SOLAR & PV OPTIMAL SPOT

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What is Solar & PV Optimal Spot

Solar & PV Optimal Spot is a mobile application developed by Simone Rizzo and Lorenzo Giannuzzo that estimates the optimal orientation and inclination of a solar or a PV collector. The physics of the arithmetical problem is based on hourly irradiance calculations referring to satellite data given by PVGIS. Through simple and innovative graphics the application guides the user to the reading of the enormous quantity of data that PVGIS offers using their related API shown at the link https://ec.europa.eu/jrc/en/pvgis.

What is PVGIS

PVGIS is a web application that allows the user to get data on solar radiation and photovoltaic (PV) system energy production, at any place in most parts of the world. It is completely free to use, with no restrictions on what the results can be used for, and with no registration necessary. PVGIS can be used to make a number of different calculations.

Introduction to solar radiation

The solar radiation that reaches the top of the atmosphere on a perpendicular plane to the rays, known as solar constant, has an average value of 1361-1362 W/m^2 which varies somewhat depending on the position of the Earth in its elliptical orbit.

As the solar radiation goes through the atmosphere it suffers different processes of absorption, dispersion or scattering that result in lower levels of solar radiation being received at the Earth's surface. These are due to the atmosphere components, such as ozone or CO_2, and solid and liquid particles in suspension like aerosols or water vapour. However, the main source of attenuation is the cloud cover. Not only the broadband value is different, but also these processes of absorption and attenuation affect differently the wavelengths of solar radiation, so the spectral distribution of the solar radiation at ground level differs from the extraterrestrial one.

The solar radiation received at ground level, known as global radiation is sum of three components. The first one, named beam or direct radiation, is the fraction of the solar radiation that reaches the ground without being attenuated by the atmosphere and can be modelled as coming directly from the solar disc. The second part or diffuse is the solar radiation that reaches the ground after being reflected or scattered by the atmosphere and is considered to arrive from the whole sky dome. The third component, not always taken into account, is the reflected radiation from the ground surface or nearby obstacles. The beam component is only available when the solar disc is not blocked by clouds, while the diffuse component is always available, being the only radiation available whenever clouds block the solar disc.

Solar radiation under clear sky conditions (without clouds) and clean and dry atmosphere is a very important parameter as it provides information about the maximum radiation available at any location. This value is normally modelled and is used as input data for other models applied for the estimation of the solar radiation at normal atmospheric conditions.

Through the pages of PVGIS web, we talk about solar radiation and use it in a generic way but we also use other terms that should be explained. Concepts like irradiance and irradiation should be clarified. Irradiance is the solar power falling into a surface per unit area and unit time. It is therefore expressed in W/m^2. While irradiation is the amount of solar energy received per unit area during a period of time, therefore energy and it is expressed in Wh/m^2. The data provided by PVGIS contains both irradiance and irradiation values.

Estimating the solar radiation intensity

There is little doubt that the very best way to measure solar radiation is to use high-quality sensors on the ground. But to be useful, these measurements should fulfill a number of conditions:

- Only high quality measurement sensors should be used.
- Measurements should be performed at least every hour.
- Sensors should be calibrated regularly.
- Sensors should be cleaned regularly.
- Data should be available for a long time period, preferably 10 years or more.

The number of ground-based radiation measurements that fulfill all these criteria is relatively low and the stations are often spaced far apart.

For these reasons it has become more and more common to use satellite data to estimate the solar radiation arriving at the earth surface. Mostly these methods use data from geostationary meterological satellites. The advantages of using such data are:

- solar radiation data are then available in the whole of the area covered by the satellite images, for instance, the METEOSAT satellites cover Africa, Europe and most of Asia up to about 60°N, with an image resolution of a few kilometers.
- normally long time series are available, up to 30 years or more.

The disadvantage of using satellite data is that the solar radiation at ground level must be calculated using a number of fairly complicated mathematical algorithms which use not just satellite data but also data on atmospheric water vapour, aerosols (dust, particles) and ozone. Some conditions can cause the calculations to lose accuracy, for example:

- snow which can be mistaken for clouds
- dust storms which can be difficult to detect in the satellite images

Geostationary satellites also have the limitation that they don't cover polar areas. Nevertheless, the accuracy of satellite-based solar radiation data is now generally very good. For this reason, most of the solar radiation used in PVGIS are based on the satellite algorithms.

Another source of solar radiation estimates is from Climate Reanalysis Data. Reanalysis data are calculated using numerical weather forecast models, re-running the models for the past and making corrections using the known meteorological measurements. The output of the models is a large number of meteorological quantities, often including the solar irradiance at ground level. Several of these data sets have global coverage, including the polar areas where the satellite methods do not have data. The disadvantages of these data sets is that they mostly have low spatial resolution (one value every 30km or more), and that the accuracy of the solar radiation values generally is not as good as the satellite-based solar radiation data over the areas covered by both types of data sets.

For the release of PVGIS 5 we have made use of two reanalysis-based solar radiation data sets:

- ECMWF ERA-5, produced by the European Centre for Medium-range Weather Forecast (ECMWF). This data set has global coverage at a resolution of about 30km, and includes both global and direct solar irradiance. At the time of writing, only the time period 2010-2016 has been released, with a longer time period to follow during 2018.
- COSMO-REA is a regional reanalysis product, covering Europe and Northern Africa [*Bollmeyer et al., 2015*]. The spatial resolution is about 6km (we use 3 arc-minutes in PVGIS), and the data are available at hourly time resolution for the period 1995-2015, although in PVGIS only the interval 2005-2015 is used at present.

COSMO-REA is limited in geographical extent to Europe and parts of Northern Africa. In contrast, ERA-5 has global coverage. However, for the PVGIS 5 release we are making these two databases available with the same extent, covering only Europe.

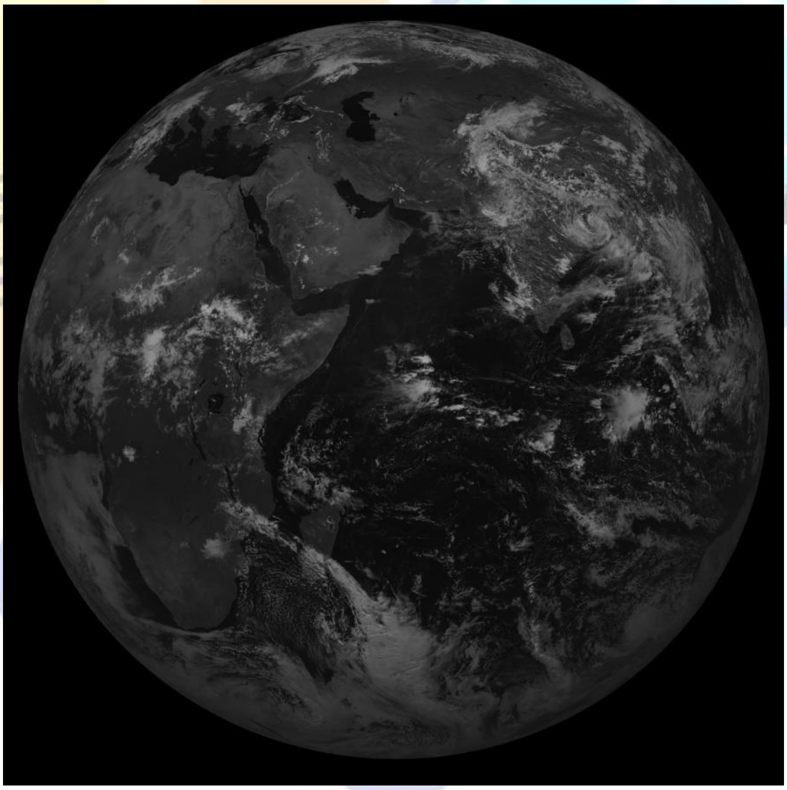
More information about the new reanalysis-based solar radiation data can be found here.

