, those measurements can be used in combination with models to create maps of surface solar radiation. An aternative possibility is to use information from geostationary satellites to estimate GHI and DNI at the surface, as it is available at regular intervals on a fixed-grid surface.

Radiation can be available for the entire globe at temporal and spatial resolutions representative of a particular satellite. This section covers an overview to satellite-based models, information about currently operational models that provide surface radiation data for current or recent periods and a summary of radiative transfer models used in the operational models.[31]

Satellite - based models

Satellite-based remote sensing is an essential player in monitoring and forecasting the state of the Earth's atmosphere. Geostationary satellites such as METEOSAT offer cloud information in a high spatial and temporal resolution. These satellites are also useful for the estimation of solar irradiance, as the knowledge of the radiance reflected by clouds is the basis for the calculation of the transmitted irradiance. Moreover, it is necessary to have a comprehensive knowledge about atmospheric parameters involved in scattering and absorption of sunlight. A precise estimation of the downward solar irradiance is not only of particular importance for assessing the radiative forcing of the climate system, but also absolutely necessary for an efficient planning and operation of solar energy systems and the estimation of the energy load. Solar resource assessment from geostationary satellites

[31] Best Practices Handbook for the Collection and Use of Solar Resource Data, NREL, 2015.

constitutes a powerful alternative to a meteorological ground network for both climatological and operational data.[32]

The European Organization for the Exploitation of Meteorological Satellites Union owns the METEOSAT series of satellites that covers Europe and Africa as well as the Indian Ocean. The visible and infrared imager on the METEOSAT first-generation satellites (up to METEOSAT 7) had 3 channels in the visible, water vapor, and infrared. The visible channel produced 8km nadir resolution; the infrared channel's nadir resolution was 5km. Repetition frequency is imagery every 30 minutes. The Spin Enhance Visible and Infrared Imager on the METEOSAT Second Generation (MSG) satellites (METEOSAT 8 onward) provide satellite imagery every 15 minutes at a nominal 3km resolution for 11 channels (Schmetz et al. 2002). The 12th channel, a high-resolution visible channel, has a nadir resolution of 1km.

Polar-orbiting satellites are also used to continuously sense the Earth and retrieve cloud properties and solar radiation at the surface. An example of one such instruments is the Advanced Very High Resolution Radiometer on the NOAA series of polar-orbiting platforms. Another recent example is the Moderate Resolution Imaging Spectroradiometer instrument on NASA's Aqua and Terra satellites. Although polar orbiters provide global coverage, their temporal coverage is limited because of their orbit, in which they essentially cover a particular location only once a day at the lower latitudes.

Physical models commonly use radiative transfer theory to directly assess surface radiation based on first principles. These can be categorized as either broadband or spectral, conditional on whether the radiative transfer calculations comprise of a single broadband calculation or multiple calculations in different wavelength bands. An advantage of physical models is that they can use additional channels from new satellites (such as MSG) to improve cloud property retrieval and, hence, surface radiation modelling.[33]

Currently available operational models

NASA/Global Energy and Water Cycle Experiment Surface Radiation Budget

The World Climate Research Programme's (WCRP) Global Energy and Water Exchanges (GEWEX) program is an integrated program of research, observations, and science activities with the mission to "Observe, understand and model the hydrological cycle and energy fluxes in the Earth's atmosphere and at the surface." The NASA/GEWEX SRB project is a key component of the GEWEX global data project portfolio. The objective of the NASA/GEWEX SRB project is to determine surface, top-of-atmosphere, and atmospheric shortwave and longwave radiative fluxes with the precision needed to describe the long-term mean and variability of the components of the surface radiation budget, and also understand its

[32] Rethinking satellite-based solar irradiance modelling: The SOLIS clear-sky module, 2004.

[33] Best Practices Handbook for the Collection and Use of Solar Resource Data, NREL, 2015.

contribution to the energy and water cycles of the planet. The NASA/GEWEX Surface Radiation Budget (SRB) Release-3.0 data sets contains global 3-hourly, daily, monthly/3-hourly, and monthly averages of surface and top-of atmosphere (TOA) longwave and shortwave radiative parameters on a 1°x1° grid.

Model inputs of cloud amounts and other atmospheric state parameters are also available in some of the data sets. Primary inputs to the models include: visible and infrared radiances from International Satellite Cloud Climatology Project (ISCCP) pixel-level (DX) data, cloud and surface properties derived from those data, temperature and moisture profiles from GEOS-4 reanalysis product obtained from the NASA Global Modeling and Assimilation Office (GMAO), and column ozone amounts constituted from Total Ozone Mapping Spectrometer (TOMS), TIROS Operational Vertical Sounder (TOVS) archives, and Stratospheric Monitoring-group's Ozone Blended Analysis (SMOBA), an assimilation product from NOAA's Climate Prediction Center.[34]

NASA Prediction Of Worldwide Energy Resources

Solar and meteorological data sets from NASA research for support of renewable energy, building energy efficiency and agricultural needs. The Renewable Energy Archive is designed to provide access to parameters specifically tailored to assist in the design of solar and wind powered renewable energy systems. The Surface meteorology and Solar Energy (SSE) project is one of the earlier activities funded by the Applied Science Program to foster use of NASA’s data holdings. The SSE data-delivery website is focused on providing easy access to parameters valued in the renewable energy industry (e.g. solar and wind energy) and was initially released in 1997.

The solar and meteorological data contained in this first release was based on the 1993 NASA/World Climate Research Program Version 1.1 Surface Radiation Budget (SRB) science data and TIROS Operational Vertical Sounder (TOVS) data from the International Satellite Cloud Climatology Project (ISCCP). Release 2 of SSE was made public in 1999 with parameters specifically tailored to the needs of the renewable energy community. Subsequent releases of SSE - SSERelease 3.0 in 2000, SSE-Release 4.0 in 2003, SSE-Release 5.0 in 2005, and SSE-Release 6.0 in 2008 – have continued to build upon an interactive dialog with potential customers resulting in updated parameters using the most recent NASA data as well as inclusion of new parameters that have been requested by the user community. Recent upgrades to the SSE component of POWER were initiated to include Geographic Information System (GIS) functionality as an option to the data ordering/access process.

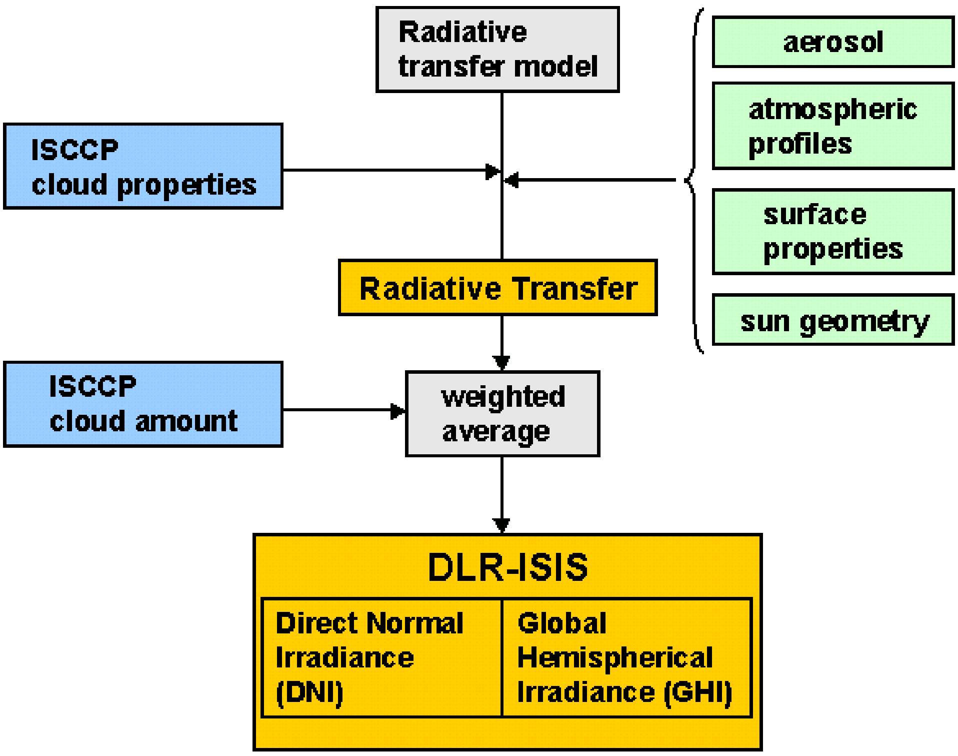
SSEGIS constituted the Release 7.0 version, but did provide updated data sets. The POWER Release-8 encompasses the three focused data components of POWER - SSE, Sustainable

[34] https://gewex-srb.larc.nasa.gov/

Building, and Agroclimatology - in a new responsive data portal built on upgrades to the underlying based metrological data, and is designed to fit on desktop, tablet and smart phone platforms, and adds geospatially enabled online tools to facilitate data ordering and viewing as well as analysis of the solar and meteorological data. The meteorological data/parameters in POWER Release-8 are based upon a single assimilation model from Goddard's Global Modeling and Assimilation Office (GMAO). The updated meteorological data are derived from the GMAO Modern Era Retrospective-Analysis for Research and Applications (MERRA-2) assimilation model products and GMAO Forward Processing – Instrument Teams (FP-IT) GEOS 5.12.4 near-real time products.

