Site Assessment of Solar Resource

Upington Solar Park

Province Northern Cape, South Africa

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1 SUMMARY

This report estimates solar resource for the Upington Solar Park, near **Upington, Province Northern Cape** in **South Africa**. The report focuses on three solar radiation parameters: Direct Normal Irradiance (DNI), Global Horizontal Irradiance (GHI), and Global Tilted Irradiance at the Optimum Angle of 28° (G28). Other meteorological parameters are also considered: Air Temperature at 2 metres, Relative Humidity, Wind Speed at 10 m and Wind Direction.

Applied data

SolarGIS time series of Meteosat MFG and MSG **satellite-derived solar radiation** are used in this study. The data cover a period of 17 years (1994 to 2010). The validation has been done for 5 sites over South Africa, and it shows high level of data accuracy in the region (Section 3.1).

SolarGIS database includes also **weather parameters**: air temperature, humidity and wind data. These parameters are calculated from the outputs of global atmospheric models GFS, CFSR and ERA Interim, which have lower spatial and temporal resolutions. Therefore, compared to solar radiation, the meteo parameters have higher uncertainty.

Local measurements, representing a period of more than four years (11/2006 to 02/2011), were used for the adaptation of satellite-based DNI time series to the local climate. The **data correlation** resulted in an enhanced accuracy of the satellite-based DNI values, namely in the reduction of bias, Root Mean Square Deviation and improved distribution statistics (Section 5.2). The ground-measured data were provided by Eskom and by Stellenbosch University.

The site-adapted solar resource data are used for an estimation of **long-term monthly and annual statistics** of Direct Normal Irradiation (DNI) as the primary parameter of interest. The information about Global Horizontal Irradiation (GHI) and Global Irradiation at the inclination angle of 28° is also supplied in Sections 6 to 8.

Solar resource, together with weather data, are used for creation of two **Representative Meteorological Year** (RMY) data sets: the P(50) data set represents the average climate conditions and the P(90) data set represents the conservative scenario (Section 5.3).

Solar resource summary

The long-term annual average of **Direct Normal Irradiance** is **2816 kWh/m^2** and the annual average of **Global Horizontal Irradiance** is **2282 kWh/m^2**. The site is not affected by shading from terrain features.

The uncertainties for the DNI and GHI estimates and the interannual variability are calculated considering 90% probability of exceedance, P(90):

- The **uncertainty of the estimate** of the long-term annual average is 3.0% for DNI, and 2.5% for GHI. This uncertainty is determined by the accuracy of the measuring instruments (satellite and ground-based), input atmospheric data, applied numerical models and the site-adaptation method.
- Solar radiation changes year by year, as it is determined by weather cycles and stochastic factors, and this source of uncertainty relates to the **interannual variability**. The annual DNI value can deviate from the long-term average up to ±3.3% in any particular year, for GHI this year-by-year variability is ±1.3%. The same uncertainty due to weather changes in a long-term (over 20 years) remains about ±0.7% for DNI and ±0.3% for GHI.

For a full assessment of DNI, besides long-term average values, also a combined effect of the two uncertainties is considered. Thus, in a **conservative scenario**, the **minimum expected solar resource at P(90) level of confidence** is calculated (Section 10).

In a conservative scenario, assuming the combined effect of the uncertainties, the annual DNI of 2690 kWh/m^2 can be expected in any single year, and 2218 kWh/m^2 for GHI. For a period of 20 years, these two combined uncertainties lead to an expectancy of the minimum average DNI of 2729 kWh/m^2 per year, and 2225 kWh/m^2 for GHI.

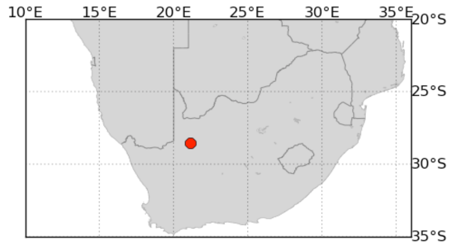
Solar irradiation/ irradiance*		Long-term average [kWh/m^2] [W/m^2]	Any single year		Average over 20 years	
			Combined uncertainty at P(90) [%]**	Minimum expected at P(90) [kWh/m^2] [W/m^2]	Combined uncertainty at P(90) [%]**	Minimum expected at P(90) [kWh/m^2] [W/m^2]
Direct Normal	DNI	**2816** 321	4.5%	2690 307	3.1%	**2729** 312
Global Horizontal	GHI	**2282** 261	2.8%	2218 253	2.5%	**2225** 254
Global at 28°	G28	**2555** 292	3.1%	2475 283	2.8%	**2483** 283

** Solar irradiance is calculated from irradiation assuming 8760 hours per year*
*** Combined uncertainty of the estimate of the site-adapted annual values and interannual variability*

Effects of possible man-induced climate change or extreme natural events such as volcano eruptions, as well as some human activities are not considered in this study.

2 CHARACTERISTICS OF THE SITE

Site name:	**Upington Solar Park**
Commune:	**Upington**, Province Northern Cape, South Africa
Geographical coordinates:	-28° 32' 33", 21° 05' 18"
Elevation above sea level:	820 to 920 m
Terrain slope inclination:	flat, slightly sloped
Terrain azimuth:	-



Location on the map: http://solargis.info/imaps/#tl=Google:Satellite&loc=-28.5424,21.0883&c=-28.543362,21.09169&z=12

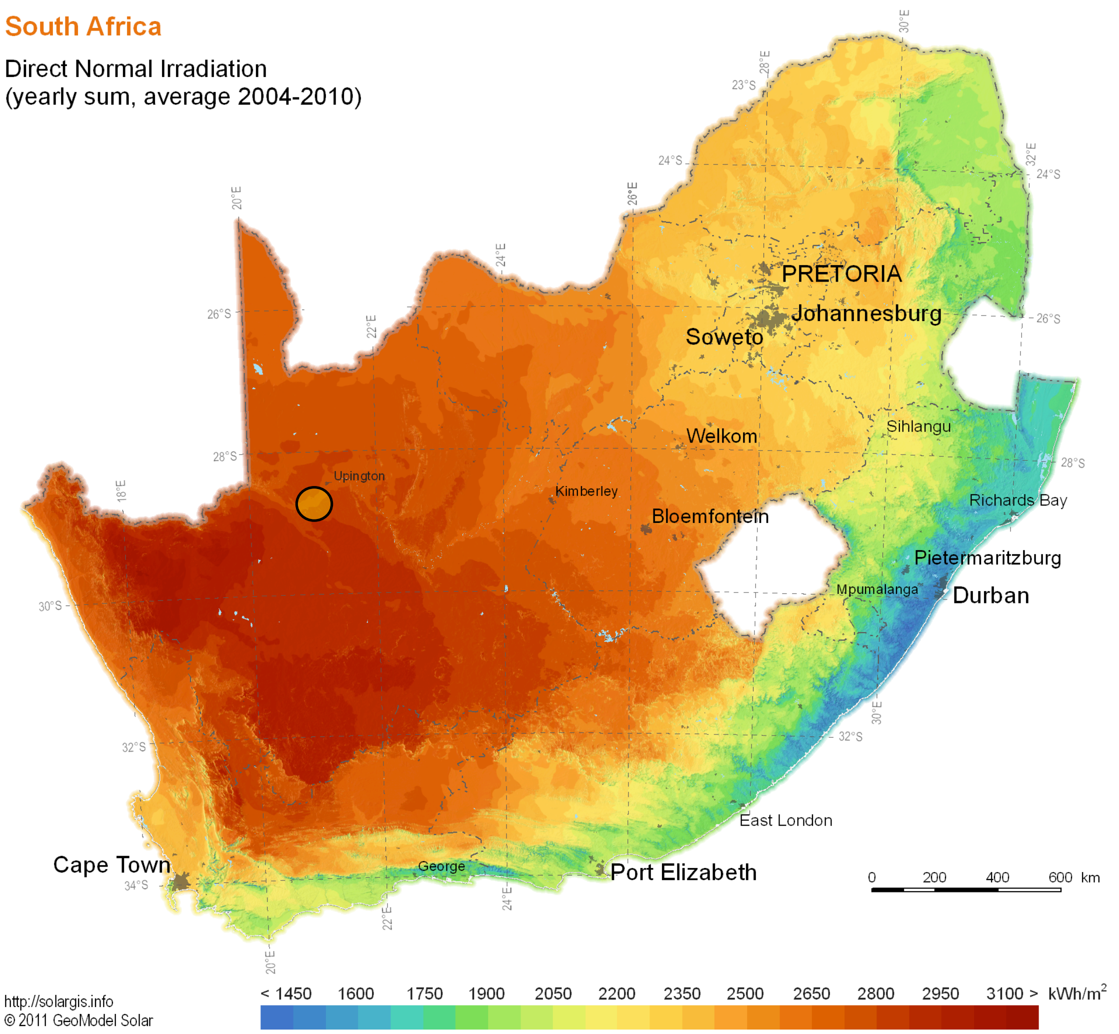


Fig. 1: Position of the Upington Solar Park in the context of DNI solar resource in the South Africa (SolarGIS v1.6 © 2011 GeoModel Solar)

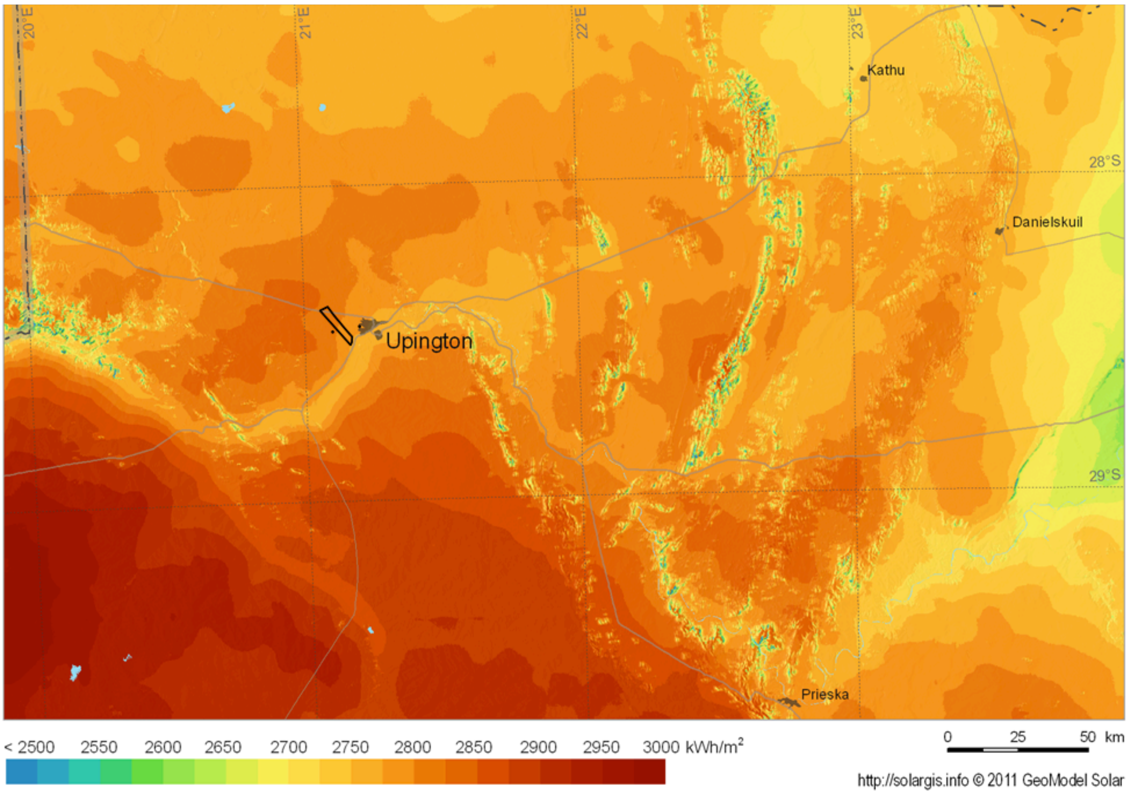


Fig. 2: Annual sum of Direct Normal Irradiation - position of the solar park on the regional map (SolarGIS v1.6 © 2011 GeoModel Solar)

