COMPARISON OF DIFFERENT METHODS FOR MEASURING SOLAR IRRADIATION DATA

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Abstract

Knowledge of solar irradiation data is very important e.g. for planning solar power plants. Unfortunately valid data in suitable regions are quite rare. Our investigations at the PSA concern the improvement of irradiation data measured with Rotating Shadowband Pyranometers at promising sites. The data show larger deviations compared to real values and need to be revised and corrected after comparison with more precise data we measure with recently installed new thermal sensors. Finally TMY of the sites as well as irradiation maps derived from satellite images will be generated.

Key words: *irradiation, RotatingShadowbandPyranometer, soiling, satellite data.*

1 INTRODUCTION

An exact knowledge of solar irradiation data at foreseen locations is very important for planning and installation of solar power plants or other devices using solar energy. Due to increased indications of climate changes in the past years, an intensified use of renewable energies in world energy generation is strongly recommended. Solar energy can provide huge amounts of the energy share especially in regions with high solar irradiation. Possibilities to access solar energy are manifold: power plants like those investigated at the Plataforma Solar de Almería (PSA) use solar energy by concentrating direct irradiation, converting it to heat and finally electricity [Geyer00]. But also flat plate collectors or photovoltaic panels, which can be installed decentralized, show promising prospects [Quaschning01].

Solar irradiation can be seen as the “fuel” for these devices and therefore takes strong influence on the costs. Small changes in the annual irradiation sum decide e.g. whether the construction of a power plant is either economically reasonable or unattractive. Unfortunately valid meteorological data in suitable regions are quite rare. Furthermore, the weather and subsequently irradiation depend strongly on the microclimate and besides vary significantly from one year to another one. Already existing tools, which allow the calculation of the expected irradiation at chosen sites by interpolating some widely spread data [Quaschning00], show rather large uncertainties and cannot be used for valid calculations for projected power plants [Quaschning02]. Methods using satellite data can provide information on the available irradiation continously in space and time. Exact measurements of the insolation at ground can help to validate these methods.

Our investigations at DLR-PSA presented in this paper treat the improvement of meteorological data measurements, which we take with industrial partners at several locations in the south of Spain and Morocco. At already existing stations the irradiation sensors are equipped with simple photodiode sensors having low accuracy. However, the deviations of their signal to reality can be corrected afterwards if only the real irradiation is known. In order to get more precise irradiation data, we installed a second meteo station at the PSA (PSA2) in direct vicinity of the existing station with a far better accuracy. Using these measurements we are able to find the correction functions for the data of the existing meteo stations as well as we can use them for adjustment and validation of the satellite data.

2 EQUIPMENT OF DLR METEO STATIONS

The already existing meteorological stations are running with the following equipment: a Vaisala Humitter 50Y for measurement of temperature and humidity, a Vaisala PTB 101 analogue barometer for measuring air pressure as well as a NRG Systems Type 40 Maximum Anemometer and a 200 Series Wind Vane for measuring wind speed and direction and a Rotating Shadowband Pyranometer (RSP) for the irradiation data (see Figure 1). A Campbell CR10X Datalogger takes measurements of the incoming signals, makes first processing steps and stores the data until they will be read out. Each of the meteo stations is independently from net connection powered by batteries, which are charged by photovoltaic elements. Data transfer is initiated automatically by a computer, which is calling the datalogger once a day via a GMS modem. Then data is processed automatically by further programs and sent as MS-Excel sheets via e-mail, including various irradiation sums, maximum, minimum and average values as well as graphics. Regarding this graphics, errors occurring during measurements can be detected easily by an experienced controller.

Figure 1: Rotating Shadowband Pyranometer (RSP) in normal position (left) and during rotation (right).

Figure 2: Meteo station with Kipp&Zonen pyranometer (GHI, DHI) and pyrheliometer (DNI).

The RSP itself consists of a horizontally mounted LI-COR Radiation Sensor in combination with a shadowband, which is mounted below the sensor in an angle of 45°, directing to the North and rotating once per minute around the sensor (see Figure 1). This way it is ensured that during rotation the shadowband once implies a shadow on the sensor, blocking out the sun for a short moment. In this moment the sensor, which is usually measuring global horizontal irradiation (GHI), now only detects diffuse horizontal irradiation (DHI). Subsequently direct normal irradiation (DNI) is calculated by the datalogger using GHI, DHI and the actual sun height angle by known time and coordinates of the location.

