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ONLINE DATA AND TOOLS FOR ESTIMATION OF SOLAR ELECTRICITY IN AFRICA: THE PVGIS APPROACH

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ABSTRACT: we present interactive web tools for map-based query of a solar radiation database and for performance assessment of solar photovoltaic systems. The high-resolution geographic database covers the Mediterranean Basin, Africa and South-West Asia. Daily global irradiation was primarily computed from Meteosat satellite images by the Heliosat-2 method and stored in the HelioClim-1 database. From this database, long term monthly and yearly averages of global horizontal irradiation were derived for the period 1985-2004. Using the PVGIS method, based on the solar radiation model *r.sun*, interpolation of the clear-sky index and terrain shadowing, the original spatial resolution of HelioClim-1 database (15’ x 15’) was enhanced to 2 km x 2 km. A set of web tools was developed to query basic climatic and geographic data for a chosen location, and to estimate and optimize energy output from photovoltaic system at arbitrary inclination and orientation of modules. The PVGIS system can be accessed at http://re.jrc.ec.europa.eu/pvgis/pv/.
Keywords: HelioClim, PVGIS, geographical information system, solar radiation, PV system

1 INTRODUCTION

This paper presents interactive web applications for map-based query of a solar radiation database and for performance assessment of photovoltaic systems. The high-resolution database covers the Mediterranean Basin, Africa and South-West Asia. This satellite-derived database was developed to complement the existing radiometric ground network which consists of small number of heterogeneously distributed stations and which is not sufficient for developing detailed maps of solar energy resource.

At the Ecole des Mines de Paris/Armines, the Heliosat-2 method was developed to calculate global horizontal radiation from Meteosat satellite images. The database known as HelioClim-1 was created using Heliosat-2, and it can be accessed through the SoDa intelligent web system.

At the Joint Research Centre, the PVGIS (Photovoltaic Geographical Information System) has been developed and implemented for the European subcontinent. PVGIS integrates a geographical database with a solar radiation model and with tools designed for technical and economic assessment of the performance of solar photovoltaic systems.

The collaboration between Ecole des Mines de Paris and Joint Research Centre has brought an added-value to renewable energy users by an integration of a subset of the HelioClim-1 data into PVGIS, by their further processing and providing the geographical extension.

In this paper we present the PVGIS internet applications that give access to the subset of HelioClim-1 data by the means of map-based query and that enable a simple assessment of solar electricity generation for a chosen location. Besides the African continent, PVGIS covers also regions of the Mediterranean Basin and South-West Asia.

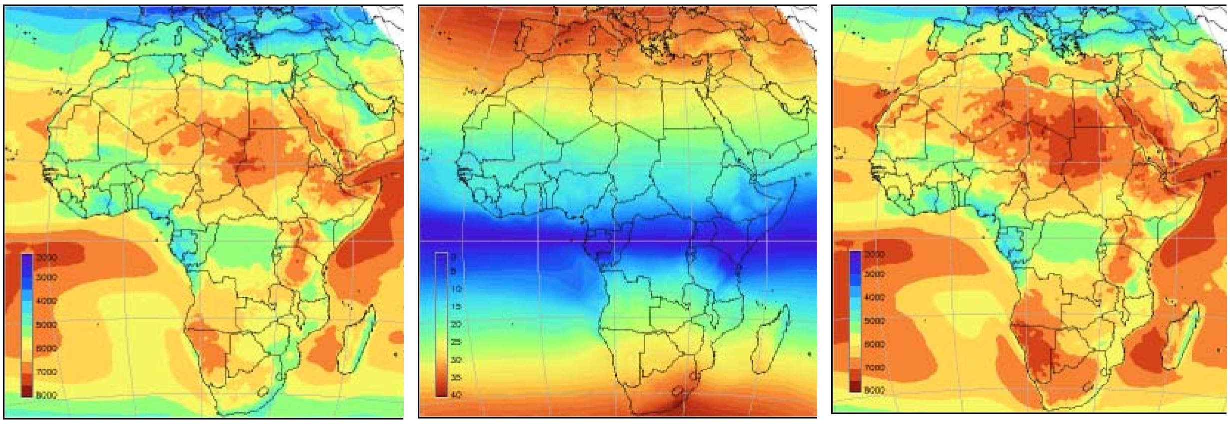
2 SOLAR RADIATION DATA IN THE PVGIS DATABASE