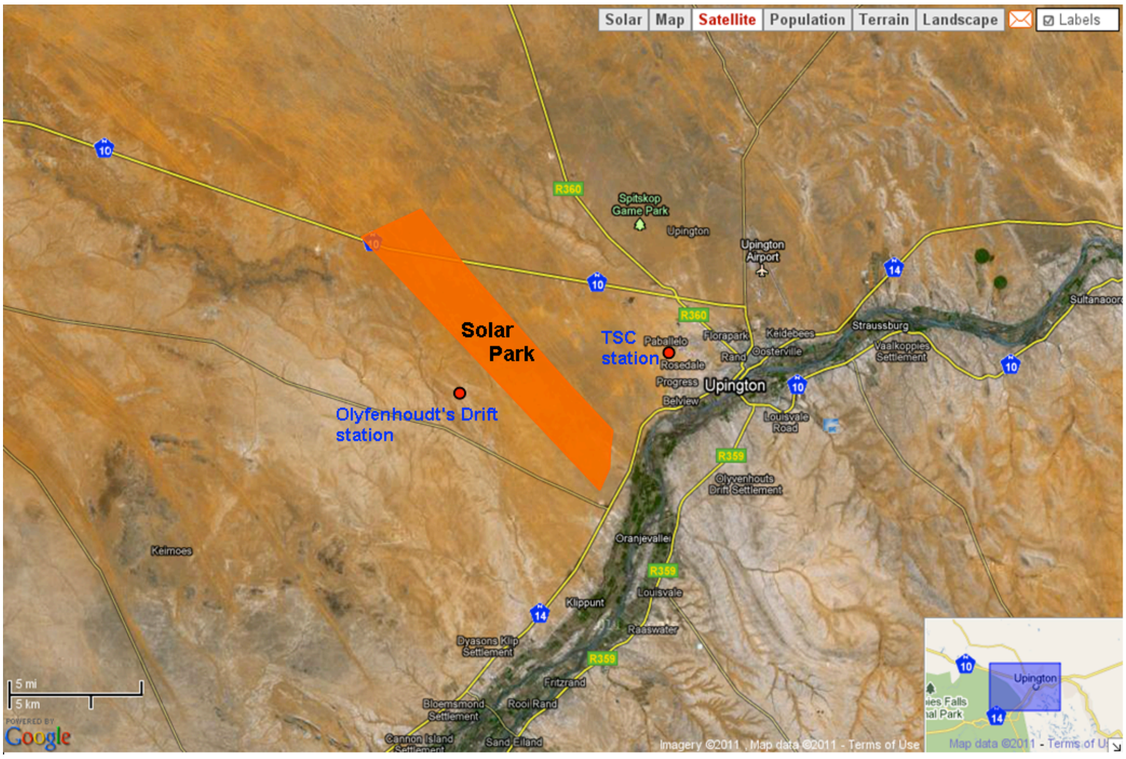


Fig. 3: Situation of the solar park (SolarGIS © 2011 GeoModel Solar, Google Maps © 2011 Google)

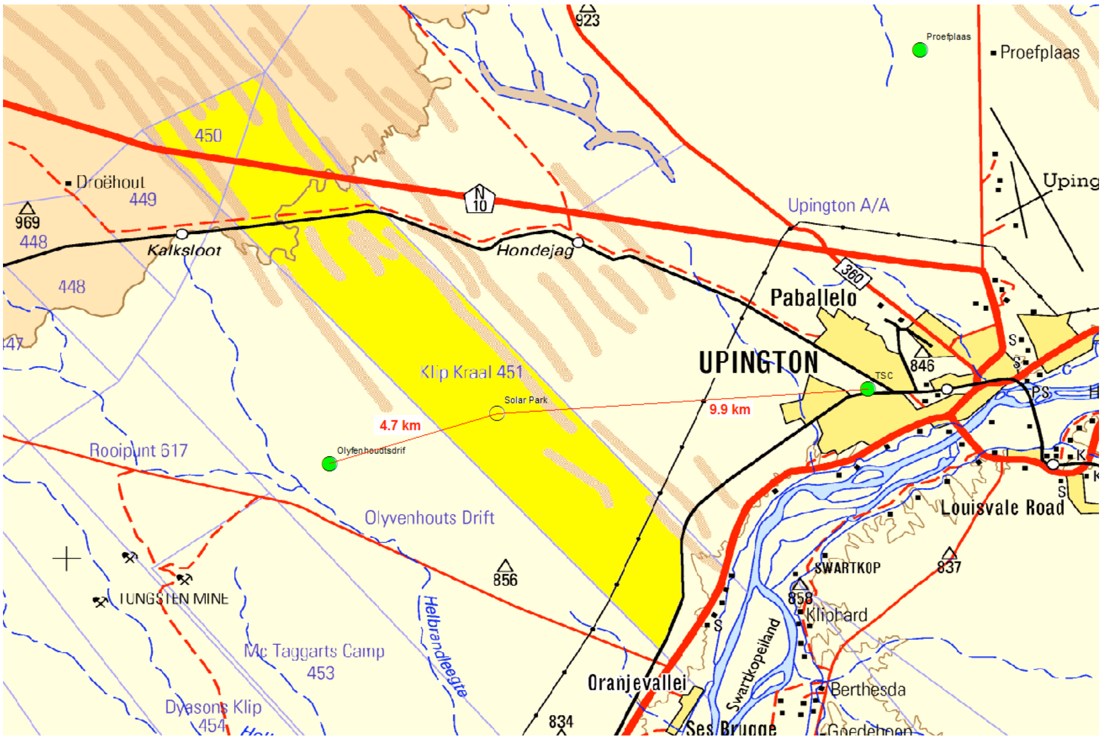


Fig. 4: Detailed situation of the solar park
(© 2011 Stellenbosch University)

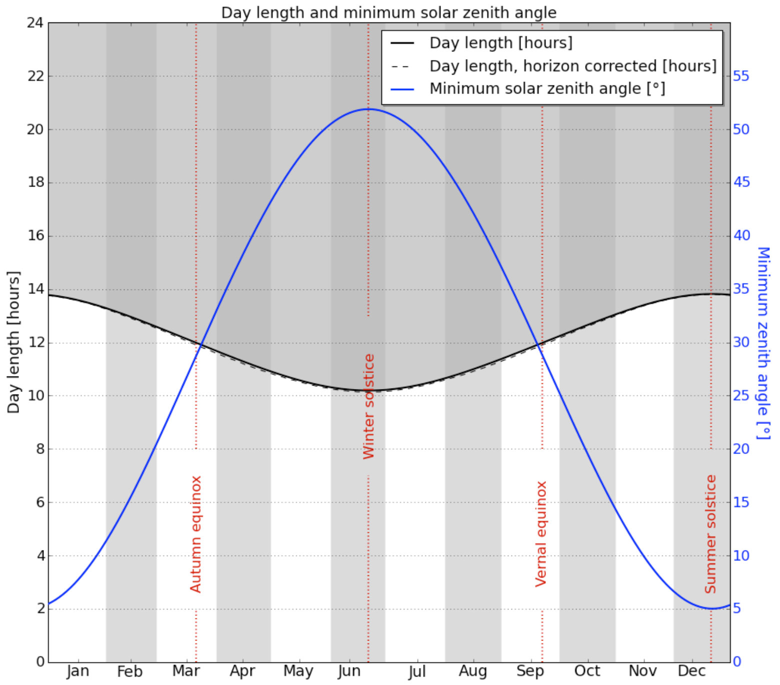
Fig. 5: East view from the Olyfenhoudtsdrif meteo station (© 2010 Eskom)

The Solar Park is located in the region with high potential for solar energy yields.

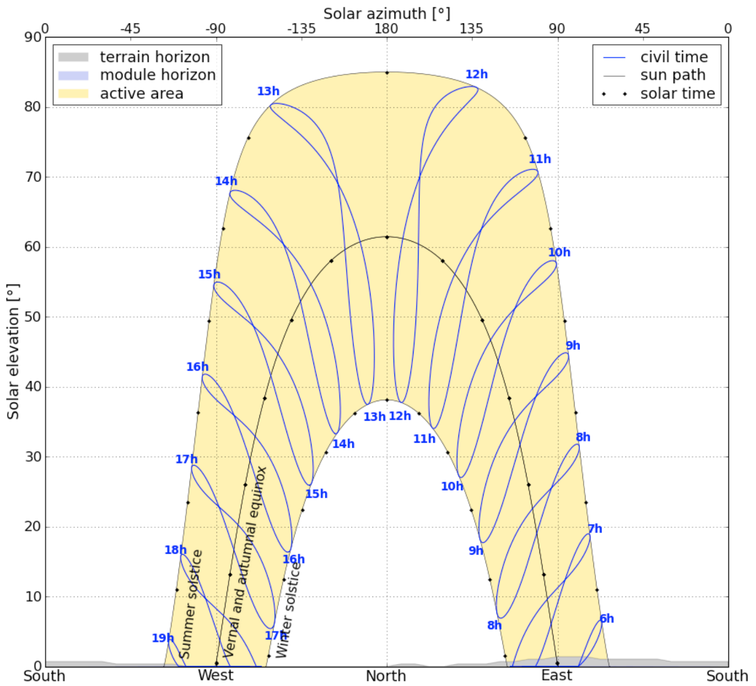
In Fig. 6, the two graphs show:

(a) Change of the day length and solar zenith angle during a year. The local day length (time when sun is above the horizon) is not obstructed by the local terrain horizon;

(b) Change of the sunpath over a year. Terrain horizon is drawn in grey colour and has no shading effect on solar radiation. Black dots show hours in True Solar Time. Blue labels on the top of the curves indicate South African Standard Time (UTC + 2 hours).



(a)
Day length and solar zenith angle



(b)
Sunpath and terrain horizon

Fig. 6: Astronomical and geographical situation

3 SOLARGIS DATABASE

SolarGIS is high-resolution grid database operated by GeoModel Solar. Its geographical extent covers most regions of Europe, Africa, Asia, Western Australia and Brazil.

3.1 Satellite-derived solar radiation

Solar radiation is calculated by numerical models, which are parameterized by a set of inputs characterizing the cloud transmittance, state of the atmosphere and terrain conditions. The methodology is described in several papers [1, 2, 3].

In SolarGIS approach, the **clear-sky irradiance** is calculated by the simplified SOLIS model [4]. This model allows fast calculation of clear-sky irradiance from the set of input parameters. Sun position is deterministic parameter and it is described by the numerical models with satisfactory accuracy. Stochastic variability of clear-sky atmospheric conditions is determined by changing concentrations of atmospheric constituents, namely aerosols, water vapour and ozone. Global atmospheric data, representing these constituents, are routinely calculated by world atmospheric data centres and delivered at a spatial resolution of about 100 km. The calculation accuracy of the clear-sky irradiance is especially sensitive to the information about aerosols.

The key factor determining short-term variability of **all-sky irradiance** is clouds. Attenuation effect of clouds is expressed by the means of a parameter called cloud index, which is calculated from the routine observations of meteorological geostationary satellites. Spatial resolution of satellite data used in SolarGIS is about 4 x 5 km and time step is 15 and 30 minutes. To retrieve all-sky irradiance in each time step, the clear-sky global horizontal irradiance is coupled with cloud index.

The **clouds** are the most influencing factor, modulating clear-sky irradiance. Effect of clouds is calculated from the Meteosat MFG and MSG satellite data (© EUMETSAT) in the form of cloud index (cloud transmittance). The cloud index is derived by relating irradiance recorded by the satellite in four spectral channels and surface albedo to the cloud optical properties. In SolarGIS, the modified calculation scheme Heliosat-2 has been adopted to retrieve cloud optical properties from the satellite data. A number of improvements have been introduced to better cope with specific situations such as snow, ice, or high albedo areas (arid zones and deserts), and also with complex terrain.

In SolarGIS, the new generation **aerosol data set** representing Atmospheric Optical Depth (AOD) is used. This data set is developed and operationally calculated by GEMS and MACC projects (© ECMWF) [5]. Important feature of this AOD data set is that it captures daily variability of aerosols and allows simulating more precisely the events with extreme atmospheric load of aerosol particles. Thus it reduces uncertainty of instantaneous estimates of GHI and especially DNI and allows for improved distribution of irradiance values. It is to be noted that coverage of high frequency (daily) aerosol data is limited to the period from 2003 onwards, the remaining years (1994 to 2002) are represented only by monthly long-term averages.

Water vapour is also highly variable in space and time, but it has lower impact on the values of solar radiation, compared to aerosols. The daily GFS and CFSR values (© NOAA NCEP) are used in SolarGIS, thus representing the daily variability from 1994 to the present.

Ozone absorbs solar radiation at wavelengths shorter than 0.3 μm, thus having negligible influence on the broadband solar radiation.

Direct Normal Irradiance (DNI) is calculated from Global Horizontal Irradiance (GHI) using modified Dirindex model [6]. Diffuse irradiance for tilted surfaces is calculated by Perez model [7].

The key solar parameters of the SolarGIS database are:

- Operational calculation of irradiance at 15 minute time step (30-minute in period 1994 to 2004);
- Primary spatial resolution is about 4 km in South Africa. The shading effects of terrain and elevation is enhanced by disaggregation of the satellite-based irradiance up to 90 metres using Digital Elevation Model SRTM-3;
- Period covered by database from 01/1994 onwards. This report represents 17 complete years from 01/1994 to 12/2010;
- Primary parameters: Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI);

- Data availability is 99%, missing values are resolved by statistical methods, i.e. there are no gaps in the data;

Solar data accuracy from SolarGIS has been compared with high-quality ground measurements measured at 60 stations over Europe and Africa, 5 stations being located in high mountains. The overall relative Mean Bias for Global Horizontal Irradiance is 1.1%, and relative Root Mean Square Difference (RMSD) is 18.5%, 9.6% and 4.8% for hourly, daily and monthly data, respectively; 99.4% data coverage. For Direct Normal Irradiance the overall relative mean bias is 1.6%, standard deviation of biases is 6.6% and relative root mean square difference is 34.9%, 21.4% and 8.9% for hourly, daily and monthly data, respectively.