The newly installed meteo station PSA2 for the high precision measurements (see Figure 2) is equipped with a 'first class' Kipp&Zonen pyrheliometer CH1 (Figure 3) for measurement of DNI and two horizontal

Figure 3: 'First class' Kipp&Zonen pyrheliometer for DNI measurement.

mounted 'secondary standard' Kipp&Zonen pyranometer CM11 (Figure 4) for the measurement of GHI and DHI. 'First class' and 'secondary standard' means that the devices are calibrated along ISO 9060 of the World Meteorology Organization (WMO) at the World Radiation Center in Davos, Switzerland. The devices are mounted on a Kipp&Zonen 2AP two-axis tracker, which is following the suns path on the sky with an accuracy of 0.1°, ensuring that the CH1 is always

Figure 4: 'Secondary standard' Kipp&Zonen pyranometer for GHI and DHI measurement.

pointing in exact direction to the sun. An additionally shadow ball is fixed on the sun tracker in that way that it is always shading the DHI sensor. The two pyranometers of course always stay horizontally mounted. For correct measurements the whole device had to be installed very precisely. Data read-out and processing is carried out in the same way as at the other stations.

In contrary to the RSP, which is only calculating DNI out of GHI and DHI, here we are measuring DNI additionally. This gives us the possibility to compare the measured value with the calculated one and verify the measurements when the deviation is within its error specifications. The PSA2 station is running since June 2002.

3 OPERATION PRINCIPLE AND SPECIFICATIONS OF THE IRRADIATION SENSORS

Whereas the pyranometer and pyrheliometer are thermal sensors, the RSP LI-COR Radiation Sensor consists of a silicon photodiode. Thermal sensors convert the incoming radiation absorbed at the front side of the sensor into heat; the arising temperature difference between the front side and the backside, which is coupled to ambient temperature, is measured by a thermo-coupling device and yields a voltage, which is proportional to the irradiation. As the temperature difference needs to come to equilibrium by changing irradiation, thermal sensors have a response time of several seconds.

The RSP Radiation Sensor as a silicon photodiode is a semiconductor creating itself an intrinsic voltage when illuminated. Therefore the LI-COR Radiation sensor is an instantaneously measuring device but shows dependence on temperature and also lacks uniform spectral response in its sensitive range between 0.4 and 1.2 µm. As the whole range of incoming radiation lies between 0.25 and over 2.5 µm and over and above its spectrum is varying with changing atmospheric conditions, this results in the mentioned low accuracy. The sensitive range of the LI-COR sensor is quite but not sufficiently constant when different sky conditions are compared. Some mayor changes can be detected at low solar elevations when a significant part of the near infrared solar radiation is absorbed by water vapor. Calibration of the RSP Radiation Sensor has been carried out by the manufacturer against an Eppley Precision Spectral Pyranometer (similar to our Kipp&Zonen pyranometers) for 3 to 4 days under daylight conditions. Depending on the exact sky conditions during that period there also may exist a certain error of the determined calibration constant.

The most important specifications of the used sensors are listed in Table 1.

Table 1: Specifications of the used sensors.

	CH1	CM11	LI-COR
Response time (95%)	7 s	< 15 s	10 µs
Zero off-set (T_{amb}-drift by 5 K/h)	±3 W/m²	±2 W/m²	—
Non-stability	< ±1 %/a	±0,5 %/a	< ±2%/a
Non-linearity (<1000 [3000] W/m²)	±0,2 %	±0,6 %	±1%
Spectral selectivity (0,35...1,5 µm)	±0,5 %	±2 %	-5 ... +10 %
Temperature response (-10...+40°C)	±1 %	±1 %	±0,15%/K
Directional response	—	±10 W/m²	< ±5%
Calibration error	±0,1 %	±0,4 %	±3 ... ±5 %
Viewing angle	5°	2π sr	2π sr