The MERRA-2 data spans the time period from 1981 to within several months of real time; the GEOS 5.12.4 data span the time period from the end of the MERRA-2 data stream to within several days of real time. The MERRA-2 and GEOS 5.12.4 versions are essentially the same and thus discontinuities that are often apparent between different assimilation models are minimized. The solar based data/parameters in POWER Release-8 will continue to be based upon satellite observations with subsequent inversion to surface solar insolation by NASA's Global Energy and Water Exchange Project /Surface Radiation Budget (SRB) and NASA's Fast Longwave And SHortwave Radiative project (FLASHFlux).[35]

DLR-ISIS Model



[35] https://power.larc.nasa.gov/documents/POWER_Data_v8_methodology.pdf

[36] Figure 21 DLR-ISIS Model.

Based on satellite data a global data set covering more than 21 years was derived at the Institute of Atmospheric Physics describing the amount and the variability of the solar irradiance imaging the earth's surface. DLR-ISIS is calculated with the radiative transfer code libRadtran that was developed at the Institute. It is based on the cloud climatology ISCCP (International Satellite Cloud Climatology Project) provided by NASA and global data sets of aerosol , water vapour and ozone distribution.

- **Solar Energy Applications**

The most important application of the DLR-ISIS data set is the use of the DNI data during the planning stage of concentrating solar power plants. The DLR-ISIS data set is used to determine the average annual irradiance at sites for new concentrating solar power plants, evaluate the variability of irradiance from year to year and study the effect of extreme atmospheric conditions on the irradiance at the surface e.g. after a volcano eruption. Sensitivity of DNI to change in cloud amount and aerosol load is very high. Therefore, variability of these atmospheric constituents results in strong variability of irradiance at the surface of the Earth. Due to this high variability, measurements of only a few years are not representative for the long-term averages.

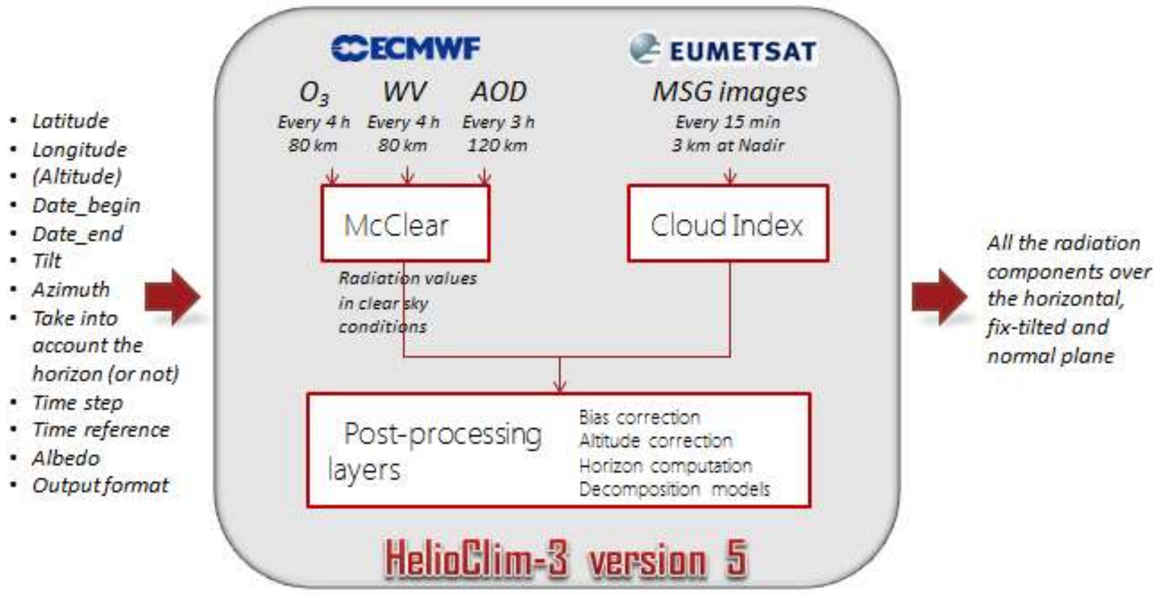
In the images below averages over one year, two years etc. of irradiance are compared to the long-term average over 21 years. DNI averages taken over only a single year of data differ from the 21-year mean by as much as 17%. Only after 13 years of measurements is the average within 5% of the 21-year mean. Considering all 6596 grid boxes of the DLR-ISIS data set, averages for a single year differ from the 21-year value by an average 20%. For all DLR-ISIS grid boxes, the derived average DNI is within 5% of the long-term mean only after a minimum of 12 years.

HelioClim

The HelioClimdatabase contains daily values of the solar radiation reaching the ground. This GEOSS (Global Earth Observation System of Systems) Data Collection of Open Resources for Everyone (Data-CORE) covers Europe, Africa and the Atlantic Ocean, from 1985 to 2005. It is freely accessible at no cost through the SoDa Service. Several assessments of the HelioClim data against measurements made in meteorological networks reveal that the HelioClimdatabase offers a reliable and accurate knowledge of the solar radiation and its daily, seasonal and annual variations over recent years. The Heliosat-2 method converts images acquired by meteorological geostationary satellites, such as Meteosat (Europe), GOES (USA) or GMS (Japan), into data and maps of solar radiation received at ground level.

Images are regularly processed with the Heliosat-2 method every 15 min to update the HelioClim3 database. Heliosat-2 combines a clear sky model with a “cloud index”. The cloud index approach is based on the assumption that the appearance of a cloud over a pixel results in an increase of reflectance in visible imagery; the attenuation of the downwelling shortwave irradiance by the atmosphere over a pixel is related to the magnitude of change between the reflectance that should be observed under a cloud-free sky and that currently observed. This magnitude of change is quantified by the cloud index. Heliosat-2 combines a clear-sky model with a "cloud index". The cloud index approach is based on the assumption that the appearance of a cloud over a pixel results in an increase of reflectance in visible imagery; the attenuation of the downwelling shortwave irradiance by the atmosphere over a pixel is related to the magnitude of change between the reflectance that should be observed under a cloud-free sky and that currently observed.

This magnitude of change is quantified by the cloud index.HelioClim-3 version 4 (HC3v4) and version 5 (HC3v5) are the two most advanced versions of the HelioClim-3 database. HC3v4 uses the ESRA clear-sky model (Rigollier et al. 2000, Scharmer et al. 2000) with the climatological database of the Linke Turbidity Factor of Remund et al. (2003) as input. The major drawback of this database is that it is never updated to take into account changes in the atmosphere turbidity due to local effects such as maritime inputs, volcanoes, fires, evolution of the water vapor content, pollution.[36] The HelioClim-3 database stores the 15 minute GHI values. When the user launch a request, post-processing layers are applied to correct these values, as illustrated by the following picture on HelioClim-3 version 5. Then decomposition models compute the radiation components on the plane orientation as requested.



Fugre 22 inputs, outputs, and models in HC3v5.[37]

[36] http://www.soda-pro.com/help/helioclim/heliosat-2
[37] Ibid 37

The table below presents the scoring scheme that has been applied for each category, thus resulting to the next figure where the color gives an indication on how a database stands among the whole databases, from green for the highest score to red for the lowest score.

Table 2. Details of the scoring scheme

Category	Sub-category	score=1 *lowest*	score=2	score=3	score=4 *highest*
Representativeness	Spatial coverage	Smaller area	Mono-satellite	Multi-satellite	Global
	Spatial resolution	Lowest to highest resolution using a logarithm scale			
	Timeframe	Lowest to highest period using a logarithm scale			
	Updating schedule	None	Potentially	Periodically	Day+1
Data type	Components	GHI only	GHI & DNI	Partially, among GHI, DHI, GTI & DNI	All components
	Time step	Monthly	Dayly	Hourly	Sub-hourly
	Aggregation	Dataset only	-	Time-series only	Dataset & time-series
Operating mode	Accessibility	Offline request only (Email)	FTP access only	Partial GUI/web service otherwise offline request	GUI / web service
	Price	Commercial	-	Free for scientific usage	Free

“Representativeness” of the database deals with the geographical area covered by the satellite, its spatial and temporal resolution and the temporal coverage; the latter is related to both the duration, in year, and the updating strategy which may reveal the potential obsolescence of the database.

“Data type” deals with the SSI data itself, i.e. the product that is delivered to the end-user. It consists in the available component of the solar radiation (GHI, GTI and diffuse – DHI – for PV projects, DNI for CPV), the possibility to retrieve a dataset for a typical year through 12 monthly values and/or to work on time-series for a specific period and time sampling. The possibility to get TMY is not addressed in this study because it involves a complex processing of the raw solar radiation estimation along with the retrieval of other relevant meteorological parameters such as the air temperature or the wind speed.

“Operating mode” finally focuses on the process used for retrieving the data, from the availability of a graphical user interface (GUI), web services and/or offline request through email exchange, to the financial conditions for accessing the data.