Quality indicators of GHI and DNI, for the available validation sites in the arid regions, are presented in Tabs. 1 and 2. The Bias for GHI is within ±2% and hourly Root Mean Square Difference (RMSD) is below 16%. The difference indicators for DNI are higher, especially in the areas with higher aerosol content – mostly due to dust originating from Sahara desert. While Mean Bias in these areas goes beyond -12%, in the South Africa sites with cleaner atmosphere the Bias is within ±3.3% and hourly RMSD is below 20%.

Absolute values of Bias are calculated for daytime hours only.

Global Horizontal Irradiance, GHI	**Mean Bias**		**Root Mean Square Deviation, RMSD**		
	[W/m^2]	**[%]**	**hourly [%]**	**daily [%]**	**monthly [%]**
De Aar (South Africa)	9.1	2.0	11.4	6.9	2.6
Sede Boqer (Israel)	-5.9	-1.2	9.1	4.2	1.5
Sonbesie (South Africa)	-4.4	-1.0	12.0	5.5	1.9
Tellerie (South Africa)	5.3	1.0	15.2	9.6	6.7
Tamanrasset (Algeria)	-10.7	-1.7	8.7	5.2	2.5

Tab. 1: Global Horizontal Irradiance – quality indicators for selected validation sites representing the arid climate (sources: BSRN, Eskom, Stellenbosch University)

Direct Normal Irradiance, DNI	**Mean Bias**		**Root Mean Square Deviation, RMSD**		
	[W/m^2]	**[%]**	**hourly [%]**	**daily [%]**	**monthly [%]**
Aggeneis (South Africa)	5.7	0.9	17.5	10.1	2.4
De Aar (South Africa)	-8.6	-1.4	17.3	11.1	3.7
Sede Boqer (Israel)	-76.3	-12.2	26.1	20.4	14.5
Paulputs (South Africa)	-13.6	-2.0	16.3	9.6	2.9
Sonbesie (South Africa)	-3.4	-0.6	19.3	10.6	2.3
Upington (South Africa)	-22.1	-3.3	18.6	10.7	6.6
Tamanrasset (Algeria)	-38.3	-6.1	23.6	19.2	7.8

Tab. 2: Direct Normal Irradiance – quality indicators for selected validation sites representing the arid climate (sources: BSRN, Eskom, Stellenbosch University)

The recent IEA Task 36 data inter-comparison activity, lead by University of Geneva, has independently confirmed that **SolarGIS is the best performing solar radiation database available on the market** [7].

3.2 SolarGIS weather parameters

The weather data are calculated from ECMWF ERA Re-analysis data (© ECMWF) and from NCEP GFS and NOAA CFSR data (© NOAA) by SolarGIS algorithms and Digital Elevation Model SRTM-3.

- Original temporal resolution is 6 hours (3 hours for the wind parameters), and it is interpolated to the time step 1 hour.
- Period covered in this report: 01/1994 to 12/2010 (17 years)

- Spatial resolution of the primary parameters is 25 km (NOAA, CFSR), 50 km (NOAA NCEP, GFS) and 74 km (ECMWF, ERA Interim).

Air temperature at 2 metres

Time resolution is interpolated to 1-hour, spatial resolution is recalculated to 1 km. Data accuracy: mean bias in Europe and Africa it is close to 0.1°C and mean monthly Root Mean Square Deviation (RMSD) is ranging between 0.4° and 0.6°C (in winter). For 90% of validation sites the RMSD is lower than 0.8°C. For hourly values the deviation of modelled values to the ground observations can reach several degrees.

Relative and specific humidity

Relative humidity for period 1994-2009 is calculated from NOAA CFSR specific humidity, air pressure and air temperature. For 2010 the relative humidity is taken from NOAA GFS data. Both datasets are delivered in 6-hourly interval, which was interpolated to hourly values. The indirect calculation of relative humidity for CFSR period may result in slightly higher deviations especially for the night values with high relative humidity.

Wind speed and direction

Wind speed and direction for period 1994-2009 is calculated from NOAA CFSR 10 m wind u- and v-components. The original 3 hourly values are interpolated by nearest neighbour method to hourly values. For the year 2010 the ground measurements from Eskom and Stellenbosch University were used.

Important note: weather parameters derived from the numerical weather model outputs (air temperature, relative humidity, wind speed and wind direction) have lower spatial and temporal resolution and they do not represent the same accuracy as the solar resource data. Especially wind and relative humidity data have higher uncertainty, and they provide only overview information for solar energy projects.

4 ON-SITE MEASUREMENTS

The data from the local meteo station Olyfenhoudtsdrif was used. The meteo station is managed by Eskom, South Africa (Tab. 3). The data are supplied by the Stellenbosch University. Solar radiation readings were validated using MESOR and SERI QC procedures by GeoModel Solar. Data not passing QC were excluded from the analysis.

- Geographical position of the site: -28° 28' 06" South, 21° 04' 17" East
- Period of time covered by measurements: 11/2006 to 02/2011
- Time step: 1 hour

Parameter	Equipment
Direct Normal Irradiance [W/m^2]	Kipp and Zonen CH1 pyrheliometer mounted on a SOLYS 2 tracker
Global Horizontal Irradiance [W/m^2]	Kipp and Zonen SP Lite2
Air Temperature [°]	Relative Humidity/Temperature Probe – Model 41382
Relative air humidity [%]	Relative Humidity/Temperature Probe – Model 41382
Wind speed [m/s]	Young - Wind Monitor – Model 05103
Wind direction [°]	Young - Wind Monitor – Model 05103
Rainfall [mm]	Young – Tipping Budget Rain Gauge – Model 52202/52203
Barometric Pressure [mbars]	Young – Model 61302

Tab. 3: Measured parameters and instruments at the Olyfenhoudtsdrif meteo station

The data were logged using Campbell Scientific CR loggers. The primary readings in 1-second interval were integrated on hourly basis. The instruments have been temporarily moved to the TSC station in Upington for the period January to July 2007, which is in about 17 km distance from Olyfenhoudtsdrif.

For the correlation of the satellite-based solar data with the ground measurements, the DNI data measured between December 2006 and February 2011 in Olyfenhoudtsdrif and Upington sites were used. The measured dataset includes both GHI and DNI measurements. Prior to the correlation, the data were thoroughly validated using several methods defined in SERI QC procedures and MESOR project as well as by visual inspection.

The quality control procedures revealed that majority of GHI values were not valid as they went beyond possible physical limits (Fig. 7) and the GHI measurements were not used in the data correlation. It was revealed that the GHI sensor had issues with radiometry and calibration. Later, it was understood that Eskom was mainly interested in the DNI measurements, and the GHI sensor was intended only for use as a back-up, should the main pyrheliometer and tracker malfunction.

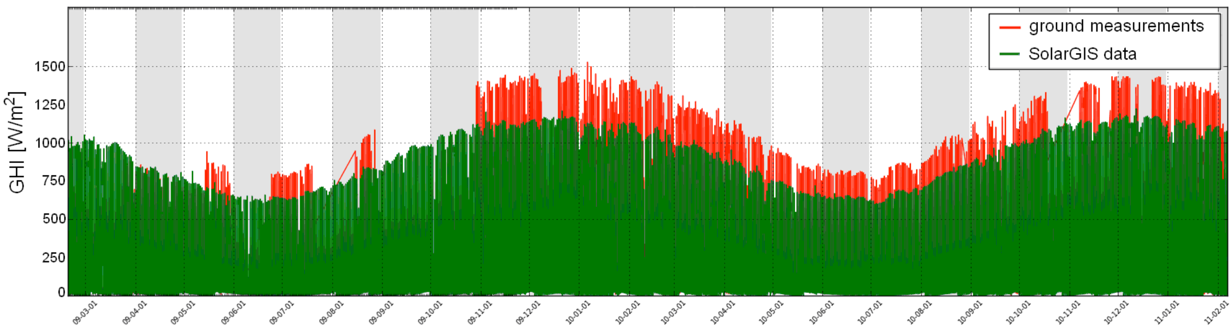


Fig. 7: Ground-measured Global Horizontal Irradiance (red) and data from the SolarGIS satellite model (green). The values of ground measurements go beyond the possible physical limits.

Most of the measurements of DNI passed the numeric tests of quality control methods. As GHI data were found invalid, the tests of DNI-GHI coherence were excluded from the analysis. This significantly limits the effectiveness of the numerical quality control procedures. Therefore additional visual check of the data was performed. Using this method a high number of days with incomplete measurements (few isolated measurements for a whole day) and other unrealistic data were identified (e.g. low DNI value for cloudless days found by the satellite method). Moreover, three periods with gradual signal degradation (compared to the satellite data) indicating the sensor soiling or miscalibration were identified (Fig. 8). All these erroneous data identified by visual check were excluded from the correlation analysis (Tab. 4). The validation procedure of DNI ground measurements identified several types of errors, resulting in significant reduction of usable data for correlation. As the DNI-GHI coherence tests were skipped, it is possible that some of the ground data issues were not identified.

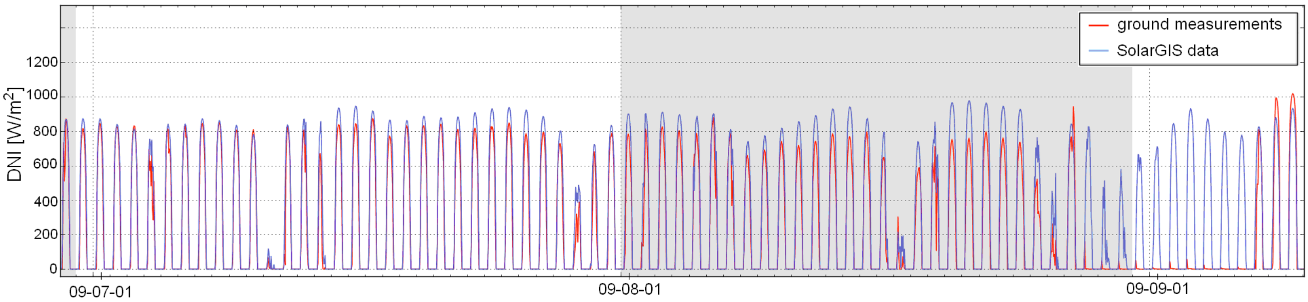


Fig. 8: DNI ground measurements issues:
a) Gradual signal degradation of DNI measurements (red) - from second half of July to August 2009.
b) Partial measurements during the day - in the end of August and beginning of September.

	Raw ground measurements		Data passed by the quality control (daytime)	
	Data points	**Days**	**Data points**	**Days**
GHI	13 304	570	0	0
DNI	31 038	1 322	9 150	755

Tab. 4: Ground measurements quality control results of radiation measurements.

5 METHODS

The SolarGIS data and the Olyfenhoudtsdrif meteo station data include solar radiation, air temperature, relative humidity, wind speed and wind direction. The on-site measurements are used for local adaptation of satellite-based historical time series of solar irradiation (DNI and GHI). The sections below describe methodology used for data correlation and for calculation of the Representative Meteorological Year.

5.1 Correlation of satellite and ground data

The fundamental difference between a satellite observation and a ground measurement is that signal received by the satellite radiometer integrates an area (a footprint of visible channel at the MSG satellite represents an area of about 4 x 5 km) while a ground station represents a pinpoint measurement. This results in a mismatch when comparing instantaneous values from these two observation instruments, mainly during intermittent cloudy weather. Nearly half of the hourly RMSD for GHI and DNI can be attributed to this mismatch (value at sub-pixel scale), which is also known as the “nugget effect” [8]. The satellite pixel is not capable to describe the inter-pixel variability in complex regions, where within one pixel diverse natural conditions mix-up (e.g. fog in narrow valleys or along the coast). In addition, the coarse spatial resolution of atmospheric databases such as aerosols or water vapour is not capable to describe local patterns of the state of atmosphere.

Especially DNI is strongly sensitive to variability of cloud information, aerosols, water vapour, and terrain shading. The relation between uncertainty of global and direct irradiance is nonlinear. Often, a negligible error in global irradiance may have high counterpart in the direct irradiance component.

The CSP projects require representative and accurate time series of DNI. Satellite-derived databases are used to describe long-term solar resource for a specific site. However, their problem when compared to the ground measurements is higher bias and partial disagreement of frequency distribution functions, which may limit their potential to record the occurrence of extreme situations (e.g. very low atmospheric turbidity resulting in a high DNI). A solution is to correlate satellite-derived data with ground measurements to improve the accuracy of the resulting time series.

Global irradiation is less sensitive, even though adaptation for the local site also improves the data quality.