Calculation of solar radiation from satellite

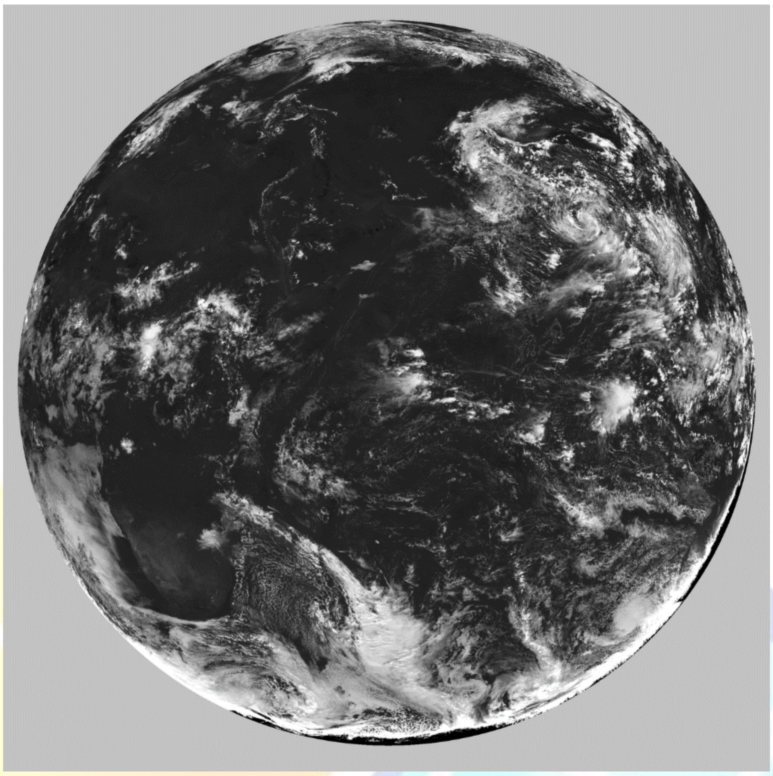
The methods used to calculate the solar radiation from satellite have been described in a number of scientific papers (*Mueller et al., 2009, Mueller et al., 2012, Gracia Amillo et al., 2014*). Here we will only give a brief outline of the methods. This description is for the calculations of solar radiation over Eurasia and Africa (the PVGIS-CMSAF and PVGIS-SARAH databases). The data from the NSRDB data set have been calculated using different methods (*Habte et al., 2017*).

The first step in the calculation is to use the satellite images to estimate the influence of clouds on the solar radiation. Clouds tend to reflect the incoming sunlight so that less radiation arrives at the ground.

The reflectivity of the clouds are calculated by looking at the same satellite image pixel at the same time every day in a month. The method then assumes that the darkest pixel in the month is the one that corresponds to clear sky (no clouds). For all the other days the cloud reflectivity is then calculated relatively to the clear-sky day. This is done for all hours in the day. In this way, an *effective cloud albedo* can be calculated. The figure below shows an example of the raw satellite image and the effective cloud albedo calculated from the image. Notice how the land surfaces are visible in the first image but in the second only the clouds are left.

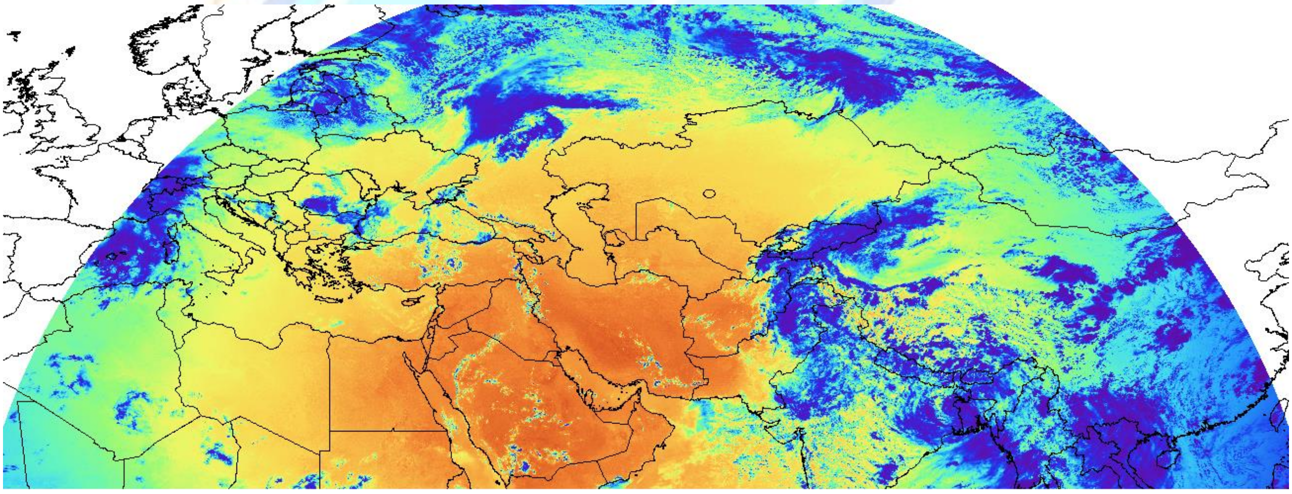


Raw satellite image from METEOSAT-7 over the Indian Ocean



Effective cloud albedo calculated from the satellite image taken at 2015-08-01 09:00 UTC.

In a second step the method calculates the solar radiation at clear sky conditions (i.e. no clouds) using the theory of radiative transfer in the atmosphere together with data on how much aerosols (dust, particles, etc.) there are in the atmosphere and the concentration of water vapour and ozone, both of which tend to absorb radiation at particular wavelengths. The total radiation is then calculated from the cloud albedo and the clear-sky irradiance. The image below shows the global horizontal irradiance calculated using the cloud albedo shown in the image above.



Global horizontal irradiance (W/m2) at 2015-08-01 09:00 calculated from METEOSAT-7 image

The method generally works well but may fail in some cases. For instance, if there is snow on the ground this may be seen as clouds by the method which then calculates too low irradiance. Also, the aerosol information used for the calculation consists of averages over many years, so short-term changes in aerosols, for instance due to dust storms or volcanic eruptions are not so well captured by the method.

For the present version of PVGIS, the satellite data used for the solar radiation estimates are from the METEOSAT satellites covering Europe, Africa and most of Asia. Depending on the type of satellite, images are captured every 15 minutes or 30 minutes. For PVGIS we have used one image per hour. The resolution of the satellite images varies, it is highest just below the satelllite (nadir) and decreases when moving towards the edge of the image. At nadir the resolution is about 4km.

Data availability

The algorithms used for the satellite-based solar radiation data present in PVGIS have been developed within the CM SAF collaboration. The solar radiation data used in PVGIS are also available directly from CM SAF via the web user interface.

Recently we have collaborated with the National Renewable Energy Laboratory to include the NSRDB data into PVGIS. This extends the coverage to North and Central America.

Validation of the satellite-based solar radiation data

The solar radiation data produced from the satellite images must be checked against measurements at ground level to get an idea of how large uncertainty there is in the satellite-based solar radiation data. This is known as the validation of the data.

A number of scentific papers have presented validation results for the satellite solar radiation data used in PVGIS by comparing with ground station measurements (*Mueller et al., 2009, Mueller et al., 2012, Huld et al., 2012, Gracia Amillo et al., 2014*). Here we will only present the basic results of the validation. Most of the ground station measurements are from the Baseline Surface Radiation Network (BSRN), which provide high-quality solar radiation measurements for stations across the world.