4 FIRST RESULTS OF IRRADIATION MEASUREMENTS AT THE PSA

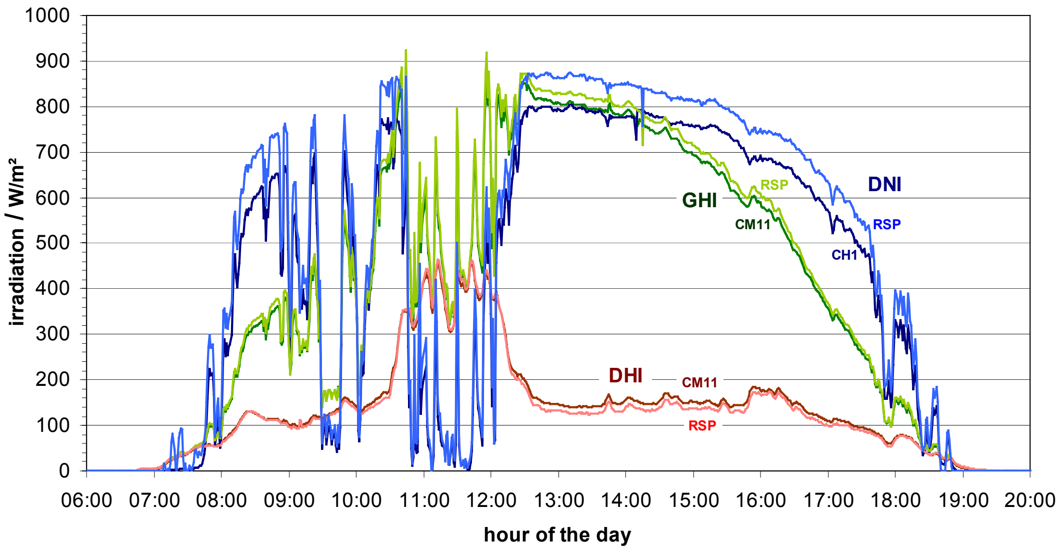
In the following sections we will show a comparison of first results of the measurements with the different irradiation sensor types at the PSA and additional influences on the signal due to soiling.

4.1 Comparison of the different sensor types

Figure 5 presents the irradiation data measured on the 19th of September 2002 at the PSA in intervals of 1 minute. The graphic shows the direct normal (DNI), the global horizontal (GHI) and the diffuse horizontal irradiation (DHI) from the RSP as well as from the high precision devices: the CM11 pyranometers and the CH1 pyrheliometer. Because sky conditions are changing, the irradiation characteristics of this day are suitable to demonstrate the differences between a cloudy and a clear sky. During the morning bands of clouds can be observed and therefore the DNI and GHI are dropping instantaneously when the cloud moves to shade the sensor. Also different kinds of clouds can be detected: The drop in DNI signal at about 9:30 is not accompanied by increasing DHI whereas it is between 10:40 and 12:00. In the latter case it seems to be a thin and light cloud cover (cirrus clouds), which increases diffuse irradiation because of low optical thickness and forward scattering of the sunlight; at 9:30 it must have been a thick dark cloud (cumulus) shading the sun. During the afternoon nearly no sudden decrease of DNI signal can be observed corresponding to a clear blue sky. The minor fluctuations are caused by a certain amount of haze existing in the atmosphere. Due to the haze the DHI signal is increased to around 150 W/m²; for a real clear sky without haze diffuse irradiation signals of around 50 W/m² have been detected.

As can be seen in Figure 5 the determined DNI value for the RSP is during most of the time higher than the signal of the CH1 pyrheliometer by an amount of 5 to 10 %. Merely during the overcast periods the DNI signals seem to fit. The to such an extent increased DNI value of the RSP is a consequence of an overestimation of its GHI signal in concurrence with the underestimation of the DHI signal. Here also the signals of RSP are in better agreement with the measurements of the pyranometer during overcast times.

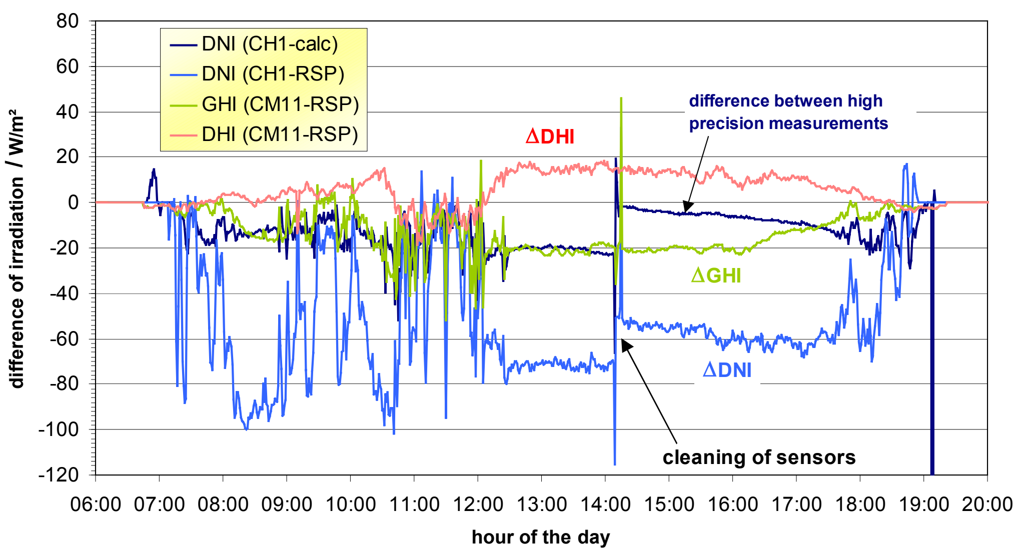
Figure 5: Measurements of the DNI, GHI and DHI signals on the 19th of September 2002 at PSA, South of Spain, with different sensors: two CM11 pyranometer for GHI and DHI and a CM1 pyrheliometer for DNI as