The SolarGIS satellite-derived data are correlated with ground measurement data with two objectives: (i) improvement of the overall bias, and (ii) fit of the frequency distribution function. Optimally, high-quality ground measurements should be available for a period of at least one year, so that all seasons are included. In case of a tight time schedule, a shorter period may be considered for on-site measurements (half of year, several months), however such data may not be capable to cover all deviations. In case of the Upington Solar Park more than 4 years of local measurements were available.

For the enhancement of DNI and GHI in this study, a method was used that is based on an adaptation of the aerosol dataset to match the output of the clear-sky model to the measured irradiance of the cloudless days. The aim of the method is to correct the main model component contributing to the systematic deviations of the modelled solar radiation in the arid areas. The corrected daily aerosols from GEMS/MACC database better represent the local conditions. The method reduces the bias and improves representation of the extreme values within the satellite-based dataset. Moreover the correction of the aerosols maintains the coherence of GHI and DNI for each data pair. For high quality ground data the overall bias of the site-adapted data is usually within the range ±2.0% from the measured data. For the assessment of the enhancement procedures in this study, the following metrics are used:

- Metrics based on the comparison of the all pairs of the 15-minute daytime data values: Mean Bias, and Root Mean Square Deviation (RMSD), in an absolute and relative form (divided by the mean DNI and GHI values);
- Metrics based on the difference of the cumulative distribution functions: KSI (Kolmogorov-Smirnov test Integral) [9].

The normalized KSI is defined as an integral of absolute differences of two cumulative distribution functions D normalized by the integral of critical value $a_{critical}$:

$$KSI\% = \frac{\int_{x\,min}^{x\,max} D_n\,dx}{a_{critical}} * 100$$

$$a_{critical} = V_c * (x_{\max} - x_{\min})$$

$$V_c = \frac{1.63}{\sqrt{N}}, \quad N \geq 35$$

where critical value depends on the number of the data pairs *N*. As the KSI value is dependent on the size of the sample, the KSI measure may be used only for the relative comparison of fit of cumulative distribution of DNI and GHI values. While the satellite data are available in 15-min (30-min) time step the ground measured data are available in a 60-min time step. Therefore all the measures are calculated using aggregated data in the hourly time step.

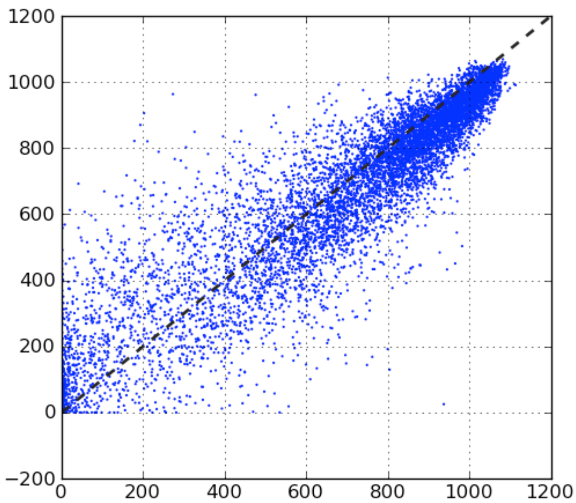
The data correlation is effective for mitigating *systematic* problems in the satellite-derived data such as under/over-estimation of local aerosol loads, especially when the magnitude of this deviation is invariant over the time or has a seasonal periodicity. **The accuracy-enhancement methods are capable to adapt satellite-derived DNI and GHI datasets to the local climate conditions that cannot be recorded in the raw satellite and atmospheric inputs.** The data adaptation is important especially when specific situations such as extreme irradiance events are important to be correctly represented in the enhanced dataset. However, the methods have to be used carefully, as inappropriate use for *non-systematic deviations* or use of *less accurate ground data* leads to accuracy degradation of the primary satellite-derived dataset.

5.2 Site adaptation of DNI and GHI

A preliminary inspection of the satellite data indicated slight underestimation of the Direct Normal Irradiance (DNI) (Fig. 9 left). Available ground measurements, which passed the quality control procedures, were used to adapt the aerosol data so that they better represent the local conditions. As the DNI data were not measured directly in the Solar Park area, the correction was first analysed for the meteo stations Olyfenhoudtsdrif and Upington, and then applied for the Solar Park data. This approach is valid for the stations close each to other with similar weather conditions. This condition is justifiable for the above-mentioned sites (in a distance up to 10 km).

The enhancement method based on the adaptation of aerosol data to the local DNI measurements improved the representation of the satellite-based DNI values (better scattered along the diagonal) - the original underestimation was mostly removed from data (Fig. 9 right).

Fig. 10 shows a comparison of the DNI hourly values in the two-dimensional space described by the DNI clearness index and sun angle – very good fit between measured (yellow) and satellite-adapted values (blue) demonstrates that the **satellite-derived DNI very well match the distribution of the ground-measured values for all types of weather conditions for the full range of sun elevation angles**.



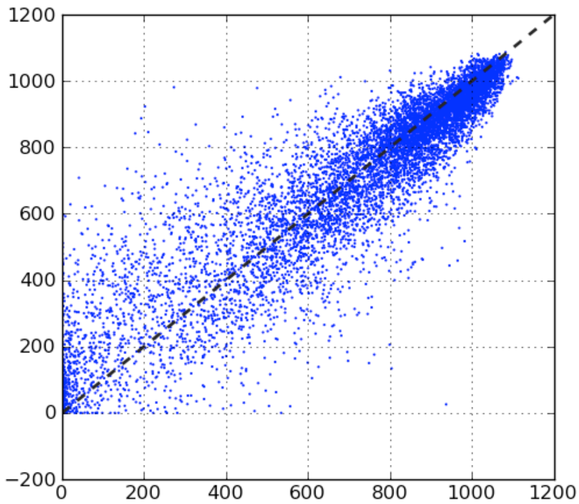


Fig. 9: Correction of the frequency distribution of DNI hourly values. Left: original data, right: site adapted data. The X-axis represents the measured DNI and the Y-axis represents the satellite-derived DNI.

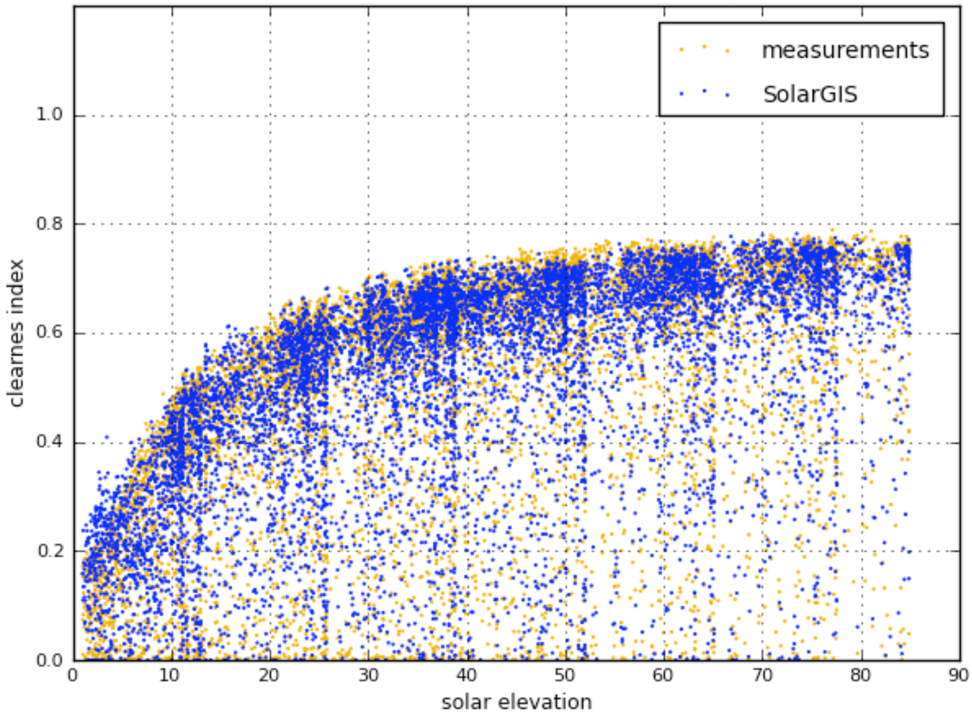


Fig. 10: Clearness index of DNI values (W/m^2) for the Upington Solar Park (South Africa).

The outcome of the site adaptation method for the selected statistical measures is summarized in Tab. 5. Even though the method was focused on the removal of bias, by adaptation of aerosols to local conditions, the RMSD and KSI indicators also improved.

	Mean Bias	RMSD			KSI
		Hourly	Daily	Monthly	
DNI original	-23 W/m^2	129 W/m^2	75 W/m^2	46 W/m^2	214
	-3.3%	18.6%	10.8%	6.6%	
DNI adapted	0 W/m^2	127 W/m^2	70 W/m^2	32 W/m^2	112
	0.04%	18.3%	10.1%	4.6%	

Tab. 5: Comparison of the original DNI satellite data with the corrected values.

The GHI ground measurements of the appropriate quality were not available; therefore it was not possible to directly characterize the improvement of this parameter. As the correction method is based on the adaptation of input parameters of the model, and not the model outcomes, it can be assumed that improvement of the Direct Normal Irradiance will have also its counterpart in the improvement of the Global Horizontal Irradiance.

5.3 Representative Meteorological Year (RMY)

The Representative Meteorological Year (RMY) includes **hourly data** derived from the time series covering complete years from 1994 to 2010. RMY is constructed on the monthly basis, comparing months of individual years with long-term monthly characteristics: cumulative distribution function and mean. The selection of the most representative month takes into account different weights of Direct Normal Irradiance (DNI), Global Horizontal Irradiance (GHI) and Air Temperature (Temper). Relative Air Humidity (Rh), Wind Speed (Wspeed) and Wind Direction (Wdir) are parameters with lower accuracy and therefore they do not have weight in deciding about the choice of the representative month.

The representative months are concatenated into a Representative Meteorological Year. In the selection criteria, the higher weight is given to DNI. In essence, RMY is comparable to the TMY file, with one difference: it is tuned to meet the modelling needs of CSP and CPV, which rely on DNI.

Two data sets are derived from site-adapted time series – one for P(50) and one for P(90). In assembling RMY, the values of DNI, GHI and Air Temperature are only considered, where the weights are set as follows: 0.6 is given to DNI, 0.4 to GHI, and 0.1 to Air Temperature (divided by the total of 1.1).

The **P(50) RMY** data set represents, for each month, the average climate conditions and the most representative cumulative distribution function, therefore extreme situations (e.g. extremely cloudy weather) are not represented in this dataset. Therefore, to capture all possible weather situations it is recommended in power production simulations to use full (17 years) time series of the data.

The **P(90) RMY** data set represents for each month the climate conditions which after summarization of DNI for the whole year result in the value close to P(90) derived by statistical analysis of uncertainties and interannual variability (the conservative DNI value 2729 kWh/m^2, see Section 10, Tab. 16). Thus RMY for P(90) represents the year with the lowest annual value of DNI over the period of 17 years.

Both RMY data sets include the following parameters:

- Direct Normal Irradiance, DNI [W/m^2]
- Global Horizontal Irradiance, GHI [W/m^2]
- Diffuse Horizontal Irradiance, Diff [W/m^2]
- Azimuth and solar angle [°]
- Air temperature at 2 metres, Temper [°C]
- Wind speed at 10 metres, Wspeed [m/s]
- Wind direction, Wdir [°]
- Relative air humidity, Rh [%]