Location	Latitude	Longitude	% difference between satellite and station		Reference
			PVGIS-CMSAF	PVGIS-SARAH	
Lindenberg (DE)	52.22N	14.12E	-3.4	-3.2	[1,3]
Cabauw (NL)	51.97N	4.93E	+0.4	-0.4	[1,3]
Carpentras (FR)	44.05N	5.03E	+2.1	+5.5	[1,3]
Payerne (CH)	46.81N	6.94E	-3.0	+0.6	[1,3]
Belsk (PL)	51.70N	20.8E	-5.5	NA	[1]
Camborne (UK)	50.22N	5.32W	+3.0	-1.9	[4,3]
Toravere (EE)	58.27N	26.47E	+5.1	-4.1	[4,3]

Location	Latitude	Longitude	% difference between satellite and station		Reference
			PVGIS-CMSAF	PVGIS-SARAH	
Sde Boqer (IL)	30.87N	34.77E	-3.3	+3.4	[4,3]
Almeria (ES)	37.50N	2.2W	-0.9	NA	[4]
Geneve (CH)	46.12N	6.01E	+2.6	NA	[4]
Nantes (FR)	47.25N	1.55W	+3.8	NA	[4]
Vaulx-en-Velin (FR)	45.78N	4.93E	+3.9	NA	[4]
Kishinev (MO)	47.00N	28.82E	+0.4	+1.4	[4,3]
Liepaja (LV)	56.48N	21.02E	+2.5	NA	[4]
Sonnblick (AT)	47.05N	12.95E	-14.0	NA	[4]
Thessaloniki (GR)	40.63N	22.97E	+5.9	+3.6	[4,3]
Wien Hohe Warte (AT)	48.25N	16.35E	-1.5	NA	[4]
Ispra (IT)	45.81N	8.64E	+8.4	+9.0	[4]
Milano (IT)	45.48N	9.26E	-0.5	NA	[4]
Roma (IT)	41.86N	12.62E	+4.1	NA	[4]
Sarreguren (ES)	42.82N	1.60W	+1.6	NA	[4]
A Coruna (ES)	43.37N	8.42W	+11.0	NA	[4]
Lleida (ES)	41.62N	0.60W	+2.4	NA	[4]
Madrid (ES)	40.45N	3.72W	-0.3	NA	[4]
Tamanrasset (DZ)	22.78N	5.51E	-6.0	+2.6	[4,3]
De Aar (ZA)	30.67S	23.99E	+2.2	+0.6	[4,3]
Solar Village (SA)	24.91N	46.41E	+3.2	-0.2	[4,3]
Florianopolis (BR)	27.53S	48.52W	NA	+0.3	[3]
Cocos Island (AU)	12.19S	96.84E	NA	+0.6	[3]
Xianghe (CN)	39.75N	116.96E	NA	+0.8	[3]

Calculation of solar radiation on inclined planes

The satellite based calculation described above produces values of global and beam irradiance on a horizontal plane, both broadband and spectrally resolved irradiance values.

However, modules and PV systems are generally installed at an inclined angle with regard to the horizontal plane or on tracking systems, so as to maximize the received in-plane irradiance. Therefore, the satellite retrieved irradiance values are not representative of the solar radiation available at the module surface, and it becomes necessary to estimate the in-plane irradiance.

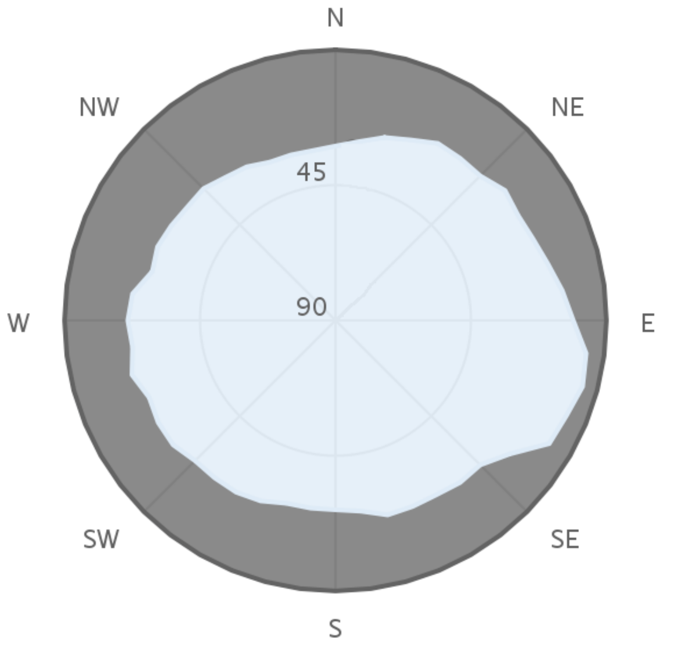
There are several models in the scientific bibliography which use as input data the irradiance values on the horizontal plane of global and diffuse and/or beam irradiance components, to estimate the values of the beam and diffuse components on tilted surfaces. The sum of those is the in-plane global irradiance on a tilted surface. The beam irradiance comes directly from the solar disc, so the value on a tilted surface can be easily calculated from the value on the horizontal plane just knowing the sun position in the sky and the inclination and orientation of the inclined surface. On the contrary, the estimation of the diffuse component over tilted surfaces is not so straightforward, as it has been scattered by the atmosphere's components and as a result can be described as coming from the whole sky dome.

The way the diffuse component is defined is the main difference between the various estimation models. A comparison of some of these models can be found in *Gracia Amillo and Huld, 2013*. Models can be divided in two main categories, isotropic and anisotropic. The first group considers the diffuse irradiance to be uniformly distributed (isotropic) over the sky dome, similarly to what is observed under overcast situations. Under this assumption, the diffuse irradiance on a tilted surface is the value on the horizontal plane scaled by a factor that depends only on the inclination of the surface and accounts for the portion of the sky dome that is visible from the plane's surface.

However, the diffuse irradiance is hardly ever isotropic. Changing cloud cover but even in cloudless situations, it is easy to distinguish regions with different brightness. Besides the isotropic background, a bright area around the sun is easily noticeable. And depending on the cloud cover there may be bright regions around the zenith or the horizon. How these regions are estimated and considered vary between the anisotropic models. They can be classified in two groups, depending on how many regions are used beside the isotropic background. Whether they consider the circumsolar and/or horizon band.

The estimation model implemented in PVGIS is the one developed by *Muneer T. (1990)* which can be classified as anisotropic of two components. It performs similarly as other more complex models like the anisotropic models of three components like those developed by Perez or Reindl. In fact, the Muneer model proved the best performance in the study carried out by ESRA (2000). It distinguishes between clear and overcast sky conditions and sunlit and shaded surfaces.

Influence of shadows from terrain



Horizon height plot (in degrees) for a location in the Italian Alps.

If you are near to hills or mountains there may be times when the sun is behind the hills and the solar radiation will be reduced to that coming from the sky or clouds. PVGIS uses information about the elevation of the terrain with a resolution of 3 arc-seconds (about 90m). This means that for every 90m we have a value for the ground elevation. From these data we have calculated the height of the horizon around each geographical location. These data are then used to calculate the times when the sun is shadowed by hills or mountains. When this happens the solar radiation is then calculated using only the diffuse part of the radiation. The calculations done within PVGIS can all make use of this information.

An example of the horizon height around a geographical point is shown in the next figure for a location in the Italian Alps (Macugnaga). The horizon is high except towards the east which is the direction down-valley from that place.

With a resolution of ~90m the calculations in PVGIS cannot take into account the effects of shadows from nearby objects such as houses or trees. However, PVGIS has the option to let the user upload a data file with the horizon height to use instead of the built-in horizon information.

Calculation of PV power output

The most important factor for the energy output of a PV system is of course the amount of solar radiation that arrives at the PV modules. But there are other factors that are important too. This chapter explains about the different effects that influence PV output and how they are calculated in PVGIS.

Nominal power of PV modules

When the power of a PV module is measured in the laboratory or at the factory, this is done under standardized conditions, known as the Standard Test Conditions (STC). These standard conditions are determined by the international standard IEC-60904-1. These conditions are:

- The light intensity (irradiance) should be 1000W/m² on the whole surface of the module. This value is about
- what you have at noon on a sunny day when the module is facing towards the sun, though under real conditions the irradiance may sometimes be even higher.
- The module temperature should be 25°C.
- The spectrum of the light should be equal to the global spectrum given in IEC 60904-3. This spectrum corresponds to the spectrum you find on a sunny day with the sun about 40° above the horizon and with the module inclined about 40° from horizontal facing the sun.