Name	Provider	URL	Coverage	Ref.
3TIER	3TIER	3tier.com	Global	-
CM SAF	DWD	cmsaf.eu	Europe, Africa	[16]
DLR-ISIS	DLR	www.pa.op.dlr.de/ISIS/	Global	[17]
EnMetSol	University of Oldenburg	energy-meteorology.de	Europe, part of Africa	[18]
focus solar	focus solar GmbH	focussolar.de	North-America, Europe, Africa, part of Asia, Oceania	-
HelioClim-1	MINES ParisTech – Armines	soda-is.com	Europe, Africa, part of South-America	[19]
HelioClim-3	MINES ParisTech – Armines	soda-is.com	Europe, Africa, part of South-America	[20, 21]
Land SAF	European consortium	landsaf.meteo.pt/	Europe, Africa, part of South-America	[22]
meteonorm	METEOTEST	meteonorm.com	Global	[23]
NASA SSE Release 6.0	NASA	eosweb.larc.nasa.gov/sse/	Global	-
OSI SAF	European consortium	osi-saf.org	Europe, Africa, America	-
PVGIS CM-SAF	JRC	re.jrc.ec.europa.eu/pvgis/	Europe, Africa	[24]
Satel-Light	ENTPE	satel-light.com	Europe, North-Africa	-
SolarAnywhere	Clean Power Research	solaranywhere.com	North-America, Hawaii, Caribbean	[25]
SolarGIS	GeoModel Solar	solargis.info	Global	-
Solemi	DLR	dlr.de/tt/solemi	Europe, Africa, part of South America, Indian Ocean, Asia	-

Figure 23 Overvie of the satellite – based databases. [38]

[38] Review of satellite-based surface solar irradiation databases for the engineering, the financing and the operating of photovoltaic systems Christophe Vernaya, , Sébastien Pitavala , Philippe Blancb, 2013

Database	Representativeness	Data type	Operating mode	Overall
3TIER	14	10	4	28
CM SAF	11	6	8	25
DLR-ISIS	10	7	4	21
EnMetSol	12	12	4	28
focus solar	14	11	2	27
HelioClim-1	9	8	8	25
HelioClim-3	12	11	5	28
Land SAF	12	8	5	25
meteonorm	11	11	4	26
NASA SSE Release 6.0	10	9	8	27
OSI SAF	11	7	6	24
PVGIS CM-SAF	11	6	8	25
Satel-Light	8	11	8	27
SolarAnywhere	11	10	4	25
SolarGIS	15	12	4	31
Solemi	13	9	4	26

Figure 24 Synthesis of the scoring of the 16 SSI databases.[39]

[39] Review of satellite-based surface solar irradiation databases for the engineering, the financing and the operating of photovoltaic systems Christophe Vernaya, , Sébastien Pitavala , Philippe Blancb, 2013

Applying solar resource data to solar energy projects

During feasibility assessments, including engineering analysis and due diligence, some periods of high-quality measurements are assumed to be available at the site; however, these relative short-term measurements must be extrapolated to long-term records that capture seasonal trends and the interannual variability of solar resources for the site. During the system acceptance and site operation stages, reliance should be on high-quality ground-based measurements, perhaps supplemented to some extent by ongoing satellite-derived measurements for the region. The project developer should consult the following table when evaluating sites through the various stages of project development.[40]

Evaluation Step	Question	Solutions and Insights
	What proposed site location(s) need(s) to be evaluated?	
	Has a single site been chosen?	If not, is the developer making a choice from among two or more sites or "searching" from a wider area? If choosing among multiple sites, the developer will profit from using maps and graphical techniques to assess both the estimated resource and the uncertainty of those resource estimates.
Predicted plant output throughout its project life	How can short-term data sets that provide projections throughout the next few years be extended to long-term (30-y) projections so that projections of cash flow throughout the life of the project can be made?	Different locations may have different interannual variability. Normally, on-site data cover at most a few years, so discuss procedures for extrapolating these data sets to long-term projections using longer-term (up to 45-y) modelled irradiance data as well as how to relate the nearest ground stations to site-specific data.
Temporal performance and system operating	How important are seasonal and diurnal patterns of the solar resource?	Many solar energy projects will produce electricity for the public utility grid. If time-of-day pricing has been implemented for the consumer, an understanding of the diurnal

[40] Best Practices Handbook for the Collection and Use of Solar Resource Data, NREL, 2015.

strategies		patterns and monthly mean values during those months when time-of-day pricing is in place may be more important than the estimate of the annual average. For example, if a CSP project includes thermal storage, the need to analyse when the system will build up storage compared to when the system provides power to the grid during daylight hours also emphasizes the importance of understanding the diurnal patterns. Thermal storage greatly mitigates the effect of system intermittency, but accurate or realistic daily, hourly, or sub hourly solar radiation data may still be needed.
	Is data needed that most closely match actual concurrent utility load data to conduct grid-integration studies and system intermittency?	In this case, daily, hourly, or even sub hourly data may be needed for a specific time period, which cannot be provided TMY data.
	What are the temporal/spatial characteristics of the data sources available to the developer, and how do these characteristics influence the evaluation of system performance?	Example: Measured solar data apply to a specific location and are usually recorded at short time intervals (6 min), then averaged to the desired time interval (often hourly in the early project phase). Example: Surface modelled data (e.g., NSRDB/METSTAT) is somewhat smoothed, because they are based on cloud cover observations that can be seen from a point location, typically a circle 40km in radius, averaged over an approximate 30-min period. Example: Satellite data usually represents snapshots in time because of the scanning characteristics of the on-board radiometers and are typically considered to range from nearly instantaneous to approximate 5-min averages. For SUNY satellite data used in the NSRDB, the individual pixel size is 1km, and the pixel is at the centre of the 10km grid cell. Newer satellite-based methodologies now average 1km pixel to 3km/5km grid cells.

Data applications for site screening and pre-feasibility assessment [41]

The site screening process

In the early stages of project development, a pre-feasibility assessment of likely sites is undertaken. An anticipated result at this phase is the projected annual energy production that could be projected from the solar energy system in various proposed locations. Historical solar resource data sets are commonly used in this stage, often in the form of maps.These data sets use a reliable methodology to consistently ascertain the regions of highest solar potential. The maps should be used to make a preliminary assessment of solar resource, assuming a fairly large potential for error (approximamtely 15%).

Substantial caution must be taken to select the correct irradiance data sets for input to the model. Experts commend multiple years of at least hourly input data, rather than data from only one year or even TMYs, to evaluate the effects of interannual variability of the solar resource on year-to-year system performance. Each hourly data set should be appraised at least to determine whether the monthly mean values from hourly data equal the best estimate of monthly mean values at the proposed site.

Desktop site screening - when multiple sites are under consideration, the calculated cost of energy, load matching quality, and other factors will play a part in rankings. Using solar resource maps and observational data, GIS layers (including land cover, land use, and development exclusions) are also to be considered along with:

- existing land use and area
- proximity to transmission
- thermal screening for line excess capacity
- shading impacts and other important siting parameters

Field assessments – the ground-truth assumptions and data used in the initial site screening (such as the presence and location of existing roads and transmission lines), and address issues such as:

- Road and transmission access
- Potential visual concerns
- Issues of cultural, environmental, historical, or other community sensitive
- Possible solar monitoring locations, including site coordinates, access, and surroundings
- Cellular telephone service reliability for automated data downloading

[41] Best Practices Handbook for the Collection and Use of Solar Resource Data, NREL, 2015.

- Influence of aerosol optical depth (AOD) - tiny solid and liquid particles suspended in the atmosphere are called aerosols. Windblown dust, sea salts, volcanic ash, smoke from wildfires, and pollution from factories are all examples of aerosols. Solar facilities should, if possible, be sited at locations that are protected from sources of these aerosols. For rural areas with low AOD, the irradiance averages from the satellite-derived (gridded) data are more likely to be correct, if it can be confirmed that the area is indeed protected from sources of aerosols.

Feasibility - a feasibility study allows you to weigh the potential risks and rewards in developing a project before you make a large investment. Need to address the following:

- Resource and energy production potential
- Technical feasibility and technology options
- Cost and revenue projections and financial pro forma
- Potential environmental concerns
- Regulatory requirements and challenges
- Interconnection requirements
- Community acceptance

Data applications for feasibility, engineering, and financial assessments [42]

After one or more nominee sites have been selected for an engineering feasibility assessment, a common problem facing solar power plant project developers is how to produce data sets that allow for the most consistent calculation of annual or interannual system performance when only short-term ground measurements, along with other estimated data sources, are available. The degree of accuracy required for system performance and energy yield estimates depends on the stage of project development, as follows:

- Prefeasibility stage - specific sites are evaluated to determine whether they may be suitable for development and thus require more comprehensive evaluation.
- Feasibility stage - sites have been selected for actual project implementation, and system design and energy performance estimates become very important. At this stage, more comprehensive knowledge of the annual resource as well as seasonal and diurnal characteristics, with known accuracies, is required. Accurate long-term site performance estimates are required, and the variability of the system output from year to year (caused by interannual variability of the resource, again within well-established confidence limits) is required.

[42] Best Practices Handbook for the Collection and Use of Solar Resource Data, NREL, 2015.

Extrapolating short-term measured data sets [43]

The basic methodology for attaining an estimate of the annual solar resource appropriate for prefeasibility analysis that can be used to make energy yield estimates is to obtain accessible long-term site estimates, such as satellite-derived estimates or nearby modeled station values. When short-term on-site estimates from new solar radiation measurements are available, they can be used to decrease the doubt in the modeled estimates. There are three methods to combine the short and long-term data to obtain a more accurate estimate of the long-term solar resource:

- **The ratio method** - assumes that at least two independent data sets are available: an on-site measurement data set (presumed to be relatively short term), and a long-term climatological data set, such as a satellite-derived database or a nearby long-term measurement station or modeled data. Ideally, at least part of the two data sets should be concurrent. If there is no concurrency in the data, the ratio method can still be applied, but the uncertainty of the resulting long-term on-site data profile will likely be much higher than if concurrent data periods are available. Basically, the method involves calculating the ratios of a selected averaging period of the concurrent data sets, such as hourly or monthly averages, then applying these ratios to the balance of the long-term data set to produce a long-term estimate for the site.
- **The weighting method** - a second method is to combine two different data sets by weighting each. They could be weighted equally or the weighting can be determined based on the inverse of the uncertainty of each data set. By supposing that the deviances from truth follow a normal distribution and are statistically independent, the Gaussian law for error propagation can be applied.
- **High-quality short-term ground data method** – in this method the frequency distribution of the ground-based data is used to improve the satellite-derived data. The method has resulted in greatly reduced bias errors and improved Kolmogorov-Smirnov Integrals in the satellite data, especially for DNI estimates, even when as little as 3 months of ground data is available.