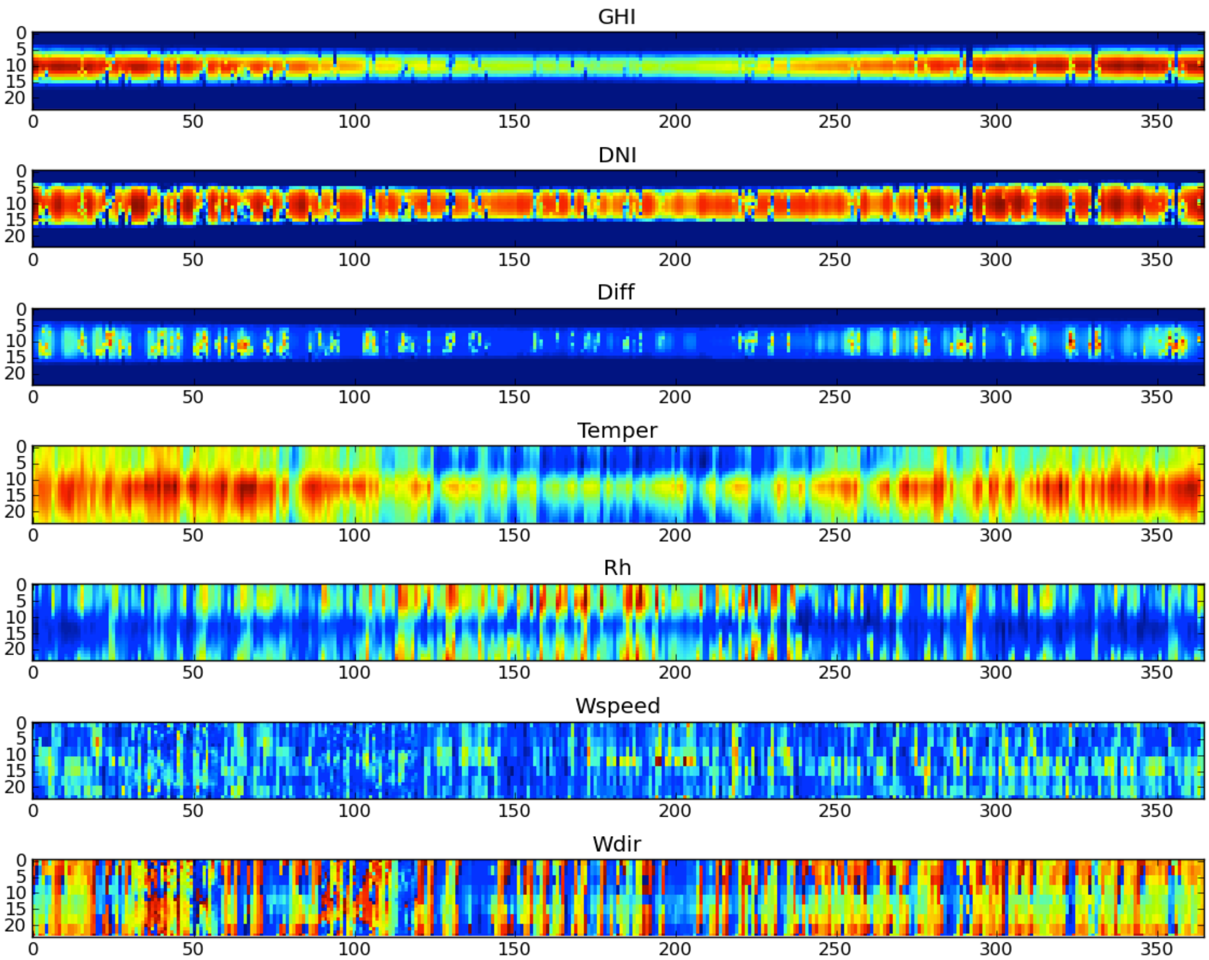


Fig. 11: Snapshot of the P(50) Representative Meteorological Year, RMY

6 GLOBAL HORIZONTAL IRRADIATION AND OTHER WEATHER PARAMETERS

To provide a complete picture of the local solar climate, Tab. 6 shows daily sums of Global Horizontal Irradiation (GHI) for each month with separate diffuse irradiation component. In the table also other parameters are shown: daily average, daily minimum and maximum air temperature, monthly average relative humidity and average wind speed.

	Monthly averages							Daily averages	
	Air temperature [°C]			Relative	Wind	Global horizontal irradiation		Irradiation [kWh/m²]	
	Average	Minimum	Maximum	humidity [%]	speed [m/s]	Sum [kWh/m²]	Int. variability [%]	Global	Diffuse
Jan	27.5	21.8	33.3	26.2	3.7	252	6.4	8.20	1.91
Feb	27.4	22.1	33.4	27.0	3.5	209	6.5	7.39	1.82
Mar	24.9	19.6	31.1	30.3	3.4	199	5.2	6.43	1.50
Apr	20.5	15.0	27.4	34.4	3.5	157	6.5	5.25	1.19
May	15.5	9.7	23.1	40.1	3.4	131	5.6	4.23	0.88
Jun	11.6	5.3	19.8	44.6	3.5	115	3.7	3.84	0.73
Jul	11.4	4.9	19.5	42.8	3.8	128	3.4	4.14	0.75
Aug	13.7	6.9	21.9	36.5	3.8	158	4.0	5.08	0.99
Sep	17.8	11.1	25.8	29.5	3.9	188	5.0	6.29	1.33
Oct	21.9	15.5	29.1	25.9	4.1	227	3.1	7.33	1.59
Nov	24.4	17.8	31.1	24.0	4.2	247	5.6	8.22	1.70
Dec	26.7	20.4	33.2	22.7	3.9	270	5.7	8.69	1.75
YEAR	20.3	14.2	27.4	32.0	3.7	2282	1.3	6.25	1.34

Tab. 6: Global horizontal irradiation (GHI), air temperature, relative humidity and wind speed

The **interannual variability** is calculated from the unbiased standard deviation of GHI calculated from **17 years** of the data (1994 to 2010), considering in a long-term, the normal distribution of monthly and yearly sums. The values in Tab. 6 represent interannual variability at 90% probability of exceedance P(90) which is calculated as ±1.28155 * standard deviation. The *monthly values* of interannual variability indicate year-by-year instability for each month. The *yearly values* give an idea of weather fluctuation when comparing yearly GHI sums. Assuming 17 years, the interannual variability for the individual months is low, ±3.1% to ±6.5%. It is expected that **yearly sum of global horizontal irradiation** will deviate from the long-term average **2282 kWh/m²** in the range of less than **±1.3%**, i.e. it is statistically expected that with 90% probability the sum of GHI will in any single year exceed 2252 kWh/m², and with 10% probability P(10) will exceed 2312 kWh/m².

Global Horizontal Irradiation in this report is calculated from SolarGIS data (see Section 3). The annual average is compared to five other data sources with different temporal and spatial resolution, and time coverage (Tab. 7), even though this approach provides only simplified image of the uncertainty. It is not advised to mechanically compare the databases, as they differ in the use of primary measurements (ground observations versus satellite data), in spatial resolution, applied methods, time coverage, and accuracy.

In general, the databases relying on the interpolation of ground-measured data, such as *Meteonorm* [10] are less reliable in regions with sparse spatial coverage of meteorological stations. *PVGIS/HelioClim-1* [11, 12] is calculated from less reliable database HelioClim-1 and this value can be also used only as an indicator. The global database *NASA SSE* [13] is represented by a very coarse spatial resolution data and simple empirical models, thus smoothing-out regional climate patterns. *SWERA/NREL* database has medium spatial resolution and is computed using CSR model by NREL [14]. SoDa/HelioClim-3 is based on Meteosat MSG data and ESRA models [15].

In general, higher uncertainties have to be expected when comparing data representing different decades due to changes in air pollution and complex climate cycles. In addition, ground observations from the last decades may have been measured with instruments of lower quality and measuring standards.

The modern satellite-based databases have high spatial and temporal resolution, and they are considered as the mainstream source of solar information for solar energy applications - for prefeasibility studies, project optimisation, financing, and for operation and management of solar power plants. *SolarGIS* database shows its high reliability, the **IEA SHC Task 36 data inter-comparison activity, lead by the University of Geneva, has identified SolarGIS as the best quality solar database on the market** [16].

In this context, high quality ground measurements still maintain their important role for validation of satellite models and for deriving key atmospheric parameters for the models.

Database	Data Source	Spatial resolution	Period	GHI [kWh/m^2]
NASA SSE	satellite + model	110 km x 110 km	1983 – 2005	2139
Meteonorm	ground + satellite	Interpolation	1981 – 2000	2280
PVGIS/HelioClim-1	satellite	30 km x 30 km	1985 – 2004	2210
SWERA/NREL	satellite	40 km x 40 km	1985 – 1991	2190
SoDa/HelioClim-3	satellite	4 km x 5 km	2005 – 2009	2145
SolarGIS	**satellite**	**4 km x 5 km**	**1994 – 2010**	**2282**
Overall average				2208
Overall P(90) uncertainty				2.8%
Expected SolarGIS uncertainty				**2.5%**

Tab. 7: Uncertainty of the estimate of long-term yearly average of global horizontal irradiation: comparison of SolarGIS calculation, used in this report, to other five data sources.

In a simplified way, the P(90) uncertainty of GHI can be estimated from the standard deviation calculated from the available data sources (Tab. 7); it results in ±2.8%. Based on the accuracy analysis (Sections 3.1 and 5.2), the conservative **uncertainty for the site-adapted Global Horizontal Irradiation of ±2.5% is considered** in this report.

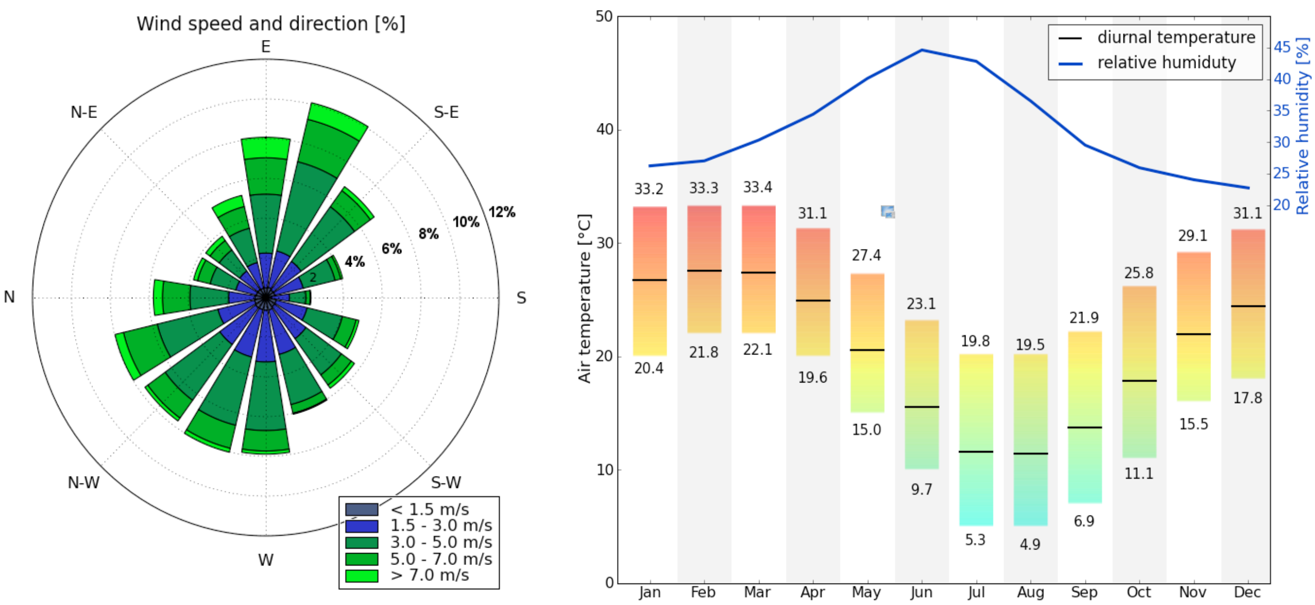


Fig. 12: Basic statistics for air temperature, relative humidity, wind direction and wind speed.

7 GLOBAL IRRADIATION FOR THE OPTIMALLY-INCLINED PLANE

The values in Fig. 13 and Tab. 8 show global irradiation received by **PV modules** G_i **inclined at an optimum angle – which is 28° with azimuth towards North**. In addition to global irradiation, also average daily sums of direct and diffuse components are shown. The monthly averages of G_i are complemented by median, and 10^{th}, 25^{th}, 75^{th}, and 90^{th} percentiles (P_{10}, P_{25}, P_{75}, and P_{90} respectively). The percentiles P_{10} and P_{90} show 80% range of occurrence of daily values within a month or year (column $P_{90} – P_{10}$), while percentiles P_{25} and P_{75} show 50% range of occurrence (column $P_{75} – P_{25}$).