well as measured by a Rotating Shadowband Pyranometer (RSP).

In order to have a better estimation of the amount of the signal deviation between the RSP and the precise instruments, the deviation is plotted in Figure 6 for DNI, GHI and DHI as subtraction of the RSP signal from the precise instrument values: ΔDNI, ΔGHI and ΔDHI. Also shown in this graphic is the difference of the DNI signal measured by the CH1 pyrheliometer and the value calculated from GHI and DHI measurements of the CM11 pyranometers, as the calculated value subtracted from the measured one.

Figure 6: Difference of the measured and calculated DNI signal from the high precision instruments as well as the deviations of the RSP signals as subtracted from the measurements of the precision instruments. Measurements from the 19th of September 2002 taken at the PSA. At 14:10 the sensors have been cleaned.



The difference of the DNI of the high precision instruments lies beyond 20 W/m² what means an accuracy in deviation of less than 4 %. At 14:10 a sudden break down of the deviation to only a few W/m² can be seen: this is caused by cleaning the sensors after a 6 days period without cleaning. The relative deviation now amount to under 1 % what proves agreement of every single measurement of each individual sensor. The deviation is only slightly increasing due to higher uncertainties with increasing sun incidence angle. In the morning hours when fluctuating irradiation occurs, these fluctuations can also be found in the deviation of the signals because of integration periods of 1 minute and smartly deviating time constants. Nevertheless, the measurements with the high precision instruments can be assumed to be validated if the sensors are kept clean. The soiling problem will be discussed in the next section.

As already mentioned above, the differences between the RSP and high precision measurements can be analyzed better in Figure 6: ΔDNI values nearly always are negative, what means that the RSP is overestimating irradiation also at somewhat cloudy skies with low direct irradiation. The extent of overestimation varies from day to day and depends quantities like temperature, he irradiation and its spectrum. After cleaning the sensors, here remains an overestimation of about 60 W/m² or a relative overestimation of 7 % for ongoing measurement. Meanwhile, the monthly sums of DNI of the RSP exceed the pyrheliometer values by 9 to 13 %.

The difference ΔGHI of global irradiation with a somewhat 20 W/m² higher RSP signal at clear skies results in a less than 5 % overestimation of the GHI by the RSP; at cloudy skies the difference is noticeably smaller. In times of high fluctuations of irradiation the differing time response of the two sensor types yields an also high variation of the signal difference. Monthly sums of RSP exceed by 3 to 5 %.

In contrary to the overestimation of DNI and GHI by the RSP, the DHI deviation shows a different characteristic: at sunny skies the RSP signal is about 10 to 20 W/m² to low resulting in an underestimation of sometimes more than 30 %, depending on the actual level of the diffuse irradiation. During cloudy times the difference is quite smaller and even may lead to a small overestimation of the RSP signal of about 5 %. The monthly sums yield an underestimation of between 3 and 7 %.