Interannual variability and exceedance probabilities

To assess the solar resource or energy yield potential of a site a model the solar resource/energy yield using best available information and methods is required. The resulting estimate is the P50 estimate or in other words the "best estimate". P50 is essentially a statistical level of confidence suggesting that it is expected by the developed to exceed the predicted solar resource/energy yield 50% of the time. However, this may represent too much risk for some investors. Therefore other probabilities of exceedance values such as P90 (exceeded 90% of the time) or P75 (exceeded 75% of the time) are considered.

[43] Best Practices Handbook for the Collection and Use of Solar Resource Data, NREL, 2015.

Applying solar resource data to planning solar energy projects [44]

The value of electricity generated by a PV plant rest on the amount of electricity generated and the grid's need for that electricity at the time it is generated. A quantitative understanding of the solar resource for the intended location and orientation of the PV array is essential.

Performance Ratio Method

The production of a PV plant can be characterized by the performance ratio metric, which defines the fraction of electricity produced by the plant comparative to what the plant would produce if it always ran at its nameplate efficiency. Usually, new PV plants work with performance ratios of 0.8 ±0.1 . Therefore, if the annual solar resource available for a given site and given array orientation (fixed or tracking) is determined, the annual output of the system can be estimated according to the following equation:

Annual output (kWh/y) = 0.8 X solar resource (kWh/m^2/y) X PV plant size (kW)

Where the PV plant size is resultant from the sum of the module nameplate ratings as characterized under normal test conditions (1,000 W/m^2), the ambiguity of this approximation must comprise of the variability of the solar resource from year to year and the variability of the performance ratio. Contributors to low performance ratios are:

- Shading losses
- Soiling or snow-coverage losses
- High-temperature operation
- Undersized inverters so that the inverters "clip" the plant output part of the time
- Older plants that have experienced degradation

Contributors to high performance ratios are:

- Operation in a cool climate
- Modules with low temperature coefficients
- Modules that generate power well above the nameplate rating

The performance ratio method is for the most part useful if there is a need to compare performance of existing systems or when it is preferred to quickly use solar resource data. Otherwise, using more refined performance models is likely to be the better approach for estimating PV plant output. At the last section you'll find a link to a calculator and models to do this.

[44] Best Practices Handbook for the Collection and Use of Solar Resource Data, NREL, 2015.

Measurement of solar resource data for power plant characterization [45]

The performance of a solar energy system is directly related to the existing meteorological conditions. For flat-plate thermal collectors and PV, the production is approximately proportional to the plane of array (POA) irradiance. For concentraitng solar technologies (CST), DNI is the key parameter; however, other meteorological effects also exist. The subsequent are a couple of the many reasons to measure meteorological conditions for comparison to solar system performance:

- **Evaluate a performance guarantee -** different approaches are present for assessing the performance guarantee. In all cases, measurements of the solar resource are involved. For **CST**, acceptance tests include DNI. For **flat-plate thermal collectors** and **PV**, the yield prediction is generally based on GHI. So, it is also common for a performance guarantee to use GHI as the basis for defining whether a plant has performed as anticipated. Nevertheless, the performance characterization of a PV plant can be accomplished with a lower uncertainty if the irradiance is measured in the POA (removing the uncertainty of the transposition of the GHI irradiance to the irradiance in the POA) and if irradiance sensors are chosen to match the expected response of the PV modules (reducing angle-of-incidence and spectral effects).
- **Monitoring power plant performance** - evaluate power plant performance for enhanced yield predictions for the fitted and future plants. During power plant operation, awareness of the present meteorological conditions and the status of the plant are of high importance. Also, the future development of the meteorological conditions are applicable. Consequently, the solar resource measurements and forecasts are incorporated in many solar energy systems. For CSP installations such measurements and forecasts are fundamental. Although many PV plants can operate successfully without any intervention, measurements and forecasts are also advantageous for PV. There can be value to washing a PV array, and equipment malfunctions can be detected more quickly if the PV plant output is being continually compared to the expected output based on the meteorological conditions. For CST, DNI measurements are involved along with the other parameters mentioned above. The closest correlation between PV plant performance and irradiance is obtained by monitoring the POA by using a reference cell or reference module that closely matches the PV module response.
- **Maintenance** – identification of conditions of poor performance, including evidence of soiling, shading, hardware malfunction, or degradation, which might lead to warranty replacement.

Before making site-specific measurements (prefeasibility, feasibility stages):

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[45] Best Practices Handbook for the Collection and Use of Solar Resource Data, NREL, 2015.

- Use screening maps and other criteria (grid connection , etc.) or choose candidate sites.
- Evaluate monthly/yearly mean irradiance values from a long-term data set. Compare it to nearby sites that have more years of data. Create a set of best-guess target values for the monthly mean irradiance.
- Assess the uncertainty of irradiance means in the target values.
- Regulate the anticipated monthly mean irradiance values upward or downward, based on these parameters.
- Select hourly data sets to match expected mean value; at the same time, have diurnal and seasonal patterns close to those of the candidate site.
- Assess the data to see how closely these mean values match the expected patterns.

Site-specific ground measurements must be incorporated in the analysis for bigger solar energy projects. If no high-quality data are obtainable for at least 1 year, new measurements have to be collected following the methods described in this toolkit. After new ground measurements are available:

- Accurately evaluate the quality of the new measured irradiance data.
- Use the ratio method to compare measured and modeled data and create updated appraisals of monthly mean irradiance.
- Use a comparison of measured and modeled irradiance to assess the variability of aerosols.
- Prepare the best possible data sets and multiple year as well as exceedance values, based on all available data, for final simulation runs.
- Evaluate the interannual variability and check to determine whether global dimming or brightening is an issue in the region of interest.

Forecasting solar radiation

Solar resource forecasting is vital in the operation phase of solar power plants, as the power generation from solar energy systems is highly intermittent. Therefore, the inconsistency of the solar resource presents new challenges to the operation of single solar power plants. In this context, consistent predictions of solar power production are becoming more and more central as a foundation for effective management and operation strategies. Following the rapidly evolving situation on the energy market with a strong need for accurate solar power predictions, increasing effort during the last 10 years has been spent on developing irradiance and solar power prediction models.

Solar irradiance forecasting methods

Contingent on the application and the equivalent necessities with respect to forecast horizon and temporal and spatial resolutions, different data and forecast models are suitable. Figures 25 and 26 on the next page summarize the existing methods versus the forecasting horizon, the objective and the time step.

Figure 25 Forecasting error versus forecasting models.[46]

[46] Machine learning methods for solar radiation forecasting: A review Cyril Voyan, 2016.

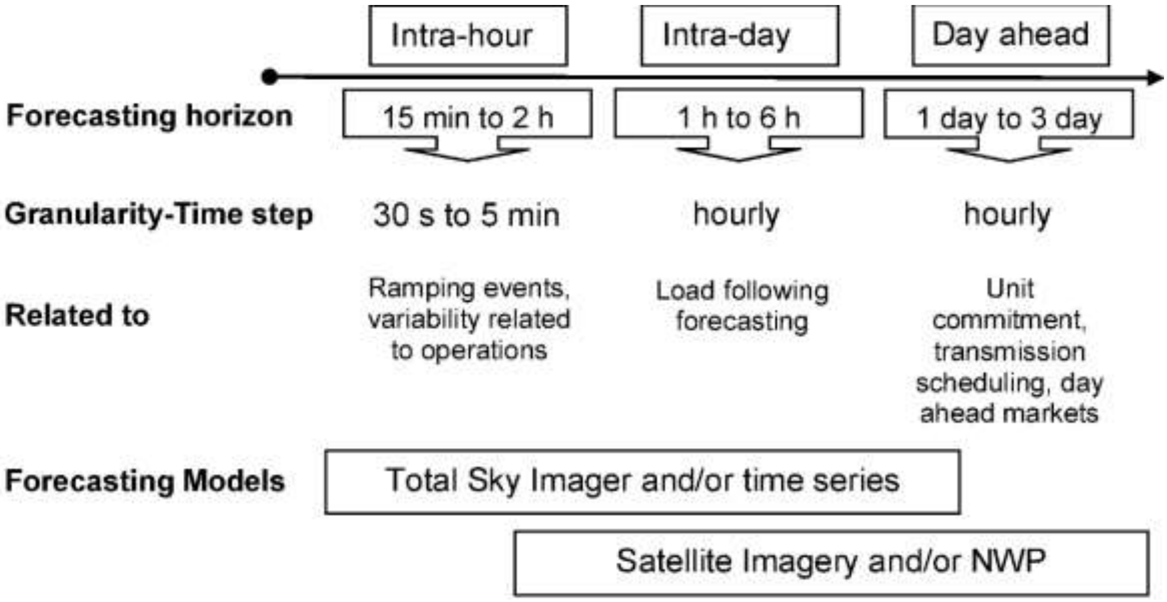


Figure 26 Relation between forecasting horizons, forecasting models and the related activities.[47]

Intra-hour forecasting with high spatial and temporal resolutions requires on-site observations of irradiance and/or cloud conditions. [48]

- Statistical time-series models with local irradiance measurements as input are used to provide point forecasts up to a few hours ahead with a temporal resolution from minutes to 1 hour. They benefit from the high autocorrelation for short time lags in time series of solar irradiance; however, changes in cloud conditions, such as by approaching clouds, can hardly be predicted.
- Information about clouds and their motion in the surroundings of a given site can be obtained with ground-based sky imagers. Based on these observations, future cloud conditions and irradiance are extrapolated with a temporal resolution down to minutes or even below and a spatial resolution in the range of 10m to 100m. Forecast horizons of sky-imager forecasts are typically up to 15 minutes to 30 minutes ahead.