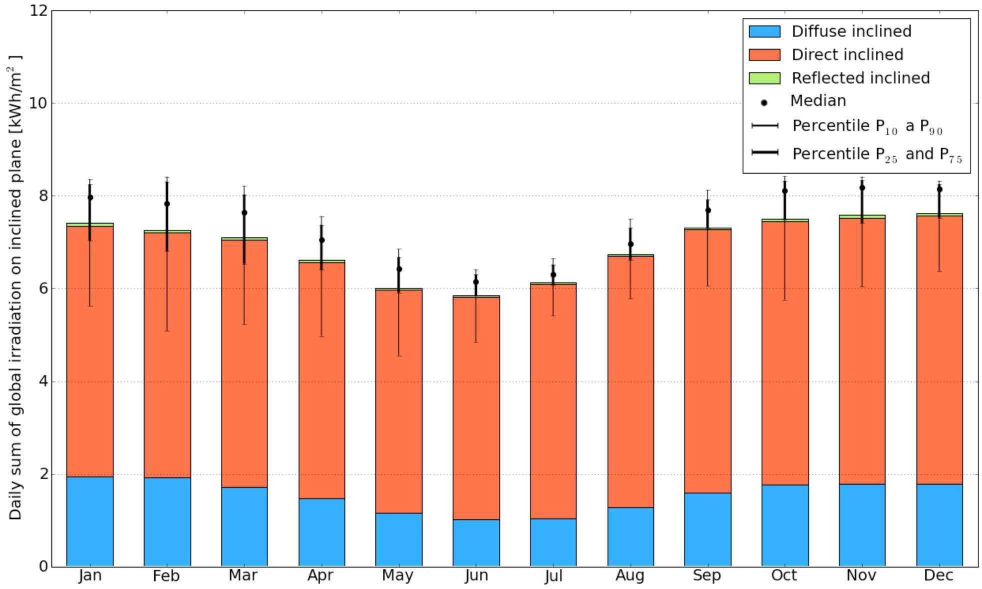


Fig. 13: Global irradiation received by **PV modules tilted at 28° towards North** - monthly values

	Daily sum [kWh/m²]						Monthly sum		
	Average			Variability			Average [kWh/m²]	Monthly share [%]	Interannual variability [%]
	Global	Diffuse	Reflected	Median	P_{75} - P_{25}	P_{90} - P_{10}			
Jan	7.48	1.87	0.06	8.05	7.10 – 8.32	5.68 – 8.43	230	9.0	6.5
Feb	7.33	1.86	0.05	7.91	6.88 – 8.38	5.14 – 8.49	207	8.1	7.0
Mar	7.17	1.65	0.05	7.72	6.61 – 8.11	5.29 – 8.30	222	8.7	5.3
Apr	6.69	1.40	0.04	7.13	6.47 – 7.46	5.03 – 7.65	201	7.9	7.0
May	6.09	1.11	0.03	6.51	5.99 – 6.76	4.62 – 6.94	189	7.4	6.3
Jun	5.92	0.96	0.03	6.22	5.93 – 6.38	4.91 – 6.50	178	7.0	4.9
Jul	6.20	0.98	0.03	6.39	6.17 – 6.60	5.48 – 6.74	192	7.5	3.9
Aug	6.83	1.21	0.04	7.04	6.70 – 7.39	5.85 – 7.59	212	8.3	4.8
Sep	7.40	1.52	0.05	7.78	7.37 – 8.00	6.12 – 8.21	222	8.7	5.0
Oct	7.58	1.68	0.05	8.19	7.56 – 8.40	5.82 – 8.50	235	9.2	3.1
Nov	7.65	1.70	0.06	8.26	7.48 – 8.41	6.10 – 8.49	230	9.0	5.5
Dec	7.69	1.70	0.06	8.21	7.60 – 8.32	6.43 – 8.40	239	9.3	5.1
YEAR	**7.00**	**1.47**	**0.05**	**7.23**	**6.37 – 8.12**	**5.35 – 8.37**	**2555**	**100.0**	**1.4**

Tab. 8: Global irradiation received by **PV modules tilted at 28°** - monthly statistics

The percentile P_{90} indicates a value of daily sum of global in-plane irradiation, which is exceeded for 90% of days within a particular month (or year). In analogy, similar interpretation applies to P_{10}, P_{25}, and P_{75}. Interannual variability is described by P(90) values (see Section 9), and it shows year-by-year weather fluctuation for each month compared to the long-term averages. The interannual variability of yearly sums G_i at P(90) is very low - in the range of ±1.4%. Thus, it is expected at P(90) that yearly sum will deviate from the **long-term average** of **2555 kWh/m^2** in the range from 2519 to 2591 kWh/m^2.

Based on the data analysis, for the annual global in-plane irradiation, **the uncertainty of ±2.8%** is considered.

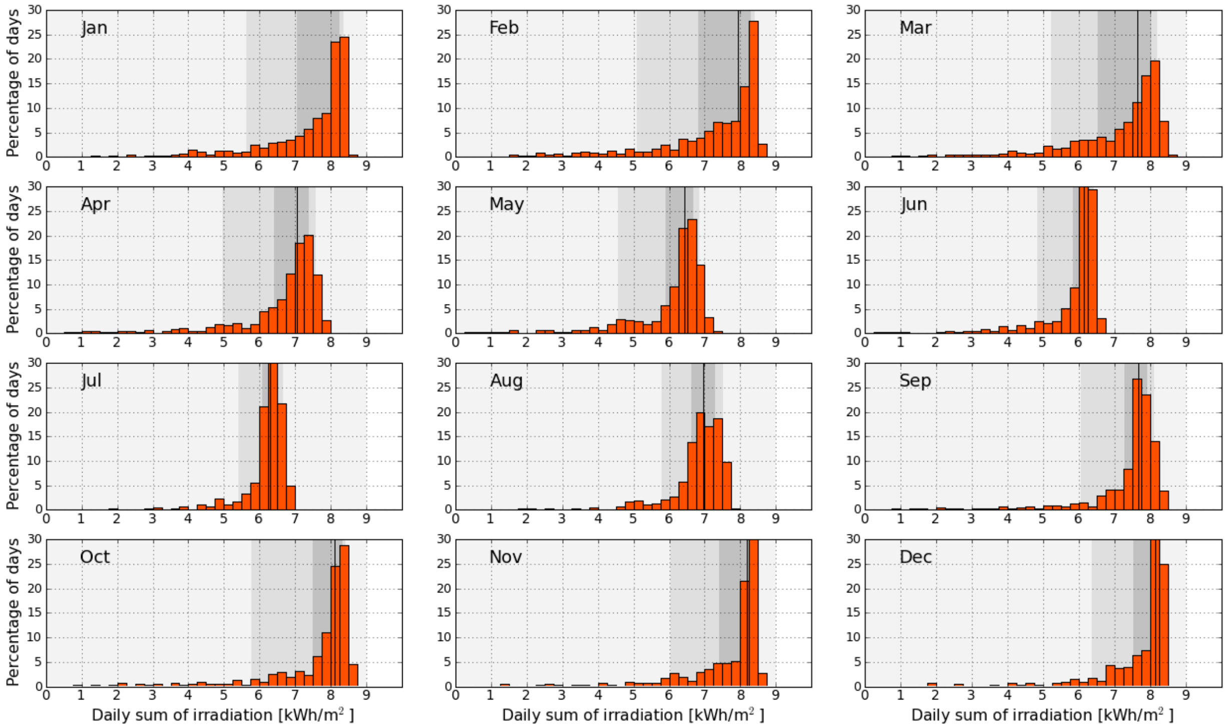


Fig. 14: Global in-plane radiation: monthly histograms of daily summaries. Median is drawn by the vertical line, and percentiles P_{10}, P_{25}, and P_{75}, and P_{90} are displayed with dark grey and light grey colour bands.

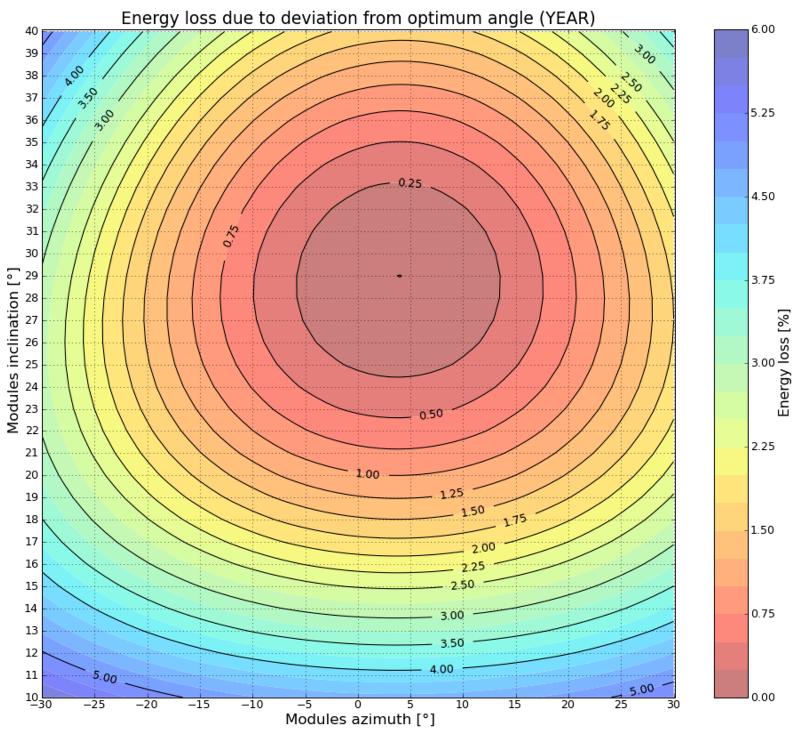


Fig. 15: Loss of annual global irradiation assuming that PV modules deviate from a theoretical optimum inclination and azimuth.

The theoretical optimum module azimuth and inclination was calculated, at which the annual solar radiation is at maximum (Fig. 15). The optimisation was carried out using 15-minute and 30-minute values of global in-plane irradiance.

The optimum inclination of modules is about 28-29°, however, considering the flat shape of the function, the useful range of optimum angles (the range where the annual output is negligibly affected by deviation from optimum) is relatively wide - about 23° to 35°, if allowing for 0.5% yearly energy loss.

8 DIRECT NORMAL IRRADIATION

The values in Fig. 16 and Tab. 9 show the daily summary statistics of the corrected time series of Direct Normal Irradiation (DNI), representing 17 years (1994 to 2010). The monthly averages of daily DNI are complemented by median, and 10th, 25th, 75th, and 90th percentiles (P_{10}, P_{25}, P_{75}, and P_{90} respectively). The percentiles P_{10} and P_{90} show 80% range of occurrence of daily values within a month or year (column $P_{90} – P_{10}$), while percentiles P_{25} and P_{75} show 50% range of occurrence (column $P_{75} – P_{25}$).

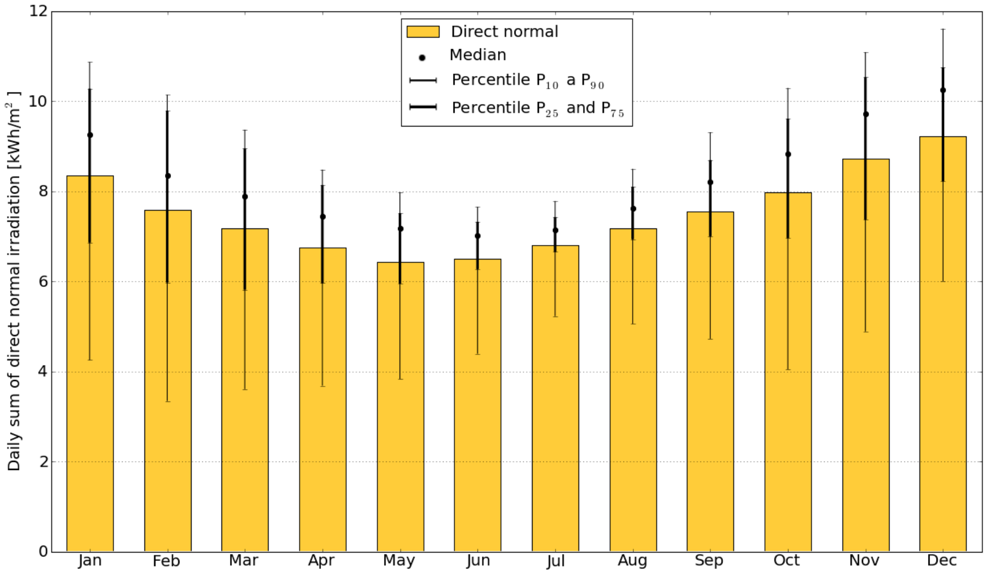


Fig. 16: Monthly statistics of daily sums of Direct Normal Irradiation

	Daily sum [kWh/m^2]				Monthly sum		
	Average	Variability			Average [kWh/m^2]	Monthly share [%]	Interannual variability [%]
		Median	P_{75} - P_{25}	P_{90} - P_{10}			
Jan	8.56	9.50	7.04 – 10.54	4.36 – 11.15	263	9.4	11.0
Feb	7.78	8.56	6.13 – 10.04	3.43 – 10.40	220	7.8	12.7
Mar	7.36	8.09	5.97 – 9.18	3.70 – 9.61	228	8.1	9.8
Apr	6.93	7.64	6.11 – 8.35	3.78 – 8.70	208	7.4	11.8
May	6.60	7.36	6.10 – 7.71	3.93 – 8.18	205	7.3	9.4
Jun	6.68	7.21	6.43 – 7.51	4.50 – 7.85	200	7.1	7.4
Jul	6.98	7.33	6.83 – 7.62	5.36 – 7.98	216	7.7	6.0
Aug	7.36	7.82	7.11 – 8.31	5.19 – 8.72	228	8.1	7.9
Sep	7.75	8.41	7.18 – 8.92	4.85 – 9.55	232	8.2	9.5
Oct	8.18	9.06	7.14 – 9.86	4.15 – 10.56	254	9.0	6.1
Nov	8.95	9.98	7.56 – 10.80	5.01 – 11.38	268	9.5	10.2
Dec	9.47	10.52	8.43 – 11.02	6.16 – 11.91	293	10.4	10.9
YEAR	**7.72**	**7.84**	**6.74 – 9.32**	**4.36 –10.60**	**2816**	**100.0**	**3.3**

Tab. 9: Direct Normal Irradiation, monthly statistics

The **long-term annual average of Direct Normal Irradiation** is **2816 kWh/m^2**.

The percentile P_{90} indicates a value of daily sum of Direct Normal Irradiation, which is exceeded for 90% of days within the particular month or year. In analogy, similar interpretation applies to P_{10}, P_{25}, and P_{75}. Distribution of daily DNI summaries for each month is shown in Fig. 17.