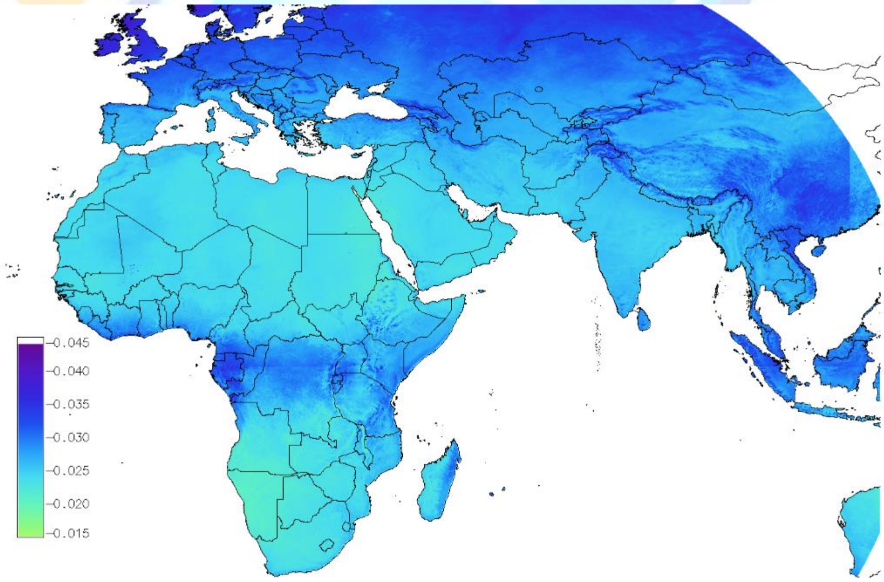
The power measured at STC is called the nominal power or peak power.

Estimating the real power output of PV modules

When the PV modules are mounted outdoors, the conditions can be very different from these standard conditions and therefore also the power output will be very different. PVGIS makes corrections for a number of different effects that influence PV power.

Shallow-angle reflection

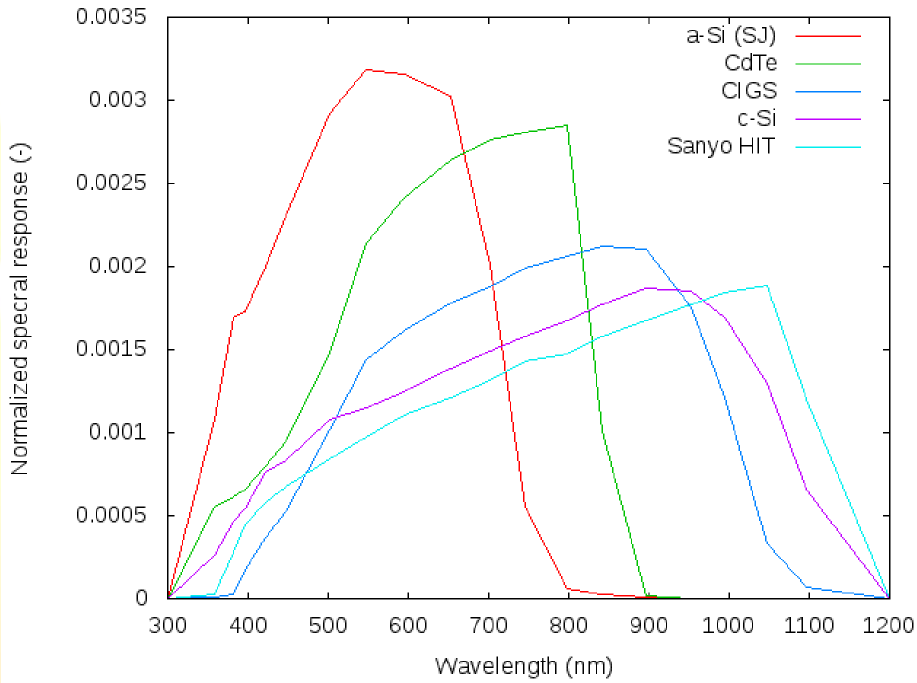
When light hits the PV module surface some of it will be reflected away without entering the module. For most module types the amount of light reflected away will increase if the light falls on the module at a sharp angle, and when the light is close to parallel to the module surface nearly all the light will be reflected away. This is calculated using a mathematical model described in (*Martin&Ruiz, 2001, Martin&Ruiz, 2013*). Generally, this effect causes a loss of 2-4% of the sunlight, though this will be lower for sun-tracking PV systems (*Huld et al., 2015*). Figure 3 shows a map of this effect. The calculation for this map used a module inclination of 20 degrees facing the equator.



Influence of reflectivity at sharp angles on PV modules on the energy output. The values in the map are the fraction of energy lost, i.e. a value of -0.02 corresponds to a 2% average loss over the year.

Effect of changes in the solar spectrum

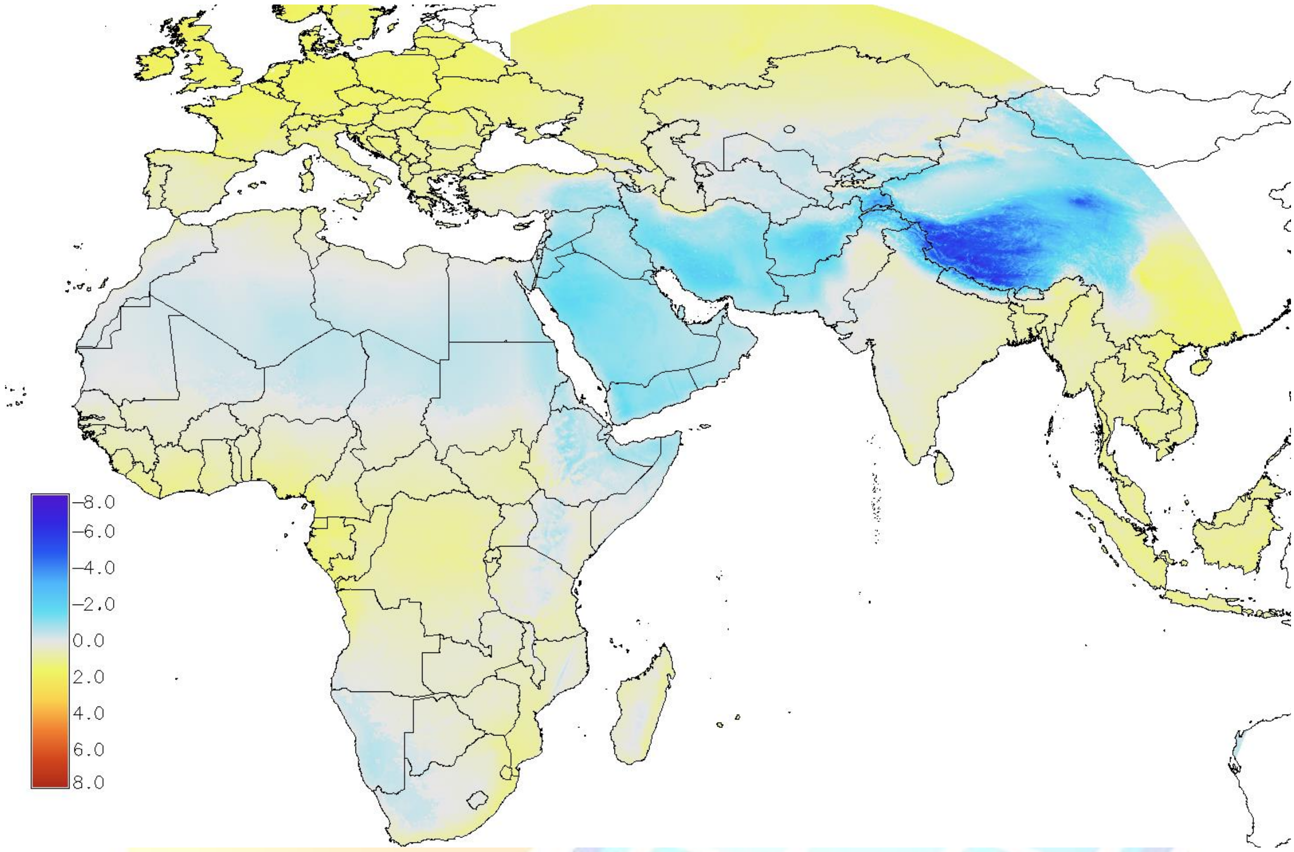
PV modules are sensitive to light only within a certain range of wavelengths. The range depends on the type of module. The curve of sensitivity is known as the spectral response. The next figure shows the spectral response curves for a number of PV technologies. Some PV technologies are sensitive to both visible and near-infrared radiation (for instance crystalline silicon) while others are more restricted towards the visible part of the spectrum (such as amorphous silicon). The measurements were performed at the European Solar Test Installation (ESTI) of the Joint Research Centre.