Forecast **up to several hours** ahead are operationally derived by analyzing and extrapolating clouds and cloud motion in satellite images that have a broad coverage. The spatial resolutions are approximately 1km to 5km for the current generation of geostationary satellites, and images are generated in every 15 minutes to 30 minutes.

Numerical weather prediction (NWP) models are employed for forecast horizons **from several hours to several days ahead.** Predicting dynamic changes of the atmosphere, including formation or dissolution of clouds as well as advection, essentially relies on physical modeling. NWP models describe the physical and dynamical processes in the

[47] Ibid 44
[48] Best Practices Handbook for the Collection and Use of Solar Resource Data, NREL, 2015.

atmosphere by numerically solving the governing equations of the atmosphere on a grid starting from observed initial conditions. Global NWPs cover the Earth with spatial resolutions ranging from approximately 0.125 degrees to approximately 0.5 degrees and temporal resolutions of 1 hour to 3 hours. Local or regional models are employed for downscaling global model forecasts for specific regions to a finer grid of typically 3km to 10km with hourly resolutions.

The application of statistical models is beneficial for all horizons, ranging from very short-term forecasting with times-series models based on local measurements to forecasting for several days ahead. Whichever model is used for forecasting, partly stochastic and systematic errors remain. These errors may be reduced with statistical models by learning from historic data sets of forecasted, measured, or satellite-derived irradiance. In particular, there is a high potential for improving forecast accuracy by combining different models with statistical learning approaches, which allow for an optimum assembling of different input data, depending on forecast horizon and weather situation.[49]

Irradiance Forecasting With Cloud Motion Vectors

Besides the daily and annual patterns of irradiance, cloud cover as well as cloud optical depth have a durable influence on solar irradiance at surface level. Clouds show a strong variability in time and space. Hence, determination of clouds at a designated time is an essential task in irradiance forecasting and modeling. Methods detecting clouds and cloud motion in satisfactory detail deliver valuable data for irradiance forecasting in the equivalent time scales. The operation of this forecasting method is degraded when local cloud formation and dissipation processes, such as strong thermal convection, are dominant over cloud advection.

The following basic steps comprise forecasting based on cloud motion vectors:

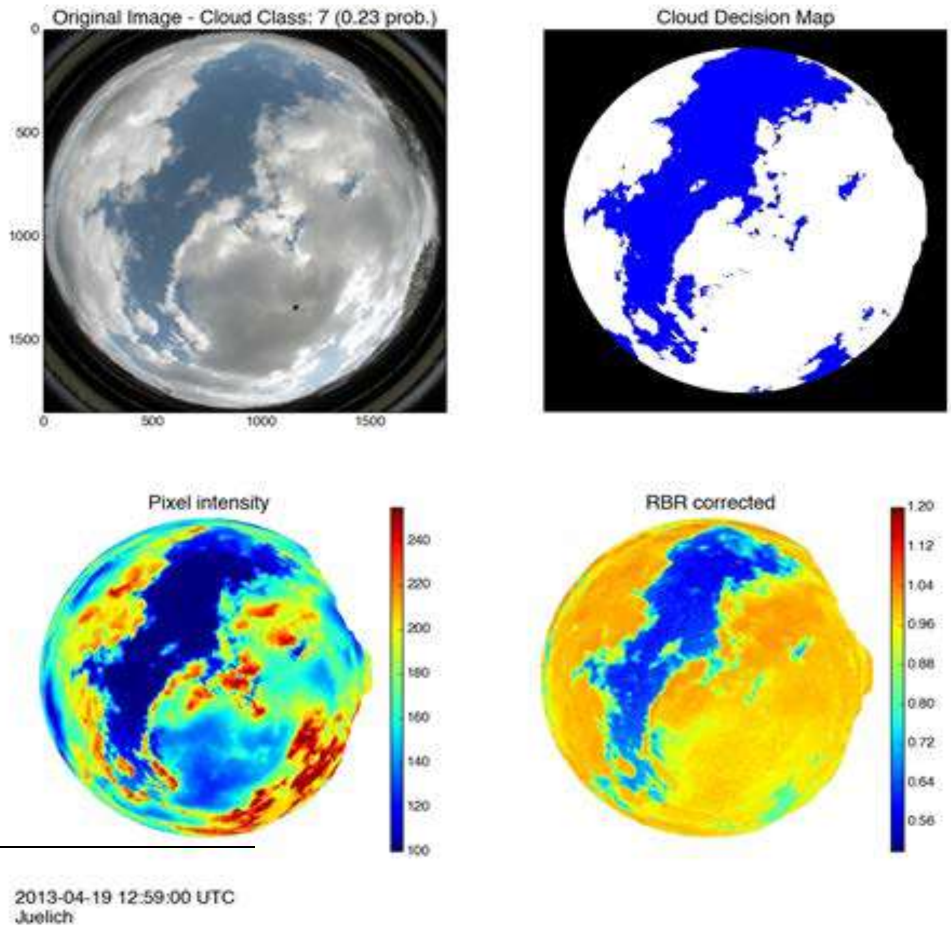
- Images with cloud information are derived from satellite or ground-based sky-imager measurements.
- Assuming stable cloud structures and optical properties for the considered temporal and spatial scales, cloud motion vectors (CMV) are determined by identifying matching cloud structures in consecutive cloud images.
- To forecast future cloud conditions, the calculated motion vectors are applied to the latest available cloud image, so cloud motion is extrapolated using the additional assumption of persistent cloud speeds and velocity.
- Forecasts of site-specific solar irradiance are inferred from the predicted cloud images.

[49] Best Practices Handbook for the Collection and Use of Solar Resource Data, NREL, 2015.

Forecasting using ground-based sky images[50]

Solar irradiance forecasts in the subhourly range with very high temporal and spatial resolutions can be derived from ground-based sky images. Through processing of satellite or ground images, clouds can be detected, characterized, and advected to predict GHI relatively accurately up to 6 hours in advance. Particularly, they have the prospective for catching rapid variations in irradiance, frequently referred to as ramps, on a temporal scale of minutes or even less. Cloud fields may be resolved in high detail, allowing partial cloud cover on large PV installations to be modeled and forecasted.

Maximum possible forecast horizons strongly depend on cloud conditions (cloud height and velocity). They are restricted by the time the monitored cloud scene has passed the location or area of interest, typically up to 15 minutes to 30 minutes ahead. Short-term irradiance forecasting based on ground-based sky imagers is a rather new research field. At present, there is no well-defined standard for sky-imaging hardware, camera calibration, or image processing techniques. Systems in use range from commercially available low-cost web-cam-based sky cameras to high-quality prototype systems developed at research institutes.



[50] Best Practices Handbook for the Collection and Use of Solar Resource Data, NREL, 2015. Figure 28 Cloud information from sky imagers[50]

Cloud detection from sky-imager pictures is achieved by assessing different image properties. The red-to-blue ratio (RBR, Figure 28, upper right) is a main indicator for clouds because of different spectral-scattering properties of clouds (high RBR) and clear sky (low RBR). Pixel intensities (bottom left) are also interrelated to cloud cover and may be exploited as an additional feature for cloud detection.

Conversion of the derived cloud maps to real-world coordinates necessitates data about cloud height, which together with the position of the sun defines the position of cloud shadows at the surface. Consequently, this is necessary for modeling and forecasting irradiance fields with high spatial resolutions. Different options to determine cloud height include ground-based observations, satellite methods, and the evaluation of sky-imager data. Most accurate information on cloud-base height is obtained from ceilometers (lidars), typically employed at airport weather stations. Cloud-top height retrieval from satellite images gives spatially continuous information but shows larger uncertainties.

Detection of cloud motion is the next step to derive irradiance forecasts. Cloud motion can be identified based on a normalized cross-correlation procedure maximizing the cross-correlation between shifted areas in two consecutive images. Alternatively, cloud movement may be analyzed by applying optical flow techniques to subsequent images. The derived cloud motion vectors are then used to project the observed cloud scenes in the future.

Cloud shadow maps at the surface are produced by projecting the forecasted cloud scenes with their assigned height using information about the position of the sun. Finally, solar irradiance is projected from these cloud shadow maps. Without information about cloud optical properties and other atmospheric parameters, this is not an easy task. Local irradiance or PV power measurements can be used to estimate irradiance or PV power for cloudy and clear skies. High-quality irradiance measurements are essential for further algorithm development. In particular, the analysis of irradiance fields with high spatial resolutions requires measurements from a dense network of observation sites.

Satellite-Based Forecasts

Forecasts of several hours onward call for observations of cloud fields in large areas. Satellite data with their broad coverage are a suitable foundation for these horizons. The errors of satellite data and sky images based forecasts proposed in the literature increase drastically under low sun elevations, high spatial variabilities and low irradiance conditions.

As far as short-term horizons are involved, satellite data is a high quality source for irradiance information because of its outstanding temporal and spatial resolution. As a result of the strong impact of cloudiness on surface solar irradiance, an accurate description of the temporal development of the cloud situation is vital for irradiance forecasting.

The satellite-based forecasting scheme from the University of Oldenburg in Germany (Lorenz, Heinemann, and Hammer 2004, Kühnert, Lorenz, and Heinemann 2013), described here, uses images of the geostationary Meteostat Second Generation MSG satellites. The semiempirical HELIOSAT method is applied to obtain information about clouds and irradiance. A characteristic feature of the method is the dimensionless cloud index, which gives information about the cloud transmissivity.