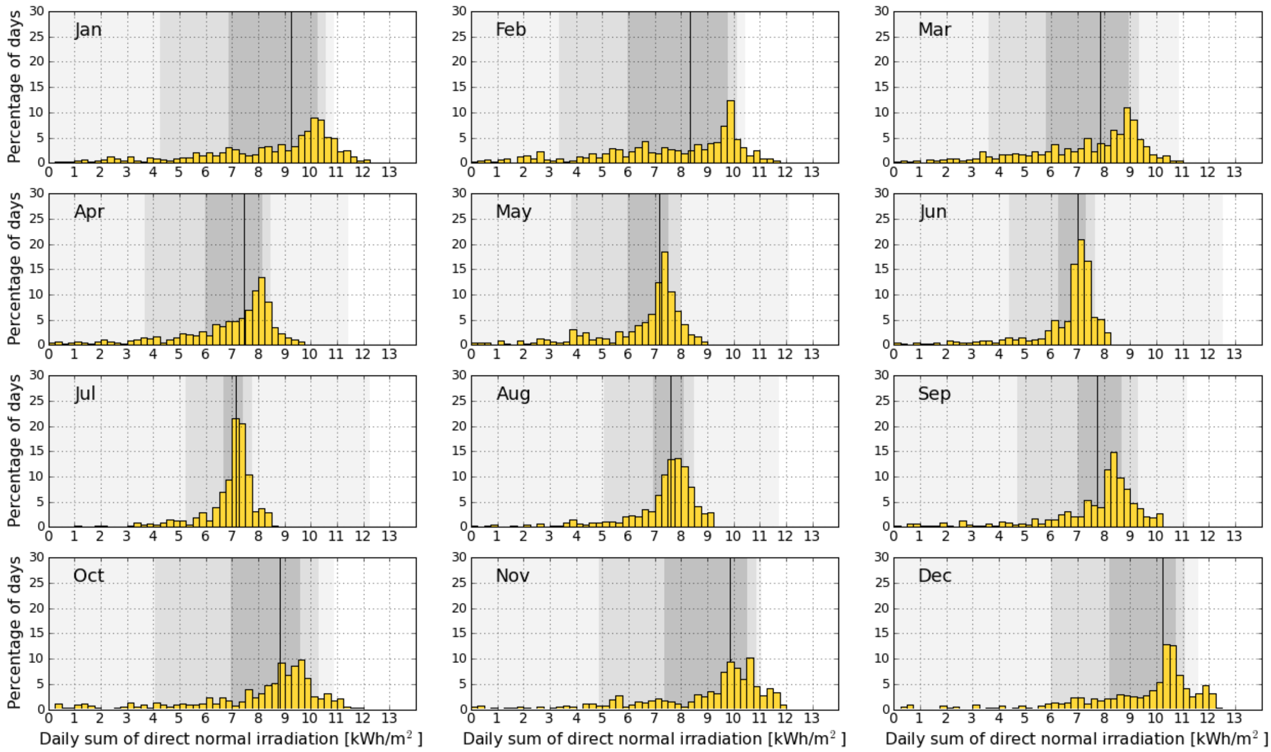


Fig. 17: Direct Normal Irradiation: monthly histograms of daily summaries. Median is drawn by the vertical line, and percentiles P_{10}, P_{25}, and P_{75}, and P_{90} are displayed with dark grey and light grey colour bands.

Interannual variability is described by P(90) values and it shows year-by-year weather fluctuation for the period of analysed time series. Based on the data from last 17 years, the interannual variability of yearly sums of DNI at P(90) is in the range of ±3.3%. The interannual variability of monthly sums goes up to 12.7% in February. The calculation of the long term interannual variability is more elaborated in Section 9.

Direct Normal irradiation in this report is calculated from SolarGIS data (see Section 3). The annual average is compared with five other data sources with different temporal and spatial resolution, and time coverage (Tab. 10). Annual DNI from other data sources is show below.

Database	Data Source	Spatial resolution	Period	D_n [kWh/m^2]
NASA SSE	satellite + model	110 km x 110 km	1983 – 2005	2708
Meteonorm	ground + satellite	Interpolation	1981 – 2000	2812
SWERA/NREL	model	40 km x 40 km	1985 – 1991	2686
SoDa/HelioClim-3	satellite	4 km x 5 km	2005 – 2009	2416
SolarGIS	**satellite**	**4 km x 5 km**	**1994 – 2010**	**2816**
Overall average				2688
Overall P(90) uncertainty				6.1%
Expected SolarGIS uncertainty				**3.0%**

Tab. 10: Uncertainty of the estimate of long-term yearly average of direct normal Irradiation (DNI): comparison of the SolarGIS estimate used in this report to other four data sources.

Calculation of the standard deviation from the available data sources (Tab. 10) results in high P90 uncertainty ±6.1%. Based on the data validation experience, achievable accuracy of local measurements, the satellite model accuracy, and of the correction method, **the uncertainty of the estimate of the site adapted annual DNI for the Upington Solar Park is estimated to ±3.0%.**

Uncertainty determined by the aerosol data

In arid zones, the Direct Normal Irradiance is controlled by the state of the atmosphere, mainly amount and composition of the aerosols. The SolarGIS approach uses aerosol data from the GEMS/MACC databases developed by ECMWF. This data represent daily variability with high accuracy, allowing to model extreme DNI situations (low and high atmospheric turbidity). The reliability of this aerosol information was also proven by the comparison with ground measurements over five other sites in South Africa (Section, 3.1, Tab. 2), where low bias and Root Mean Square Difference indicated a very good fit. The availability of the local ground measurements of DNI allowed for adapting relatively coarse aerosol data (~125x125 km resolution) to the local conditions (Section 5.2).

The Solar Park is located in the area with very low aerosol load, with higher concentrations in summer (November to January) and lower in winter (May to July). This trend is confirmed by several databases (see Fig. 18) even when they differ in the aerosol load magnitude. The magnitude of aerosols adapted for the local site conditions is within the range 0.025 to 0.3 with majority of values below 0.1. During the summer an average aerosol load is around 0.06. This pattern is very stable over the whole period; therefore the average monthly value can be used as a good approximation for the periods without GEMS/MACC aerosol data coverage (1994 to 2002). On the other hand the aerosol data represented by monthly average are not capable to represent extreme situations, thus resulting in slightly simplified daily variability. As the magnitude of the aerosol load is not large, this simplification will result, for majority cases, in deviation lower than ±5% on the daily basis, and within ±2.0% on the yearly basis. Moreover, some variability imposed by water vapour is still presented for the whole 17 years data period.

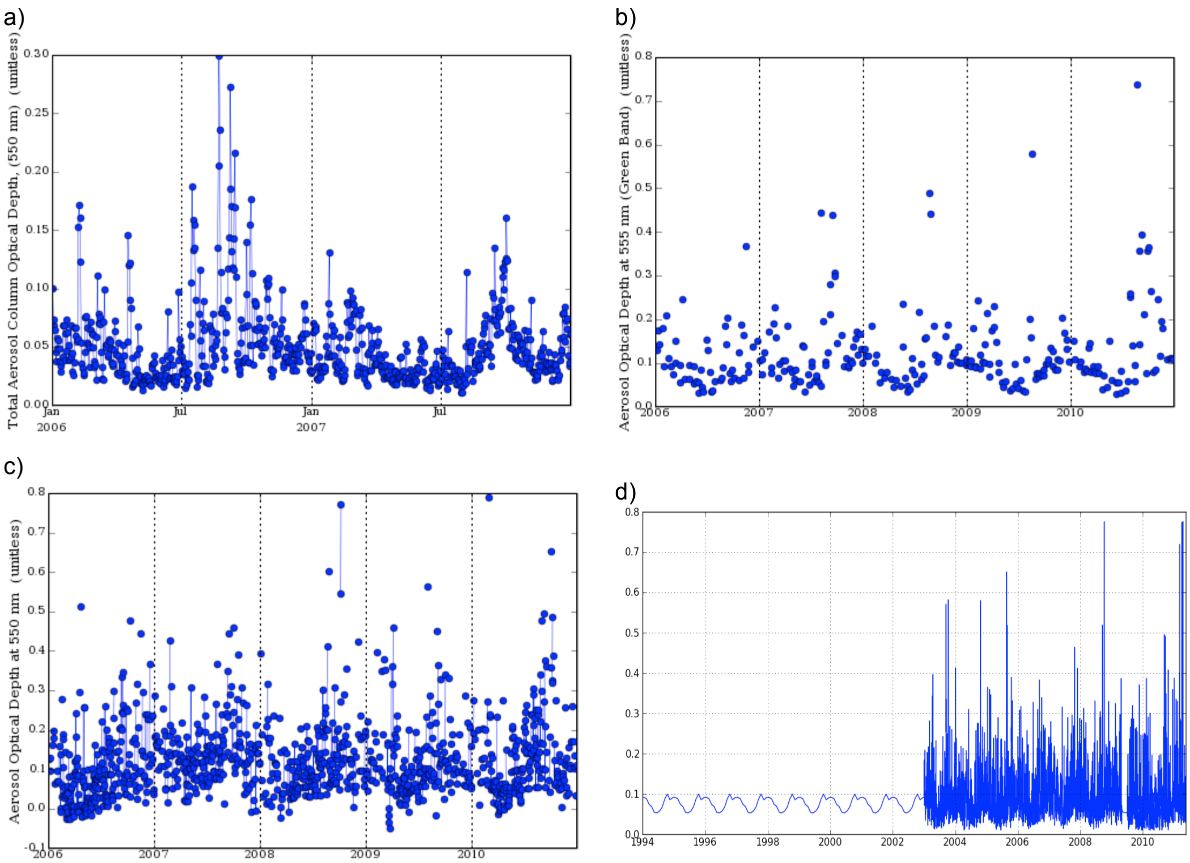


Fig. 18: Comparison of Aerosol Optical Depth from different sources: a) GOCARD, b) MISR-terra, c) MODIS-aqua and d) GEMS/MACC. Analyses and visualizations of data products a) to c) were produced with the Giovanni online data system, developed and maintained by the NASA GES DISC.

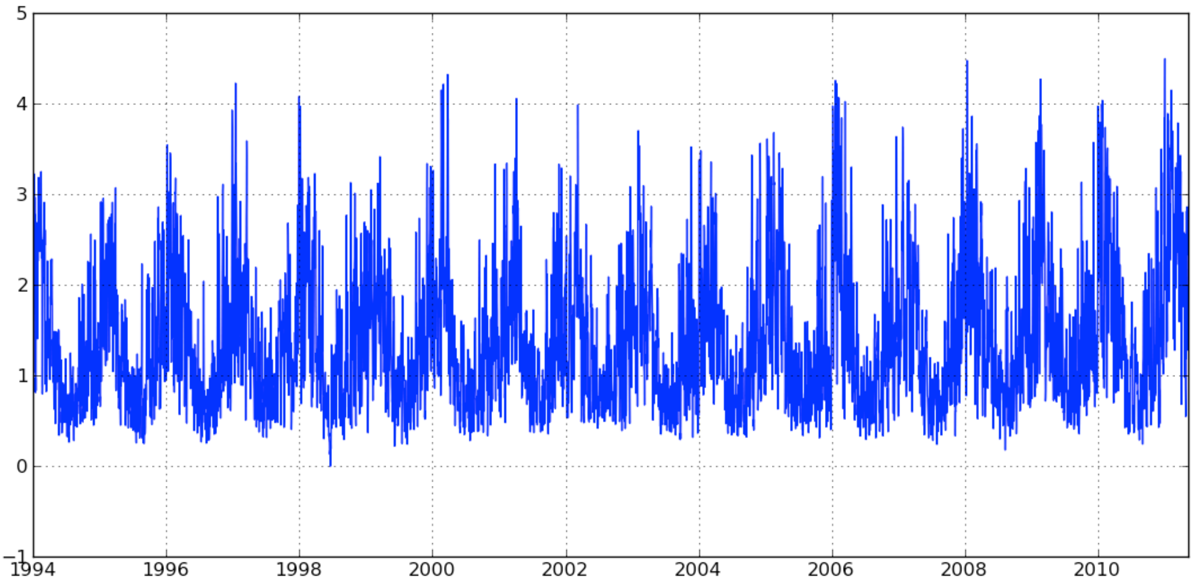


Fig. 19: Water vapour database from GEMS and CFSR (NOAA) database used in the SolarGIS model.

Local spatial variability of solar radiation

The planned Solar Park extends over an area of ca 50 km^2. This area is flat without specific terrain features and no significant microclimatic effects are expected. The Northern and Southern parts of the Solar Park are in a distance of ca 20 km, with an elevation difference of about 100 m (820-920 m a.s.l). The arid landscape is homogeneous, providing similar conditions in the whole area.