Spectral sensitivity of different PV technologies. Shown are sensitivity curves for crystalline silicon (c-Si), CIGS, Cadmium Telluride (CdTe), single-junction amorphous silicon (a-Si) and a Sanyo HIT heterojunction module.

The spectrum of sunlight changes with time of day and with the meterological conditions. It is well known that sunlight is more red near sunrise and sunset. It is perhaps less well known that light coming from the clouds has a higher content of blue light and decreased red light. All this means that the PV power will depend on the spectrum of the sunlight.

We have used solar radiation data from satellite that have been calculated for different spectral bands (*Mueller et al., 2012*) to calculate the effect of spectrum changes on the PV energy output. Maps of the calculations results can be found in *Gracia et al, 2014* and *Huld & Gracia Amillo, 2015*. The spectral effects have been calculated for crystalline silicon and for Cadmium Telluride modules. These results are included in the PVGIS calculations for these two module types. The next figures show the effect of spectral variations on energy output for two PV technologies. The maps show the percentage increase (or decrease) in the energy output due to spectral effects, i.e. value of -3 means the spectral effects cause a decrease in the energy output of 3%.



Effect of spectral variations on PV energy output for crystalline silicon

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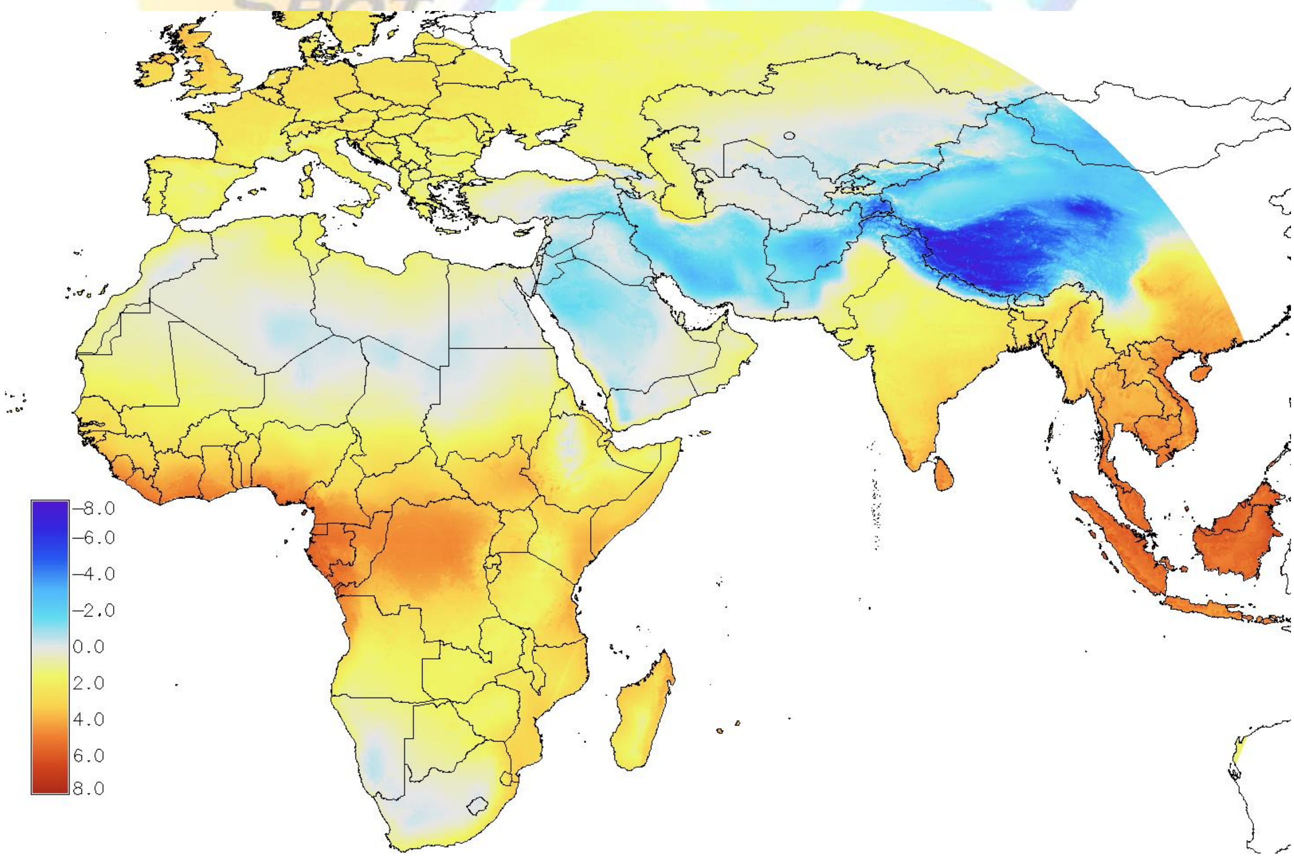
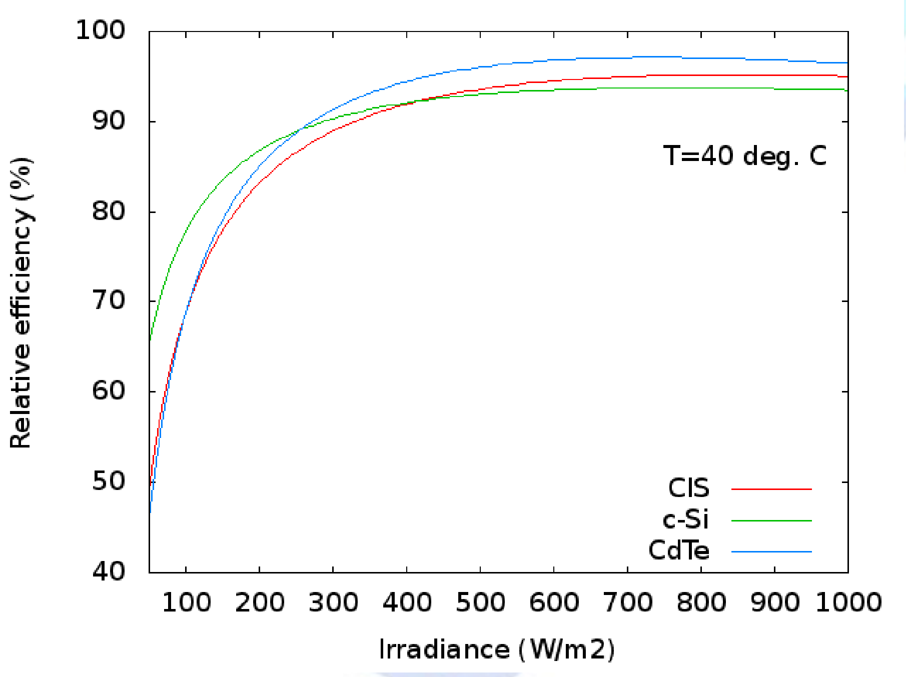