As a measure of cloudiness, cloud index images according to the Heliosat method, are calculated from the satellite data. To predict the cloud index image in a first step motion vector fields are derived from two consecutive images. The future image is then determined by applying the calculated motion vector field to the actual image. Finally, solar surface irradiance is derived from the predicted cloud index images with the aid of the Heliosat method. Figure 2 gives an overview of these steps to derive the irradiance forecast. The figure below is an illustrative flowchart of the process.[51]

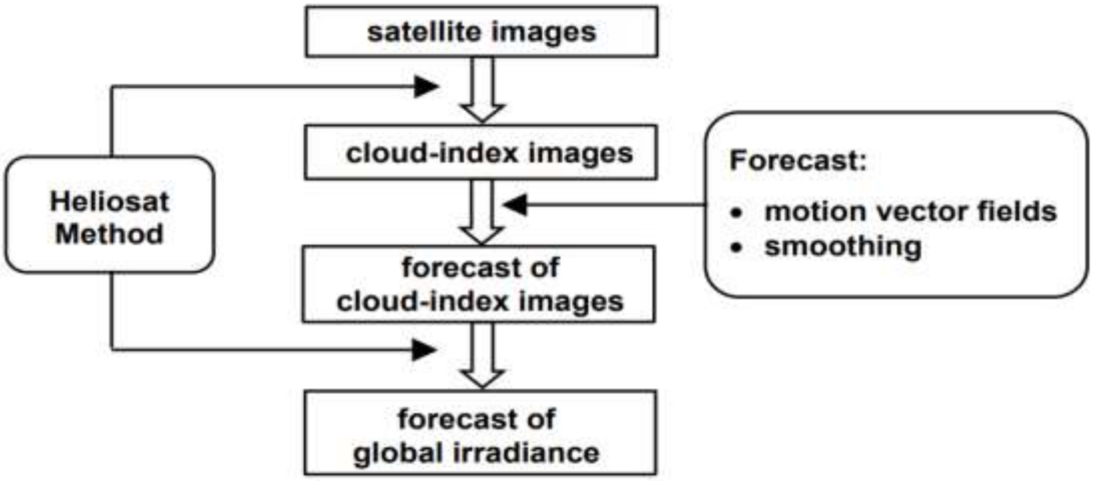


Figure 27 Short-term forecasting flowchart using statistical methods on satellite imagery.[52]

For an effective application of forecast in formation, it is important to estimate the uncertainty of the forecast accuratly. The accuracy of the forecasted irradiance depends on the meteorological situation. Thus, it is possible to distinguish different levels of accuracy. It will be shown that there are good results of the forecast for situations with high irradiance, where as it is more difficult to forecast situations with variable cloud cover or low sun elevations.

[51] Forecasting of Solar Radiation, Detlev Heinemann, Elke Lorenz, Marco Girodo.
[52] Ibid 51

Numerical weather prediction (NWP) [53]

Numerical weather prediction (NWP) models are operationally used to forecast the state of the atmosphere up to 15 days ahead. Starting from initial conditions that are derived from worldwide observations, the temporal development of the state of the atmosphere is modeled by the fundamental differential equations that describe the physical laws governing the weather. This physical modelling is essential for any forecast more than several hours ahead. Global models usually have a coarse resolution and do not allow for a detailed mapping of small-scale features, although resolution has increased rapidly during the last few years, depending on the model, is in the range of 16−50km. The temporal resolution of the model output is 1 hour, 3 hour, or 6 hour, limited by storage requirements.

In the next step, different concepts may be applied to account for local effects and to derive improved site-specific forecasts. One possibility is the downscaling by mesoscale models, which are also referred to as regional models. Mesoscale models cover only a part of the Earth but can be operated with a higher spatial resolution. They are routinely run by national weather services and private weather companies. Weather services typically operate mesoscale models with a spatial resolution in the range of 3 km to 20 km and provide hourly forecasts, but also higher resolutions are feasible. The higher spatial resolution allows for an explicit modelling of small-scale atmospheric phenomena.

Also, post processing methods may be applied to model local effects. They allow the correction of systematic deviations in dependence on different meteorological parameters and for modelling of the irradiance if it is not provided as output parameter of an NWP model. The utility of NWP plays a large part because it predicts transient variations in clouds, which are the major modulator of solar irradiance at the ground. In the forecasting process, assimilation of initial observational data takes place first; next, the NWP forecast propagates these initial conditions forward in time; statistical post processing then corrects errors in the forecast based on past performance.

Forecasts beyond 6 hours, up to several days ahead, are generally most accurate if derived from NWP models. NWP models predict GHI using columnar radiative transfer models (RTM). Heinemann showed that the MM5 mesoscale model can forecast GHI in clear skies without bias. However, the bias was highly dependent on cloud conditions and becomes strong in overcast conditions. A limitation of NWP forecasting is its coarse resolution. Even the 0.1°x 0.1°NAM spatial resolution is insufficient to resolve most clouds. Only an average cloud cover can be forecasted for a given point. However, even if the spatial resolution is finer, the temporal output intervals would not permit the assessment of time dependent cloud cover variability: vital in predicting ramp rates and ranges of variability for solar power plants. Any patterns with characteristic time scales less than an hour are unresolved.

[53] Review of solar irradiance forecasting methods and a proposition for small-scale insular grids Hadja Maïmouna, 2013.

Statistical Methods and Post-Processing [54]

Forecasting methods based on historical data of solar irradiance have two categories: statistical and learning methods. Statistical learning models are commonly applied in solar irradiance and power forecasting. The efficient dependence between input variables (predictors) and forecast values (predictands) is established in a training phase by learning from historic data, assuming that patterns in the historical data sets are recurrent in the future and thus may be exploited for forecasting.

Linear models or time series models

Statistical methods have been used effectively in time series forecasting for several decades. Using the statistical approach, relations between predictors, variables used as an input to the statistical model, and the variable to be predicted, are derived from statistical analysis.

Persistence model

It is beneficial to check whether the forecast model delivers better results than any reference model. It is worthwhile to implement and run a complex forecasting tool only if it is able to clearly outperform trivial models. Probably the most common reference model in the solar or wind forecasting community for short term forecasting is the persistence model. The persistence model supposes that global irradiance at time t is best predicted by its value at time t − 1: $\hat{X}_{t+1} = X_t$

The persistence model can be used to benchmark other methods. Persistence forecast accuracy declines with forecast duration as cloudiness changes from the current state. Generally, persistence is an inaccurate method for more than 1 hour ahead forecasting and should be used only as a baseline forecast for comparison to more advanced techniques.

Preprocessing of input data

When using statistical time series analysis, any type of conditional forecast model is structured to deal with stationary series, at least weekly. This means no trend nor seasonality, and the series is homoscedastic (constant variance). There are several ways to deal with non-stationary series to get them into an appropriate form.

- **Processes to obtain stationary solar irradiance time series** - The solar insolation is the real quantity of solar radiation incident upon a unit horizontal surface over a stated period of time for a specified area. It is contingent on the solar zenith angle. For statistical models, it may be advantageous to treat the effects of the deterministic solar geometry and the nondeterministic atmospheric extinction independently. For this purpose, two transmissivity measures have been introduced.

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[54] Review of solar irradiance forecasting methods and a proposition for small-scale insular grids Hadja Maïmouna, 2013.

- clearness index (k) - is defined as the ratio of irradiance at ground level I to extra-terrestrial irradiance Iext on an horizontal plane: $$k = I/I_{ext}$$

  It defines the overall elimination by clouds and atmospheric constituents in relation to the extraterrestrial irradiance. This method decreases seasonal and daily patterns in view of the effect of the zenith angle, which is modeled by I_{ext}. The clearness index is extensively applied to reduce the deterministic trend in irradiance time series. However, the clearness index accounts for only the trends caused by geometric effects on solar position. As atmospheric elimination is subject to the length of the path of the radiation through the atmosphere, it is also governed by solar geometry.
- clear-sky index (k^*) - drops with increasing of solar zenith angle. To account for this effect, the clear-sky index k^* is introduced. k^* is defined as the ratio irradiance at ground level I to irradiance of a defined clear-sky model I_{clear}:
  $$k^* = I/I_{clear}$$

  For the calculation of the clear-sky index, a clear-sky model and data on atmospheric input parameters are necessary. A clear sky model evaluates the GHI, usually referred to as clear-sky irradiance I_{clear}, in clear sky conditions at any given time.

The Autoregressive Moving Average (ARMA) model

It is typically applied to auto correlated time series data. This model is a great tool for understanding and predicting the future value of a specified time series. ARMA is based on two parts: autoregressive (AR) part and moving average (MA) part. The reputation of the ARMA model is based on its capability to extract valuable statistical properties and the adoption of the Box–Jenkins methodology . ARMA models are very flexible since they can embody numerous different types of time series by using different order. It has been attested to be fit in prediction when there is an underlying linear correlation structure lying in the time series. One major requirement for ARMA model is that the time series must be stationary.

The ARIMA (Auto–Regressive Integrated Moving Average) model

Consist of reference estimators in the prediction of global irradiance field. It is a stochastic process coupling autoregressive component (AR) to a moving average component (MA), after differencing at appropriate time steps to remove any trends. It is in this way that ARIMA models allow treatment of non-stationary series.

CARDS model

Is an autoregressive (AR) and dynamical system model to forecast solar radiation time series on hourly and intra-hourly time scales.

<u>Non linear models</u>

There has been great interest in research on artificial intelligence (AI) techniques, not only for forecasting but also for a broad range of applications, including control, data compression, optimization, pattern recognition, and classification.

Artificial Neural Network (ANN)

As an alternative to conventional methods, ANNs have been successfully applied for solar irradiance estimation. ANNs recognize patterns in data and have been applied to solar forecasting. Using training data, ANNs reduce normalized root mean square error (rRMSE) of daily average GHI by as much as 15% when compared to 12−18 hour ahead NWP forecasts.