The opposite sides of the Solar Park show small difference of the long-term average of Direct Normal Irradiance (1.9%) and Global Horizontal Irradiance (1.2%), which may be attributed to the cumulative effect of two factors:

- Small change of the aerosol load and cloudiness over the distance of ca 20 km,
- Different optical thickness of the atmosphere due to slight change of the elevation.

The site used to characterize Solar Park in this report was chosen in the central part of the Solar Park. The variability of the long-term average of DNI and GHI within the Solar Park should stay below ±1.0% and ±0.6%, respectively.

9 INTERANNUAL VARIABILITY OF SOLAR RADIATION

Weather changes in cycles and has also stochastic nature. Therefore annual solar radiation in each year can deviate from the long-term average in the range of few percent. The estimation of interannual variability below shows the magnitude of this change. The uncertainty of DNI prediction is highest if only one single year is considered, but when averaged for a longer period, weather oscillations even out and approximate to the long-term average.

The **interannual variability** is calculated from the unbiased standard deviation of Global Horizontal Irradiation (GHI) and Direct Normal Irradiation (DNI) over **17 years**, considering, in the long-term, the normal distribution of the annual sums (Tab. 20).

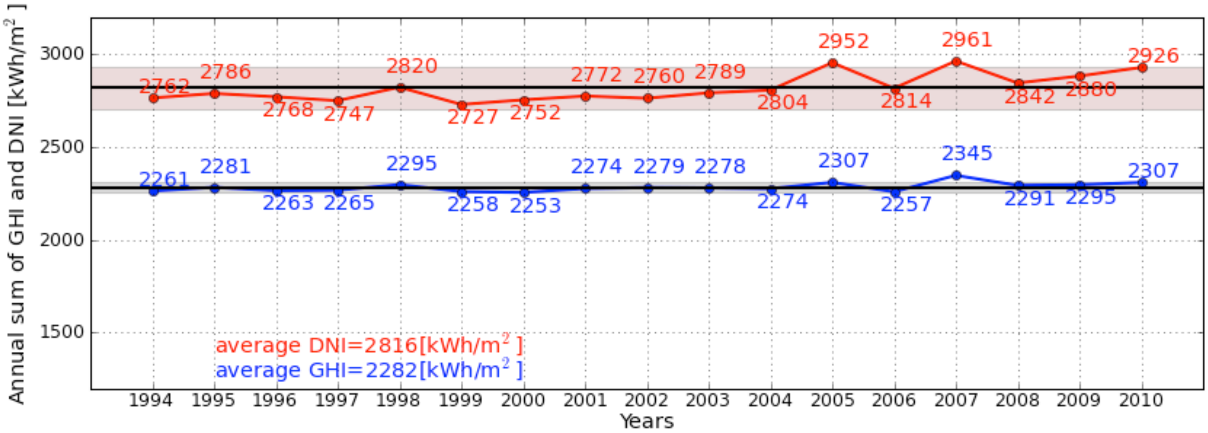


Fig. 20: Annual sum of Global Horizontal Irradiation (GHI) and Direct Normal Irradiation (DNI) in the 1994 – 2010 period, including average (*avg*, black line) and standard deviation (*stdev*, grey band) [kWh/m^2]

Tab. 11 and 12 shows an expectation of GHI and DNI values that is to be exceeded at P(90) for a consecutive number of years. The variability (*var*) for a number of years (*n*) is calculated from the standard deviation (*stdev*):

$$\mathrm{var}_n = \frac{stdev}{\sqrt{n}}$$

The uncertainty characterised by P(90), i.e. 90% probability of exceedance, is calculated from the variability (*var$_n$*), multiplying it with 1.28155.

Years	1	2	3	4	5	6	7	8	9	10	20
Variability [±%]	1.0	0.7	0.6	0.5	0.5	0.4	0.4	0.4	0.3	0.3	0.2
Uncertainy P(90) [±%]	1.3	0.9	0.8	0.7	0.6	0.5	0.5	0.5	0.4	0.4	0.3
Minimum G_h at P(90) [kWh/m^2]	**2252**	**2261**	**2264**	**2266**	**2268**	**2270**	**2270**	**2270**	**2273**	**2273**	**2275**

Tab. 11: Annual sum of **Global Horizontal Irradiation (GHI)** that should be exceeded with 90% probability in the period of 1 to 10 (20) years

Years	1	2	3	4	5	6	7	8	9	10	20
Variability [±%]	2.6	1.8	1.5	1.3	1.2	1.1	1.0	0.9	0.9	0.8	0.6
Uncertainy P(90) [±%]	3.3	2.3	1.9	1.7	1.5	1.4	1.3	1.2	1.1	1.1	0.7
Minimum D_n, P(90) [kWh/m^2]	**2723**	**2751**	**2762**	**2768**	**2774**	**2776**	**2779**	**2782**	**2785**	**2785**	**2796**

Tab. 12: Annual sum of **Direct Normal Irradiation (DNI)** that should be exceeded with 90% probability in the period of 1 to 10 (20) years

Tabs. 11 and 12 show consequences of interannual variability if DNI and GHI for different number of consecutive years is estimated. Few examples how this information can be interpreted:

i. GHI interannual variability of 1.3% has to be considered for any single year. In other words, assuming that the long-term average is 2282 kWh/m^2, it is expected (at 90% probability) that annual Global Horizontal Irradiation exceeds at any single year value of 2252 kWh/m^2;

ii. Within a period of three consecutive years, it is expected at P(90) that annual average of DNI exceeds value of 2762 kWh/m^2;

i. For a period of 20 years, it is expected at P(90) that due to interannual variability the estimate of the long-term annual DNI average may be off within the range of ±0.7%. Thus assuming that the estimate of the long-term average is 2785 kWh/m^2, it can be expected at P(90) that *due to variability of weather*, it should be at least 2796 kWh/m^2.

It is to be underlined that prediction of the future power production is based on the analysis of the recent historical data. Future weather changes may include man-induced or natural events such as volcano eruptions, which may have impact on this prediction.

10 UNCERTAINTY OF ESTIMATES

In this Section, the uncertainty of the estimate of the annual values is quantified.

In arid zones with sparse clouds the accuracy of the model output is mainly determined by the parameterization of the atmosphere, especially the qualitative and quantitative properties of aerosols. The accuracy of the **GHI and DNI values calculated from the satellite-based solar radiation models** depends on the following factors:

- Quality of input parameters describing actual state of the atmosphere, such as aerosols and water vapour;
- Simulation accuracy of the cloud transmittance derived from the satellite data,
- Uncertainty of irradiance models, which always have inherent simplifications.

The uncertainty of the **ground-measured GHI and DNI** depends on the following factors:

- Accuracy of the instruments
- Maintenance practices, including cleaning, calibration, and quality-check procedures.

Taking into account uncertainties of both types of data (satellite and ground measured), the combined effect of two integrated components of the uncertainty of the site adapted GHI and DNI values has to be considered:

1. Uncertainty of the estimate of the site-adapted annual GHI and DNI values (Section 5.2);
2. P(90) interannual variability in any particular year, due to changing weather, which is ±3.3% for DNI and 1.3% for GHI. The uncertainty due to weather variability over a period of 20 years decreases to about ±0.7% for DNI and 0.3% for GHI (Section 9).

The two above mentioned uncertainties may combine in the conservative expectation of the minimum GHI and DNI for any single year (Tab. 13 and 15) and averaged over the period of 20 years (Tab. 14 and 16).

	Uncertainty [%]	Cumulative uncertainty [%]	Annual GHI [kWh/m^2]
Annual average			2282
Minimum value assuming P(90) uncertainty of the estimate	2.5%	2.5%	**2225**
Minimum value assuming P(90) uncertainty of the interannual variability for one year	1.3%	2.8%	**2218**

Tab. 13: Cumulative uncertainty of **GHI for any single year**

	Uncertainty [%]	Cumulative uncertainty [%]	Annual GHI [kWh/m^2]
Annual average			2282
Minimum assuming P(90) uncertainty of estimate	2.5%	2.5%	**2225**
Minimum assuming P(90) uncertainty of interannual variability for 20 years	0.3%	2.5%	**2225**

Tab. 14: Cumulative uncertainty of **GHI for a period of 20 years**

	Uncertainty [%]	Cumulative uncertainty [%]	Annual DNI [kWh/m^2]
Annual average			2816
Minimum value assuming P(90) uncertainty of the estimate	3.0%	3.0%	**2732**
Minimum value assuming P(90) uncertainty of the interannual variability for one year	3.3%	4.5%	**2690**

Tab. 15: Cumulative uncertainty of **DNI for any single year**

	Uncertainty [%]	**Cumulative uncertainty [%]**	**Annual DNI [kWh/m^2]**
Annual average			2816
Minimum assuming P(90) uncertainty of estimate	3.0%	3.0%	**2732**
Minimum assuming P(90) uncertainty of interannual variability for 20 years	0.7%	3.1%	**2729**

Tab. 16: Cumulative uncertainty of **DNI for a period of 20 years**

This analysis is based on the data representing a history of year 1994 to 2010, and on the expert extrapolation of the related weather variability. This report may not fully reflect possible man-induced climate change or occurrence of extreme events such as large volcano eruptions in the future.

11 CONCLUSIONS

11.1 Site adaptation of the satellite based data

Correlation of the satellite-based solar time series with ground measurements allows mitigating the systematic deviations present in the satellite data at the Upington Solar Park. The correction derived from the DNI measurements at the Olyfenhoudtsdrif and Upington meteo sites were applied to the centre part of the Solar Park. The method based on adaptation of aerosol values to the DNI measurements reduced bias of the data for period with available data, and it has been further applied to the complete time series (17 years of data). All three measures of the data accuracy (bias, RMSD and KSI) show improvements.

11.2 Representative Meteorological Year

Representative Meteorological Year (RMY) was derived for P(50) and P(90) cases. The RMY was constructed on the monthly basis, selecting from the 17 years of time series the monthly best representing mean and distribution of values compared to the long-term statistics. For the selection of the most appropriate month, the highest weight was given to DNI and GHI parameters. The P(50) RMY data set represents the average climate conditions and the most representative cumulative distribution function, therefore extreme situations (e.g. extremely cloudy weather) are not represented in this dataset. The RMY for P(90) probability represents the conservative estimate by choosing months to compose an artificial year describing the weather conditions with the lowest annual value of DNI over the period of 17 years.

11.3 Uncertainty and interannual variability of solar resource

Uncertainty of the annual Direct Normal Irradiation prediction based on the SolarGIS data is estimated to ±3.0% and 2.5% for annual value of the Global Horizontal Irradiation. This estimate considers correlation of the satellite data with ground measurements and adapting the accuracy of the satellite data to the local conditions

Interannual variability of solar resource is determined by weather cycles and at probability P(90). It is estimated that Direct Normal irradiation in any single year may deviate up to ±3.3% from the long-term annual average estimated in this study, and this value for Global Horizontal Irradiation is ±1.3%. For a period of 20 years this uncertainty remains about ±0.7% fro DNI and about ±0.3% for GHI, respectively. Possible man-induced climate change or global volcano eruptions are not considered in this study.

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13 SUPPORT INFORMATION

13.1 Background on GeoModel Solar

Primary business of GeoModel Solar is in providing support to the site qualification, planning, financing and operation of solar energy systems. We are committed to increase efficiency and reliability of solar technology by expert consultancy and access to our databases and customer-oriented services.

The Company builds on 20 years of expertise in geoinformatics and environmental modelling, and 10 years in solar energy and photovoltaics. We strive for development and operation of new generation high-resolution quality-assessed global databases with focus on solar resource and energy-related weather parameters. We are developing simulation, management and control tools, map products, and services for fast access to high quality information needed for system planning, performance assessment, forecasting and management of distributed power generation.

GeoModel Solar operates a set of online services, integrated within SolarGIS® information system http://solargis.info, which includes data, maps, software, and geoinformation services for solar energy.

Members of the team have long-term experience in R&D and are active in the following international initiatives:

- International Energy Agency, Solar Heating and Cooling Program, Task 36 Solar Resource Knowledge Management and the newly established Task 46 Solar Resource Assessment and Forecasting
- EU COST Action ES 1002: Weather Intelligence for Renewable Energies (WIRE).

Our key reference for years 2001-2008 has been development and operation of the PVGIS web site, and R&D activities in the ESTI laboratory of the European Commission's Joint Research Centre. At present, the experts of GeoModel Solar pursue collaboration with international partners in solar energy, such as NREL (US), SUNY (US), JRC (EU), CENER (ES), Mines ParisTech (FR), DLR (DE), Fraunhofer ISE (DE), Stellenbosch University (ZA), University of Geneva (CH), and consultancy and engineering companies from Europe, North America, South Africa, India, and China.

13.2 Legal information

Considering the nature of climate fluctuations, interannual and long-term changes, as well as the uncertainty of measurements and calculations, GeoModel Solar cannot take guarantee of the accuracy of estimates. GeoModel Solar has done maximum possible for the assessment of climate conditions based on the best available data, software and knowledge. SolarGIS is the registered trademark of GeoModel Solar. Other brand names and trademarks that may appear in this study are the ownership of their respective owners.

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