Effect of spectral variations on PV energy output for CdTe

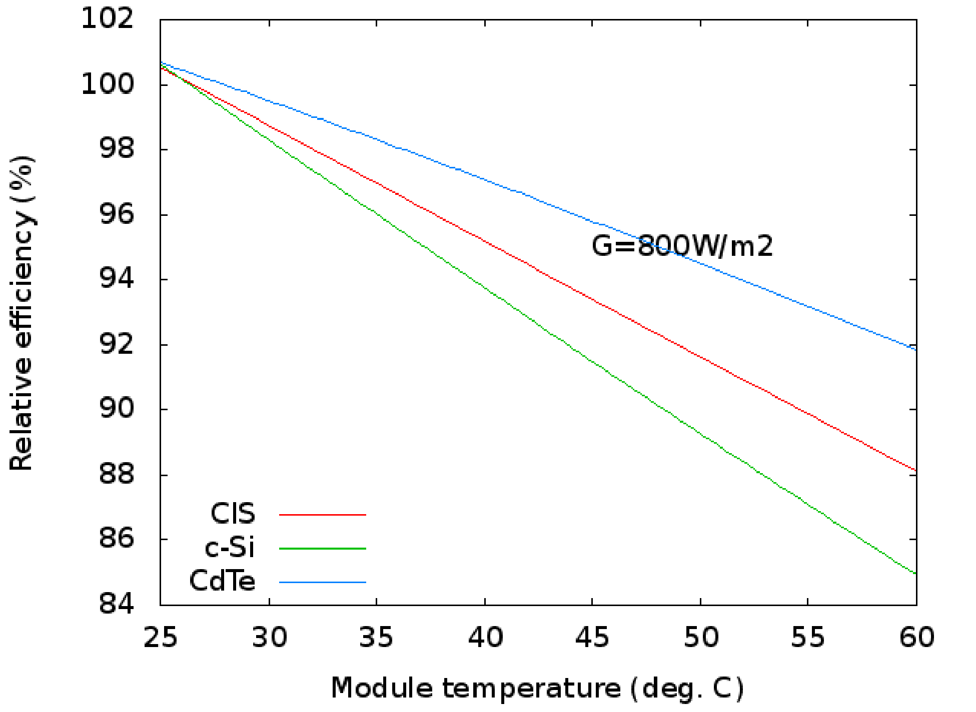
PV power dependence on irradiance and module temperature

The efficiency of PV modules depends on the temperature of the module and on the solar irradiance. Generally, the efficiency decreases with increasing temperature, and the strength of this effect depends on the PV technology. For most module types, the efficiency is nearly constant for irradiances from about 400W/m^2 to at least 1000W/m^2 (for constant module temperature), but at lower irradiance the efficiency tends to decrease. Since the standard test conditions measure module power at high irradiance (1000W/m^2) and fairly low temperature (25°C) the overall result is that for most places the average module efficiency is a bit lower than the efficiency measured at the factory.

The next figure shows the effects of temperature and irradiance for a number of PV module types. The curves show the relative efficiency, that is, the module efficiency as a percentage of the efficiency measured at STC. The first one, shows the relative efficiency at constant temperature T=40°C at different irradiance levels; while the second shows the relative efficiency at constant irradiance at different module temperatures. The measurements were performed at [the European Solar Test Installation (ESTI) of the Joint Research Centre.]



Relative efficiency (compared to the efficiency at STC) of three PV technologies: crystalline silicon (c-Si), CIGS, and Cadmium Telluride (CdTe).



Relative efficiency (compared to the efficiency at STC) of three PV technologies: crystalline silicon (c-Si), CIGS, and Cadmium Telluride (CdTe).

PVGIS calculates the effects of irradiance and module temperature using a model described in (*Huld et al., 2011*), The power is assumed to depend on irradiance G and module temperature Tm in the following way:

[*1*] $P = G/1000 * A*eff(G,T_m) = G/1000*A*eff_{nom} * eff_{rel}(G,T_m)$

[*2*] $eff_{rel}(G',T'_m)=1+k_1\ln(G')+k_2\ln(G')^2 +k_3T'm +k_4T'_m\ln(G') +k_5T'm\ln(G')^2 +k_6T'_m{}^2$

where $G'=G/1000$ and $T'_m=T_m-25$.

The coefficients k_1 to k_5 are found for each PV technology by fitting to measured data. The coefficients used in PVGIS are based on measurements performed at ESTI and are given in the next table.

Coefficient	**c-Si**	**CIS**	**CdTe**
k_1	-0.017237	-0.005554	-0.046689
k_2	-0.040465	-0.038724	-0.072844
k_3	-0.004702	-0.003723	-0.002262
k_4	0.000149	-0.000905	0.000276
k_5	0.000170	-0.001256	0.000159
k_6	0.000005	0.000001	-0.000006

Module temperature

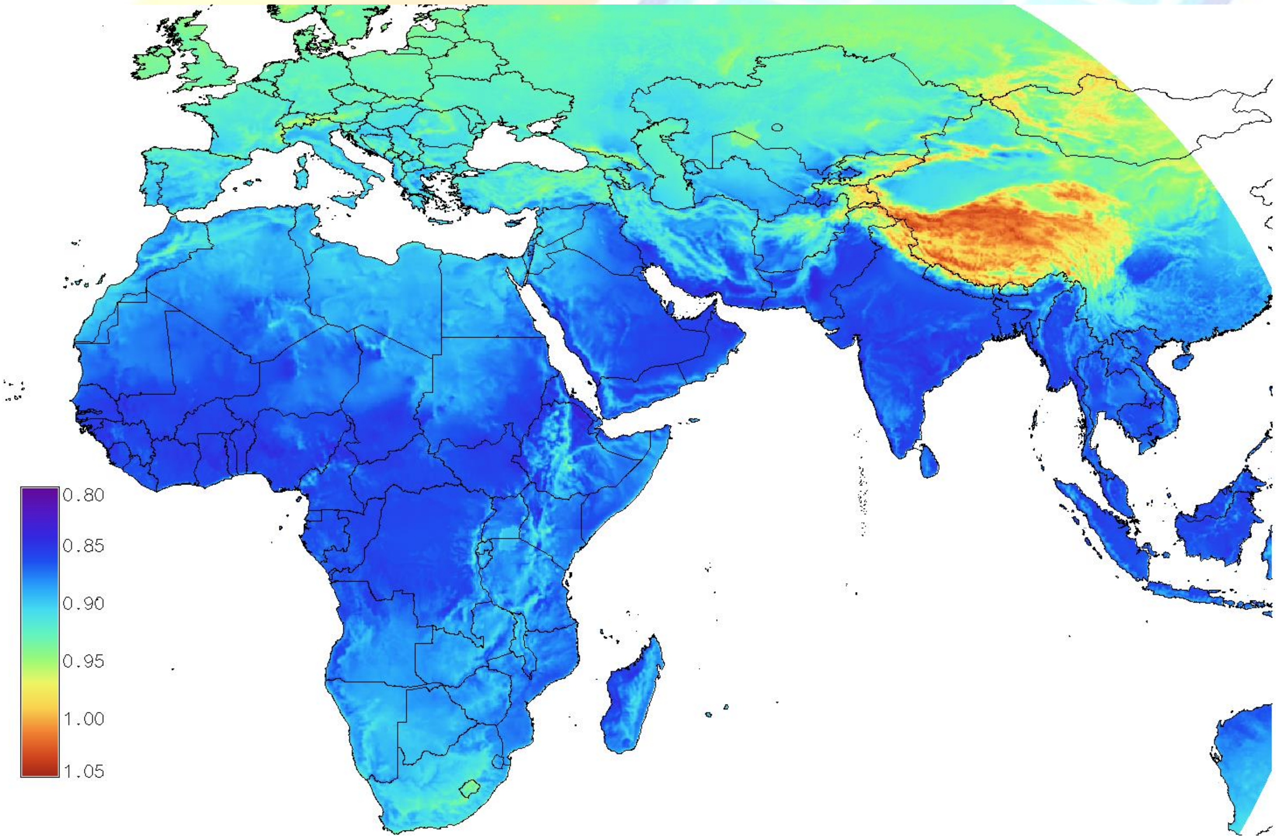
When the sun shines on the PV modules the temperature of the modules will rise above the local air temperature. This means that the module temperature depends on both air temperature and the irradiance (strictly speaking the irradiance corrected for reflectivity since light that is reflected away will not heat the module). In addition, if there is wind it may help to cool the modules.

These effects are treated in PVGIS using a model suggested by Faiman (*Faiman, 2008*). The module temperature Tm can be calculated as:

[***3***] $T_m = T_a + G/(U_0+U_1W)$

Here, T_a is the air temperature and W is the wind speed. The coefficients U_0 and U_1 used in PVGIS have been taken from the paper of (*Koehl et al, 2011*).

The overall change in PV output due to all the effects described above are shown in the next figure and can also be found in *Huld &Gracia Amillo, 2015*.



Relative efficiency (compared to the efficiency at STC) for crystalline silicon (c-Si), taking into account all the effects (reflectivity, spectral effects, temperature and low irradiance).