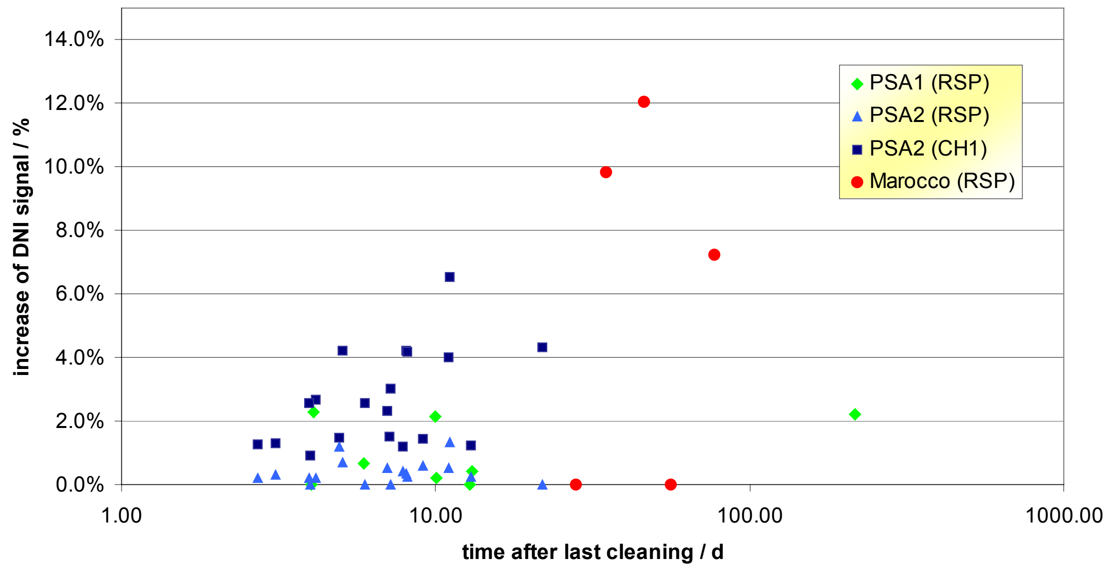
Analyzing the deviations of the RSP measurements demonstrated above in Figure 5 and Figure 6 gives just a first impression of their principal characteristics. A comparison to a second RSP showed corresponding signals of both RSP sensors. Yet this single day represents only a small portion of the manifold irradiation and temperature conditions, which can occur. To get representative coherences between the RSP signal and real irradiation, based on a broad spectrum at different conditions, examination of the deviations for a longer period of time will be necessary. Over all, the necessity of a recalibration of the RSP is obvious.

4.2 Soiling of the sensors

Whereas the deviations of the RSP signal, originating from temperature and spectral changes of irradiation, show exact functional dependencies, soiling of the sensors is a statistical process that hardly can be described by mathematical coherences. Soiling is strongly dependent on the weather conditions because of factors like the actual amount of dust in the air (influenced by the nature of the ground around the station), corresponding with air velocities at the location and humidity or dew on the sensors. Other circumstances like rain may even clean the sensors or also deposit more dust. Also soiling occurs to the RSP as well as to the pyranometer and the pyrheliometer, but not necessarily to the same extent because of a different shape. Regular cleaning of the sensors is necessary in order to get correct data values. Otherwise, if regular cleaning is not possible, a value for the average decrease of the signal due to soiling has to be found to describe the reality as far as possible.

To get an estimation of time dependence and the extent of the decreasing signal due to soiling, we note the rise of the signal each time we clean the sensors. Figure 7 shows the increase of the DNI signal of several sensors in dependence of the cleaning interval. As soiling is supposed to depend exponentially on time, it is plotted against a logarithmic time scale.

Figure 7: Soiling of sensors: increase of the DNI signal by cleaning different sensors at different sites in dependence of the time period after the last cleaning.



Whereas the two RSP at the both meteo stations PSA1 and PSA2 show nearly the same extent of the signal increase of less than 2 %, soiling at the CH1 pyrheliometer and the RSP at the Morocco site is significantly higher: the pyrheliometer values increase more than 6 % and the RSP located in Morocco up to more than 12 %. In Morocco due to the near desert the atmosphere seems to be rather dusty so that sufficient dust particles are depositing on the flat horizontal sensor surface. The pyrheliometer front surface is permanently changing its orientation in direction to the sun and consists of a glass plate, which is surrounded by shield serving as rain protection. This shield prevents air streaming over the glass plate and like this high air velocities beneath the plate, favoring dust particles to settle down.

Therefore for each different kind of sensor and each location another constant describing the average soiling condition will be necessary for making valid corrections of the measured data sets.