Wavelet Neural Network

Mellit suggested an adaptive wavelet-network model for forecasting daily total solar irradiance. In this study, several structures have been investigated for resolving the missing data problem. In this particular estimation process, the model consists of an adaptive neural-network topology with the wavelet transformation embedded in the hidden units.

Statistical models can be used to derive irradiance forecasts solely based on measurements without involving any physical modeling (time series models with no exogenous input). They also play an important role in enhancing the output of NWP models and can be applied to cloud motion forecasts. Different terminology is used for this combination of statistical and physical forecasting methods, depending on the perspective of the researchers. The community of statistical modeling and artificial intelligence refers to these models as “statistical models with exogenous input.”

<u>Post-processing methods</u>

They are frequently applied to refine the output of NWP models. In particular, they may be utilized to:

- reduce systematic forecast errors (correction of systematic deviations)
- account for local effects (e.g. topography)
- derive parameters that are not directly provided by the NWP models (e.g. solar surface irradiance is still not a standard output parameter)
- combine the output of different models in an optimum way.

Best practices in on-site monitoring programmes [55]

On-site monitoring of relevant solar and meteorological parameters can deliver substantial value to assessing a project's potential, translating to higher confidence in energy estimates and decreased project uncertainty. For larger projects, this type of campaign may be critical in providing the site-specific data that may be necessary to secure external financing. The following sections highlight major components of these campaigns to be measured for successfully decreasing uncertainty in the project's solar resource.

Program Design

Monitoring program design necessitates careful planning and coordination, constrained by budget and schedule limitations. Clear objectives are needed so the best approach is taken to obtain desired results. The success of the campaign relies heavily on proper equipment siting, a sound measurement plan, consideration of technical and current industry standards, trained maintenance staff, quality equipment, and thorough data analysis.

Measurement Plan

Common to all monitoring programs is to ensure that the measurement and monitoring program provide the data needed to meet the program objectives. A comprehensive plan includes (please see GREBE RERA Wind for more details around those components):

- Measurement parameters: irradiance, temperature, precipitation, relative humidity, wind speed, wind direction and barometric pressure
- Equipment type, quality, and cost
- Equipment orientation and positioning (e.g. no shading or obstructions and access for maintenance or repair)
- Site requirements (e.g. permitting and security)
- Data sampling and recording intervals
- Parties responsible for equipment procurement, installation, maintenance, data validation and reporting
- Data transmission, screening and processing procedures
- Quality control measures
- Data reporting intervals and format
- Communication and data acquisition procedures
- Troubleshooting expectations/plan

[55] SMART SOLAR RESOURCE ASSESSMENTS, Marie Schnitzer, 2010

Installation

One of the first steps in the process is to categorize and buy the equipment which meets the measurement plan and goals. Prior to deploying equipment in the field, acceptance testing and inspection of each measurement device will ensure all inventory is accounted for and in proper condition for field deployment. During this inspection, broken or missing parts can be identified and components that do not meet technical specifications can be returned to the manufacturer for prompt replacement. To measure solar irradiance, you need the right hardware sensors. The best practice is to apply at least two pyranometers in the plane of the PV array, at least one pyranometer is required for each array orientation. Ensure the pyranometers are properly assigned to the different arrays for the calculation of the performance ratio (PR) and expected yield.

Advanced field preparation will save time and decrease the risk of problems requiring a costly return visit. Datalogger programming, communications protocol and checks, modem programming, properly packaged equipment and tools as well as a detailed installation plan will pave the way for a successful deployment and mobilization of the equipment.

For solar monitoring programs, field verification of the irradiance measurement equipment provides a means to identify a baseline relationship with high-quality measurement equipment. Assuming the reference instrumentation follows industry calibration standards, this verification provides increased confidence that the sensors were deployed correctly and will measure the solar resource as expected.

Re-examining the initial relationship, performed during the campaign or decommissioning, may be useful in identifying any sensor degradation or drift in the measurements. Awareness of these issues can then be integrated into the data analysis phases of the program.

During installation, it is important to document all aspects of the work. Site information logs and field commissioning forms will provide documentation to support the measurement plan goals and aid in future data analysis. Detailed site descriptions and photos, equipment listings which include the manufacturer, model and serial number of each sensor, telecommunications information and contact information are all key elements of good documentation.

Site Commissioning

Apt site commissioning comprises of on-site testing of all measurement equipment, confirming successful remote communications, and completing field verification. Commissioning tests include confirming that all sensors are reporting reasonable values, validating data logger programming inputs, attest data retrieval process and guarantee the data logger is properly operating. Assembling final documentation of field commissioning forms and site commissioning information offers thorough documentation and traceability through the monitoring period and prevents loss of valuable campaign knowledge.

Station Operation and Maintenance

The integrity of all system components necessities to be sustained and documented to guarantee smooth and continuous data collection through the monitoring period. Some instruments will need periodic calibration while other instruments need to be maintained on a more regular basis. To achieve this, a simple but thorough operation and maintenance plan that incorporates various quality assurance measures and provides procedural guidelines for all program personnel needs to be developed and implemented (please see GREBE RERA Wind for more details around those components).

Key elements of the plan include scheduled visits, inspection parameters, checklists and documentation logs, calibration, sensor integrity checks, training of maintenance staff, and spare parts inventories. Quality maintenance visits are conducted on a regular schedule and integrate approaches to document the cleanliness and operation of all sensors, provide feedback on weather conditions during the visit, and validate site security.

Monitoring, Validation and Reporting

Monitoring

The key aim of the data reporting and monitoring process is to safeguard the quality of the monitoring campaign by ensuring minimal data loss and identify any sensor anomaly or failure as promptly as possible. A practice of weekly or bi-weekly monitoring of communications and data completeness will help achieve this goal.

Validation

Upon collection of measurements, data validation assesses the quality of the data. Data validation involves the inspection of data for completeness and reasonableness while applying a method to detect and flag bad (invalid or suspect) values in the data record without rejecting falsely identified valid data. While a number of approaches can be used for data validation, no data-validation procedure is likely to discover every bad record and at times, good data may be wrongly rejected. Data validation is akin to any statistical decision process subject to both false positive and false negative errors. A good data-validation procedure seeks to minimize both types of error.

Reporting

Reporting the results of a measurement campaign on a regular basis allows the sponsor and/or stakeholders in a monitoring program regular access to validated data and operational updates. Transfer of post-processed data to a standard reporting template on a monthly or quarterly basis allows campaign and sponsoring managers to view measurement statistics (averages, maximum, and minimum values) that can be used to characterize the site. Upon completion of the monitoring program, a summary report for the year provides a more complete record of results and the measured data can then be used to estimate the long-term solar resource and energy production.

SolarPower Europe compiled a report on best practices for solar operations and maintenance and enhancing solar PV performance, as summarized below:

- To measure solar irradiance, you need the right hardware sensors. The best practice is to apply at least two pyranometers in the plane of the PV array, at least one pyranometer is required for each array orientation. Ensure the pyranometers are properly assigned to the different arrays for the calculation of the performance ratio (PR) and expected yield.
- Use record irradiance data from high-quality satellite-based data services as a complement to data from ground-based sensors.
- The accuracy of the temperature sensor, including signal conditioning, should be < ±1 °C. Very large plants should have measurement of module temperature at different places across the PV array. For large arrays, the module temperature should be measured at different representative positions (e.g. for a module in the center of the array and for modules at edge locations where temperature variation is expected).
- Measure ambient temperature and wind speed with the installation of a local meteorological station in accordance with the manufacturers' guidelines. Ambient temperature must be measured with a shielded thermometer.
- It is recommended to increase up-time for timely detection of faults. Measurement requirements using one second sampling and one minute averaging as the data logger is being used more and more.
- It is very important to collect all inverter alarms. Inverter alarms are a valuable source of information for fault detection, organization of the maintenance and even setting up preventive maintenance actions. Auto-configuration should be used when possible. This allows for inverter replacement detection.
- A high-accuracy energy meter for the total output of the plant with an uncertainty of ± 0.5% is required for plants greater than 100 kW and highly recommended for all plants – also those smaller than 100 kW.
- The AC switch positions for (sub) plants should be monitored and alarms should be relayed via the communication bus.
- As a minimum requirement, data loggers should have sufficient memory to store at least one month of data. Historical data should be backed up. After a communication failure, the data logger should automatically resend all pending information. As best practice, the data logger should store a minimum of six months of data and a full data backup in the cloud.

Global tools and data sources available online to make preliminary resource potential assessments

Global data resources

- **Global solar atlas**
  http://globalsolaratlas.info/

The World Bank and the International Finance Corporation, collectively The World Bank Group, have provided this Global Solar Atlas in addition to a series of global, regional and country GIS data layers and poster maps, to support the scale-up of solar power. The primary aim of this Global Solar Atlas is to provide quick and easy access to solar resource data globally, at the click of a mouse. GIS layers and poster maps showing global, regional, and country resource potential can be found in the Downloads section. Further description of the data provided, the methodology for estimating solar resource potential, and guidance on how to use it, can be found in the Knowledge Base section.

The Atlas provides long-term averages of solar resource (global, diffuse and direct normal), the principal climate phenomena that determines solar power generation. Understanding solar resource is crucial for the development of solar energy applications. In particular for the solar power sector, Photovoltaic (PV) technologies typically require an analysis on Global Horizontal Irradiation (GHI) and Global Tilted Irradiation (GTI, i.e. solar radiation received by the surface of photovoltaic modules). On the other hand, solar thermal energy technologies, such as Concentrated Solar Power (CSP) and Concentrated Photovoltaics (CPV), rely on Direct Normal Irradiation (DNI). Air temperature (TEMP) is also shown as it is the second most important climate variable determining the performance efficiency of solar power systems. Terrain elevation, relative to the sea level (ELE), also determines the choice of a site and performance of the solar energy system.