System losses and degradation with age

All the calculations described above will in the end give the PV power that can be delivered at the connectors of the module (or array). But before the power arrives at the grid it must be transformed into AC current by the inverter, which causes another loss. There are also losses in cables and because the modules are not all exactly the same power. At the moment we do not have enough information to calculate all these effects, so the loss can be input by the user.

In addition the power of PV modules tends to decrease slowly with age. A large study (*Jordan and Kurtz, 2013*) found that PV modules typically lose about 0.5% of power per year of operation. With an expected system lifetime of 20 years this would mean that the power at the end of the 20 year period the power would be down to 90% of the original power and on average over 20 years the power would be 95% of the original power.

Considering the system losses and the losses due to ageing we recommend a value of 14% for the "system loss" that the user gives as input to PVGIS.

Other effects not considered in PVGIS

There are a number of other effects that can influence the energy output of PV systems. These effects are not included in the PVGIS calculations. Among these are:

- Snow. If the PV modules are covered (even partially) by snow the energy output is typically very low. This effect depends on how often it snows but even more importantly on how long the snow stays on the modules before melting or sliding off. This in turn depends on the temperature but also on the module inclination and how the modules are installed.
- Dust and dirt. In areas with a lot of dust in the air the modules will tend to be covered in dust. How long the dust stays on the modules depends on rainfall and on the inclination of the modules. The effect will of course be different if the modules are cleaned from time to time.
- Partial shadowing. If only a part of a PV module is in shadow it may reduce the energy output strongly. This effect is very local and depends on the exact way the modules are installed. At the moment we have no way of taking this into account, but it should of course be considered when installing the PV system.

Calculation of PV electricity cost

PVGIS can calculate the cost of electricity produced by a grid-connected PV system. The calculation takes into account the cost of buying and installing the PV system, the cost of maintenance, and the cost of financing. All these costs are then compared with the estimated PV energy production during the expected lifetime of the system.

The calculation of PV electricity cost is done using a "Levelized Cost Of Energy" (LCOE) method. In this calculation an initial loan is used to pay the whole cost of the PV system and is repaid in fixed yearly installments until the end of the lifetime of the system. In addition to the repayment of the loan the calculation assumes that operation and maintenance of the system will be 2% of the original cost of the system every year of the life of the system.

The calculation is described in more detail in the report by (*Huld et al., 2014*).

Calculation of off-grid PV system performance

It is more complicated to calculate the performance of off-grid PV systems than to estimate the energy production by grid-connected PV systems. Grid-connected systems can send any power not consumed locally to the grid, which then acts as an infinitely large battery. For off-grid PV systems the energy produced by the PV system cannot be transported away and must either be consumed or stored, typically in batteries. This makes it more difficult to estimate the PV energy production, because it depends on the energy consumption, and it will depend on when the energy is consumed. If there is too much energy left over when the consumption needs have been met, the battery will become full and the PV power will have to drop. If the PV production is too low the battery may become empty and not enough energy will be delivered.

PVGIS calculates the off-grid PV energy production taking into account the solar radiation for every hour over a period of several years. The calculation is done in the following steps:

- For every hour calculate the solar radiation on the PV module(s) and the PV power
- If the PV power is greater than the energy consumption, store the rest of the energy in the battery.
- If the PV power is less than the energy consumption, get the missing energy from the battery.
- If the battery becomes full, calculate the energy "wasted" because the PV power could be neither consumed nor stored.
- If the battery becomes empty, calculate the missing energy and add the day to the count of days where the system ran out of energy.

The energy consumption varies during the day but the pattern of consumption is assumed to repeat in the same way every day. PVGIS uses by default a particular energy consumption pattern where most of the energy is consumed after sunset, but the user may upload a different hourly consumption pattern.

Choice of solar radiation database

The solar radiation databases (DBs) available in PVGIS are:

Database	Type	Start Year	End Year	Spatial res.	Comments
PVGIS-SARAH	Satellite	2005	2016	0.05° x 0.05° (~ 5 km)	Default DB for Europe, Asia, Africa and South America (below 20 S)
PVGIS-NSRDB	Satellite	2005	2015	0.038° x 0.0.38° (~ 4 km)	Default DB for the Americas (above 20 S)
PVGIS-CMSAF	Satellite	2007	2016	0.025° x 0.025° (~ 2.5 km)	This operational database is not produced any more. Please, use PVGIS-SARAH instead.
PVGIS-ERA5	Reanalysis	2005	2016	0.25° x 0.25° (~ 25 km)	Default DB for Europe above 60 N
PVGIS-COSMO	Reanalysis	2005	2015	0.055° x 0.055° (~ 5 km)	Alternative to ERA5 (high-resolution regional reanalysis over Europe)

All databases provide hourly solar radiation estimates.

Most of the solar radiation data used by PVGIS have been calculated from satellite images. There exist a number of different methods to do this, based on which satellites are used. The choices that are available in PVGIS at present are:

- **PVGIS-SARAH** This data set has been calculated by CM SAF and the PVGIS team. This data cover Europe, Africa, most of Asia, and parts of South America.
- **PVGIS-NSRDB** This data set has been provided by the National Renewable Energy Laboratory (NREL) and is part of the National Solar Radiation Database.
- **PVGIS-CMSAF** This data set has been calculated by the CM SAF collaboration for the area covering Europe and Africa, as well as parts of South America. The data cover the period 2007-2016.

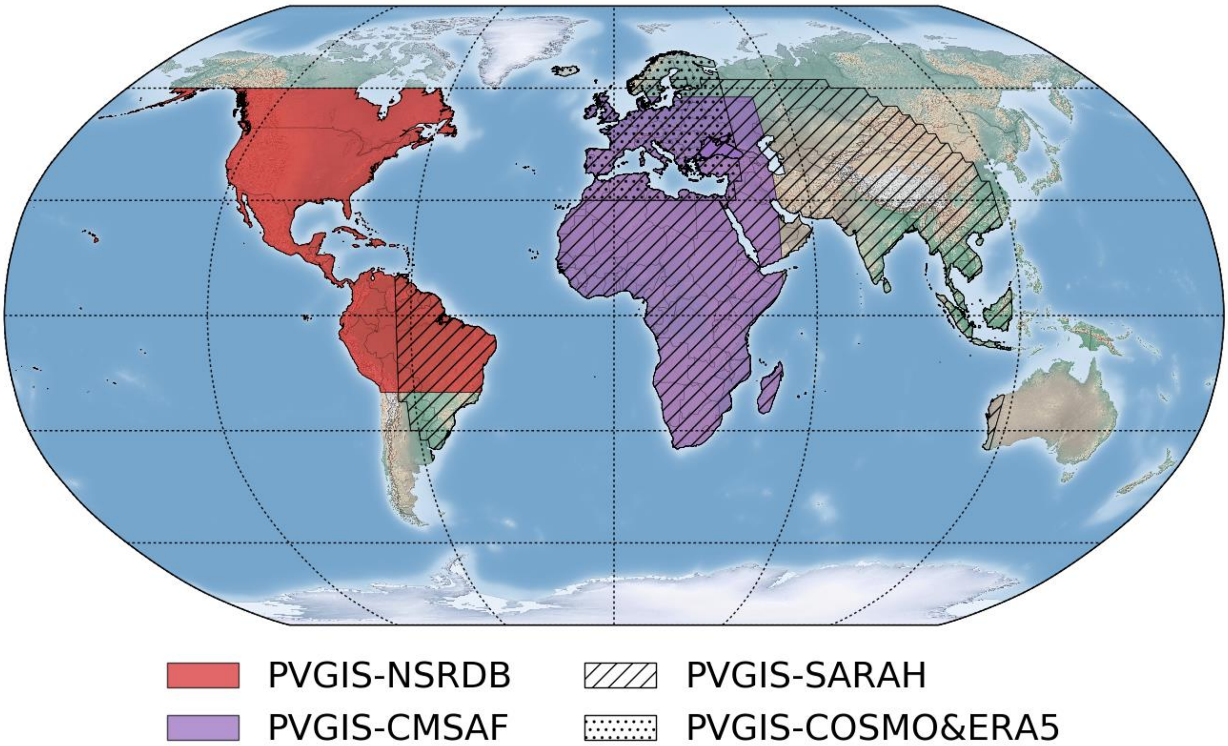
Some areas are not covered by the satellite data, this is especially the case for high-latitude areas. We have therefore introduced two additional solar radiation databases for Europe, which include northern latitudes:

- **PVGIS-ERA5** This is the new reanalysis product from ECMWF. Coverage is worldwide at hourly time resolution and a spatial resolution of 0.28° lat/lon. At the moment, in PVGIS we are making this database available for Europe.
- **PVGIS-COSMO** COSMO-REA6 is a regional reanalysis product, covering Europe at hourly time resolution and a spatial resolution of about 6km (we use 3' lat/lon in PVGIS). The original data set is available here

More information about the reanalysis-based solar radiation data is available.