5 IRRADIATION MAPS DERIVED FROM SATELLITE DATA

Evaluating the direct normal irradiance at ground, a method, developed by DLR, using data of the geostationary satellite METEOSAT is used [Schillings02, Broesamle01]. DNI can be calculated depending on the sun elevation for a clear sky when the actual amount of aerosols, water vapour and gases like ozone, O_2 and CO_2 in the atmosphere is known for the examinated site. Considering also Rayleigh scattering, the various transmission coefficients for these quantities can be determined. To calculate the DNI also for cloudy skies a further transmission coefficient is necessary, taking into account the coverage of the sky by clouds. Clouds have the strongest impact on the extinction of solar irradiation. An algorithm to calculate this coefficient from METEOSAT data has been developed by [Mannstein99]. This cloud detection scheme uses infrared (IR) and visible (VIS) channels from the METEOSAT-7 satellite with a spatial resolution of up to 5×5 km². It is based on self adjusting, local thresholds which represent the surface conditions undisturbed by clouds. The calculated cloud-index (CI) represents the effective cloud transmission, which is an integral value influenced by the cloud amount and by the average cloud optical depth within the analysed pixel and is in the of 0 for no clouds to 100 for completely cloudy pixels with high optical depth. It is calculated by comparing the actual image to a reference image without clouds, which is constructed from previous cloudless images.

Information about the spatial and time dependent distribution of aerosols are taken out of the NASA-GACP [Michschenko02] as monthly values in patches of 4°lat × 5°lon. This still is a rather rough estimation; a better resolution hopefully will be available in the future with new satellites (ENVISAT, MODIS, etc.). For the water vapour due to its high variability daily data of precipitable water from NCEP-Reanalysis of the Climate Diagnostic Center with a spatial resolution of 2.5°×2.5° is used [Kalnay96]. Whereas finally for ozone zonal monthly mean values derived by the Total Ozone Mapping Spectrometer (TOMS onboard NASA's Earth Probe satellite) have been taken, for the rest of the gases as well as for Rayleigh scattering of the clear atmosphere fixed values for the atmospheric components based on the U.S. Standard Atmosphere 1976 are sufficient.

Advantages of the satellite-derived data generation are that as a result you get maps of whole countries or continents and not only data for single sites; furthermore, neither the construction of a meteo station nor time-consuming maintenance due to soiling and/or failure of some measuring device are necessary. Like this generation of satellite derived irradiation data shows less gaps due to failure of sensors or errors due to soiled sensors and in addition is usually cheaper.

Nevertheless, the existence of a few ground stations taking measurements is necessary for validation of the satellite-derived data. Some uncertainties in correct determination of the CI are still remaining: e.g. in mountainous, strong heterogeneous and sometimes snow-covered regions the determination of correct CI is difficult. Further errors can occur at some sun positions in combination with special geometrical viewing conditions of the satellite, when the altitude and vertical extension of the clouds is necessary to be known in order to calculate a correct CI. Finally different types of clouds as well as multilayer clouds, which show different influence on irradiation and therefore resulting in another CI value, can hardly be distinguished by the used mechanism. This opens way for further work to be done in the future to improve the so far used algorithm.

Comparisons of satellite-derived values with data originating from ground measurements have been done e.g. for Saudi Arabia. Whereas hourly data show a root mean square error of 36°%, deviations of yearly averages are decreasing to 8 % [Schillings2002].

6 SUMMARY AND CONCLUSION

Besides some already existing meteo stations equipped with a Rotating Shadowband Pyranometer (RSP) for irradiation measurements, we built up and installed a new station for irradiation measurements with two Kipp&Zonen CM1 pyranometer and one CH1 pyrheliometer mounted on a 2AP solar tracker. With these instruments we are taking high precision measurements of DNI, GHI as well as DHI with signal deviations of less than 1 % since July 2002. Compared with measurements of the RSP, which is standing aside the newly built meteo station, we found an overestimation of the DNI signal by the RSP depending on the weather conditions of about 5 to 10 % and an overestimation of the monthly sum of 9 to 13 %. This results as a consequence of overestimation of the GHI measurement and underestimation of DHI measurement by the RSP at clear sky conditions. During overcast skies the deviations of the signals are observed to be smaller than at clear skies. First functional dependencies of the deviations of the RSP signal to real irradiation values are derived and will be precizised with ongoing measurement. For a valid determination of these functional coherences a comprehensive set of different irradiation and weather conditions is necessary as well as the knowledge of the average soiling characteristic at each location. With these functional coherences in dependence of temperature, sun elevation and further atmospheric conditions we will correct the collected data of all of the examined sites afterwards. Finally by using satellite data derived from measurements lasting several years, we are able to construct Typical Meteorological Years (TMY) and irradiation maps of single countries or whole continents. The irradiation maps can be fed into the software tool STEPS [Broesamle01] for the simulation of energy production in various types of power plants. Including economic calculations and further spatial data about infrastructure, etc. maps showing spatial distributed energy output and electricity costs can be generated for different power plants. These maps are a powerful tool, which can support companies selecting appropriate locations and an optimal plant type for the construction of new solar power plants.

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