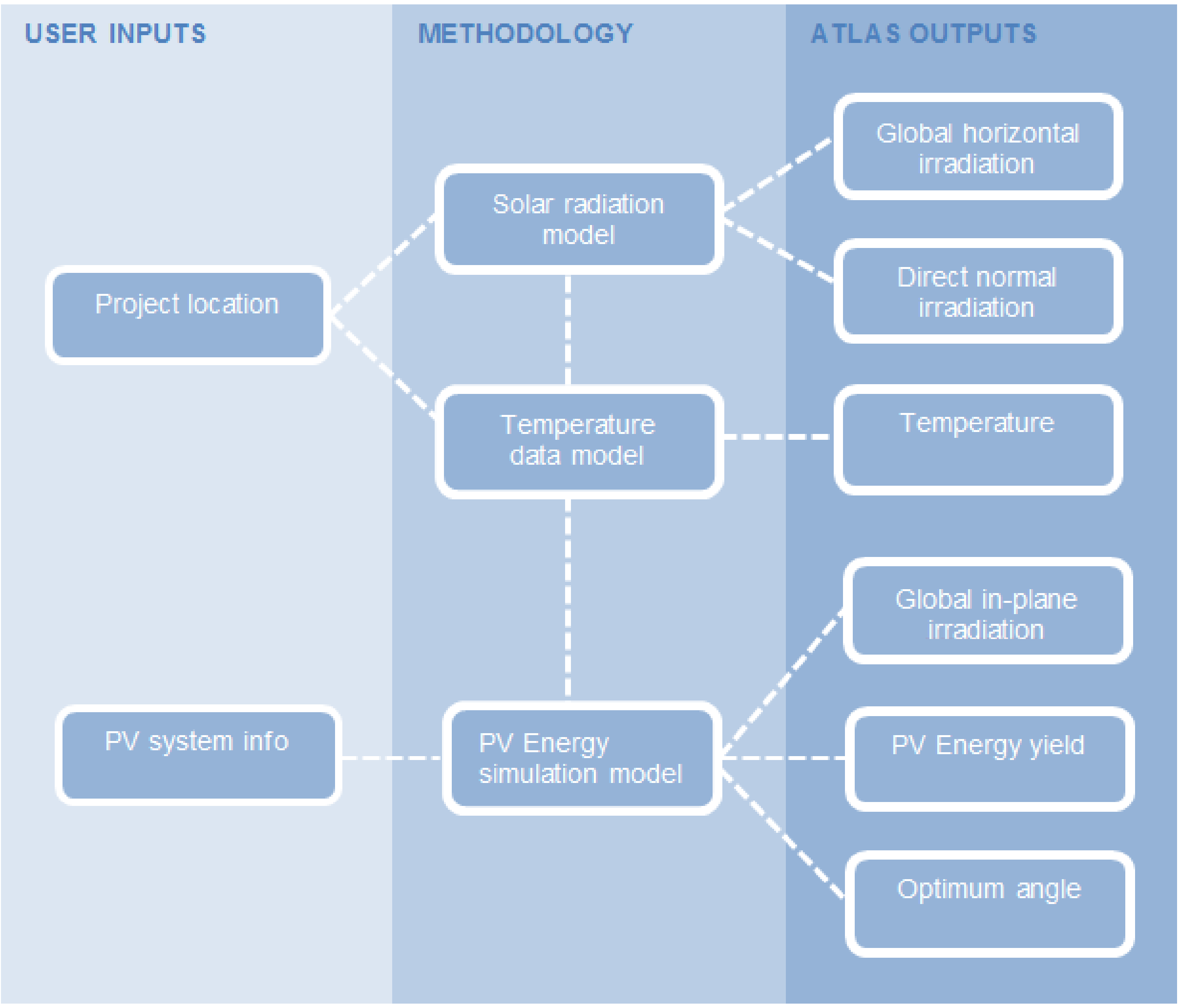
Photovoltaic (PV) is the most widely applied and also most versatile technology. Therefore this Atlas shows an indicative estimate of yearly average PV power generation values for three types of PV system: (i) small residential rooftop, (ii) distributed, or medium-size commercial roof-mounted system, and (iii) large or utility-scale PV power plant. The PV electricity simulation algorithm, incorporated in the Atlas, provides an approximate estimate of the potential photovoltaic energy (PVOUT), which can be produced at any location covered by the interactive map. This Atlas supports only the first stage of a solar energy project lifecycle: prospection and preliminary assessment.

Data time representation

The solar resource and PV power potential represent a time period from January 1994/1999/2007 until December 2015, depending on the satellite data coverage (see Figure below). Temporal resolution (time step) of solar resource depends on the satellite region, and this ranges between 10/15/30 minutes. Presently, Solargis processes data from three satellite data providers (EUMETSAT, Japanese Meteorological Agency and National Oceanic and Atmospheric Administration) with geostationary satellites operating at five key positions, to cover the entire world (except polar and subpolar regions). Air temperature data are derived from CFSR and CFSv2 meteorological models and they are available at the time step of 1 hour.

Solar resource, PV power potential, and air temperature data is aggregated long-term into yearly averages. The PV energy simulation is based on the use of re-computed and statistically aggregated 15-minute solar resource and air temperature data. This approach is consistent in terms of space and time, and it is provided as a quick assessment tool for exploration, site prospection and pre-feasibility analysis.

How it works



- **Photovoltaic Geographical Information System (PVGIS)**
  http://re.jrc.ec.europa.eu/
  - TYPICAL METEOROLOGICAL YEAR GENERATOR
    http://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#TMY
    A typical meteorological year (TMY) is a set of meteorological data with data values for every hour in a year for a given geographical location. The data are selected from hourly data in a longer time period (normally 10 years or more). The TMY can be used to interactively visualise all the data or to download as a text file.
  - MONTHLY SOLAR RADIATION DATA
    http://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#MR
    Calculate the monthly averages of solar radiation for the chosen location, shown in graphs or tables how the average solar irradiation varies over a multi-year period. The results are given for radiation on horizontal and/or inclined planes, as well as Direct Normal Irradiation (DNI).
  - DAILY SOLAR RADIATION DATA PROFILE
    http://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#DR
    Average solar irradiation for each hour during the day for a chosen month, with the average taken over all days in that month, during the multi-year time period for which we have data. In addition to calculating the average of the solar radiation, the daily radiation application also calculates the daily variation in the clear-sky radiation, both for fixed and sun-tracking surfaces.
  - HOURLY SOLAR RADIATION AND PV DATA
    http://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#HR
    Get the full data set of solar radiation and other data needed to calculate PV power hour by hour for long time periods. PVGIS can also perform the hourly PV power calculation. In this case the amount of data is so large that the only output option is to download the data in CSV format.
  - PERFORMANCE OF GRID-CONNECTED PV SYSTEMS
    http://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#PVP
    This tool makes it possible to estimate the average monthly and yearly energy production of a PV system connected to the electricity grid, without battery storage. The calculation takes into account the solar radiation, temperature, wind speed and type of PV module. The user can choose how the modules are mounted, whether on a fixed mounting at a certain slope and orientation, or on a sun-tracking mounting. PVGIS can also calculate the optimum slope and orientation that maximizes the yearly energy production.
  - PERFORMANCE OF SUN-TRACKING GRID-CONNECTED PV SYSTEMS
    http://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#PVTR

- **Renewables Ninja**
  https://www.renewables.ninja/
  Renewables ninja allows you to run simulations of the hourly power output from solar power plants located anywhere in the world.
- **PV*SOL**
  http://pvsol-online.valentin-software.com/#/
  Made by the developers of the full featured market leading PV simulation software, this online tool lets you input basic data like:
    - Location of your system
    - Load profile and annual energy consumption
    - PV module data (manufacturer, model, orientation, quantity etc.)
    - Inverter manufacturer

- **EARTHDATA**

  https://earthdata.nasa.gov/

The Earth Observing System Data and Information System (EOSDIS) is a key core capability in NASA's Earth Science Data Systems (ESDS) Program. It provides end-to-end capabilities for managing NASA's Earth science data from various sources – satellites, aircraft, field measurements, and various other programs.

- **Corine Land Cover 2006**

  http://maps.eea.europa.eu/EEAGalleryBasicviewer/v1/?appid=f9b34d047a154184805687707eb7dfe5&group=9a0c196cb389491ea114eaca9fb07b5e

CORINE Land Cover (CLC) is a geographic land cover/land use database encompassing most of the countries of Europe.

Protected Areas

- **Protected planet** – https://www.protectedplanet.net/

  Protected Planet is the most up to date and complete source of information on protected areas, updated monthly with submissions from governments, non-governmental organizations, landowners and communities.

- **EUNIS** - https://eunis.eea.europa.eu/index.jsp

  The European nature information system, EUNIS, brings together European data from several databases and organisations into three interlinked modules on sites, species and habitat types.

Northern Periphery and Arctic Programme 2014–2020

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GREBE

Generating Renewable Energy Business Enterprise

@ GREBE_NPA

GREBEProject

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Project Partners

GREBE will be operated by eight partner organisations across six regions:

WDC

Action Renewables
the future of energy, today

Luke
NATURAL RESOURCES INSTITUTE FINLAND

FORSKNINGSPARKEN I NARVIK

eri

Fermanagh & Omagh District Council
Comhairle Ceantair Fhear Manach agus na hÓmaí

Innovation Center Iceland

Karelia

About GREBE

GREBE is a €1.77m, 3-year (2015-2018) transnational project to support the renewable energy sector. It is co-funded by the EU's Northern Periphery & Arctic (NPA) Programme. It will focus on the challenges of peripheral and arctic regions as places for doing business, and help develop renewable energy business opportunities provided by extreme conditions.