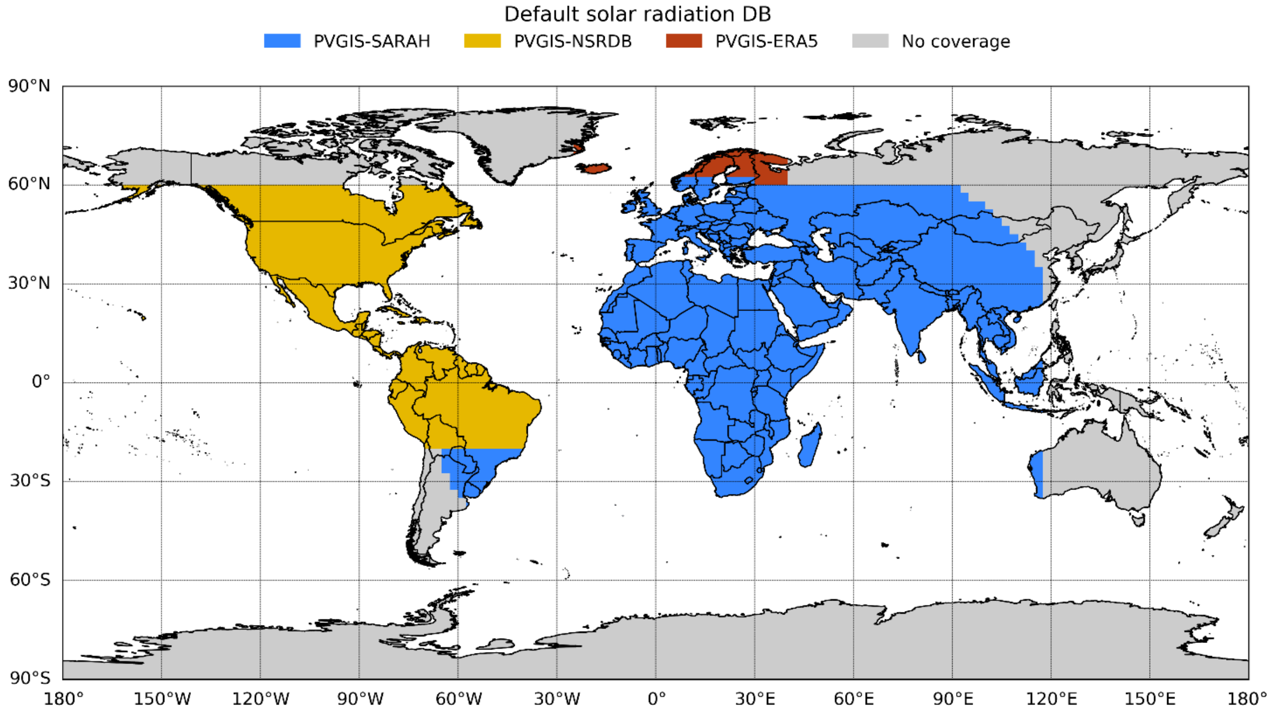
For each calculation option in the web interface, PVGIS will present the user with a choice of the databases that cover the location chosen by the user.

The figure below shows the areas covered by each of the solar radiation databases.



Geographical extent of the solar radiation data sets in PVGIS

Based on the different validation studies performed the databases recommended for each location are the following:



These databases are the ones used by default when the raddatabase parameter is not provided in the non-interactive tools. These are also the databases used in the TMY tool.

Calculation of grid-connected PV system performance

Photovoltaic (PV) systems convert the energy of sunlight into electric energy. Although PV modules produce direct current (DC) electricity, often the modules are connected to an Inverter which converts the electricity into AC, which can then be used locally or sent to the electricity grid. This type of PV system is called *grid-connected PV*. The calculation of the energy production assumes that all the energy that is not used locally can be sent to the grid.

Inputs for the PV system calculations

PVGIS needs some information from the user to make a calculation of the PV energy production.

PV Technology

The performance of PV modules depends on the temperature and on the solar irradiance, but the exact dependence varies between different types of PV modules. At the moment we can estimate the losses due to temperature and irradiance effects for the following types of modules: crystalline silicon cells; thin film modules made from CIS or CIGS and thin film modules made from Cadmium Telluride (CdTe).

For other technologies (especially various amorphous technologies), this correction cannot be calculated here. If you choose one of the first three options here the calculation of performance will take into account the temperature dependence of the performance of the chosen technology. If you choose the other option (other/unknown), the calculation will assume a loss of 8% of power due to temperature effects (a generic value which has found to be reasonable for temperate climates).

PV power output also depends on the spectrum of the solar radiation. PVGIS can calculate how the variations of the spectrum of sunlight affects the overall energy production from a PV system. At the moment this calculation can be done for crystalline silicon and CdTe modules. Note that this calculation is not yet available when using the NSRDB solar radiation database.

Installed Peak Power

This is the power that the manufacturer declares that the PV array can produce under standard test conditions, which are a constant 1000W of solar irradiation per square meter in the plane of the array, at an array temperature of 25°C. The peak power should be entered in kilowatt-peak (kWp). If you do not know the declared peak power of your modules but instead know the area of the modules and the declared conversion efficiency (in percent), you can calculate the peak power as *power = area * efficiency / 100*.

System loss

The estimated system losses are all the losses in the system, which cause the power actually delivered to the electricity grid to be lower than the power produced by the PV modules. There are several causes for this loss, such as losses in cables, power inverters, dirt (sometimes snow) on the modules and so on. Over the years the modules also tend to lose a bit of their power, so the average yearly output over the lifetime of the system will be a few percent lower than the output in the first years.

We have given a default value of 14% for the overall losses. If you have a good idea that your value will be different (maybe due to a really high-efficiency inverter) you may reduce this value a little.

Mounting position

For fixed (non-tracking) systems, the way the modules are mounted will have an influence on the temperature of the module, which in turn affects the efficiency. Experiments have shown that if the movement of air behind the modules is restricted, the modules can get considerably hotter (up to 15°C at 1000W/m^2 of sunlight).

In PVGIS there are two possibilities: *free-standing*, meaning that the modules are mounted on a rack with air flowing freely behind the modules; and *building- integrated*, which means that the modules are completely built into the structure of the wall or roof of a building, with no air movement behind the modules. Some types of mounting are in between these two extremes, for instance if the modules are mounted on a roof with curved roof tiles, allowing air to move behind the modules. In such cases, the performance will be somewhere between the results of the two calculations that are possible here.

Slope of PV modules

This is the angle of the PV modules from the horizontal plane, for a fixed (non-tracking) mounting. For some applications the slope and azimuth angles will already be known, for instance if the PV modules are to be built into an existing roof. However, if you have the possibility to choose the slope and/or azimuth, PVGIS can also calculate for you the optimal values for slope and azimuth (assuming fixed angles for the entire year).

Azimuth (orientation) of PV modules

The azimuth, or orientation, is the angle of the PV modules relative to the direction due South. - 90° is East, 0° is South and 90° is West. For some applications the slope and azimuth angles will already be known, for instance if the PV modules are to be built into an existing roof. However, if you have the possibility to choose the slope and/or azimuth, PVGIS can also calculate for you the optimal values for slope and azimuth (assuming fixed angles for the entire year).

SOLAR & PV OPTIMAL SPOT