HelioClim-1 is a solar radiation database that was developed from Meteosat satellite images by the application of the Heliosat-2 method [1, 2]. This database consists of daily values of global horizontal irradiation that were systematically calculated over the period 1985-2005. The spatial extent of the HelioClim-1 database corresponds to the field of view of the Meteosat Prime disc (the satellite being centered at latitude 0° and longitude 0°). The primary spatial resolution is about 15 arc minute, i.e. a grid cell close to the equator represents an area of about 30x30 km². The accuracy of the HelioClim-1 was assessed by comparisons with measurements of the WMO radiometric network in Europe (55 sites) and Africa (35 sites) for the period 1994-1997. The RMS error is 35 $W.m^{-2}$ (17%) for daily mean irradiance, 25 $W.m^{-2}$ (12%) for monthly mean irradiance, and bias is less than 1 $W.m^{-2}$ for the whole data set.

The primary HelioClim-1 data (daily values and monthly averages) can be accessed through the SoDa web system [3]. However in such a form they can be used only by a limited number of experts. Therefore the HelioClim-1 data were integrated into PVGIS and processed to provide enhanced information and functionality.

The processing took place in the year 2005, therefore the PVGIS database includes values representing time period of 1985-2004. The solar radiation database for Africa consists of two segments:

1. Long-term monthly and yearly averages of daily global and diffuse horizontal irradiation. This segment was spatially enhanced by digital elevation model to 2-km grid resolution.
2. Probability distribution statistics of daily values of global horizontal irradiation that is kept in the original data resolution (15 arc-minutes).



a) b) c)

Figure 1: a) yearly average of daily global horizontal irradiation (Wh m^{-2}); b) optimum inclination angle of fixed equator-facing PV modules to maximize energy yield (degrees); c) yearly average of daily global irradiation on a plane inclined at the optimum angle (Wh m^{-2})

2.1 Monthly and yearly averages

The first data segment contains HelioClim-1 long-term monthly and yearly averages of daily sums of global horizontal irradiation that were calculated from 20-years time series of daily values. The original data were converted to Lambert azimuthal map projection and their spatial resolution was enhanced using SRTM-30 digital elevation model [4] to 2x2 km^2. The method is based on the use of solar radiation model *r.sun*, spatial interpolation and other tools implemented in the open source geographical information system GRASS [5]. The data account for terrain shadowing by mountains as simulated in the 2-km grid resolution. More information about the methodology can be consulted in our previous publications [6, 7, 8].

To allow for calculation of solar electricity from PV modules at arbitrary inclination and orientation, the diffuse component is needed. To estimate it, we have implemented the Page model [9]: We took the point values of the clearness index from the NASA SSE (Surface meteorology and Solar Energy) reference sites [10] and interpolated them over the region. This resulted in grid data layers with 2-km grid resolution representing monthly averages of diffuse horizontal irradiation. However it should be noted, that due to uneven distribution of the input data and their absence over the ocean, the Page model provides only approximate estimation of the diffuse component of global irradiation.

An example of the solar radiation database is shown in Figure 1 that shows yearly average of daily global horizontal irradiation, optimum inclination angle of equator-facing PV modules to maximize energy yield, and the average daily global irradiation at this angle.

2.2 Probability distribution statistics

The second segment contains probability distribution statistics of daily global horizontal irradiation for each month and year. It is kept in the geographical longitude/latitude coordinate systems with 15 arc-minute grid resolution. These data were calculated from the original HelioClim-1 daily values by categorizing them into bins, each with a width of 500 Wh m^{-2}. The distribution statistics makes it possible to derive a histogram for each location in the region for the whole year or the chosen month. The values represent larger areas (about 30x30 km² at the equator) without considering the possible shadowing by local terrain. Therefore in a complex terrain the local variation may differ from the regional pattern represented in this segment of the database.

2.3 PVGIS outputs

The database, in combination with developed tools, is used for calculation of various outputs related to solar electricity generation. The values represent long-term monthly and yearly averages of the period 1985-2004:

- global irradiation for horizontal and inclined surfaces and its beam, diffuse and reflected components;
- clear-sky and real-sky daily profiles of irradiances for each month for arbitrary inclined and oriented surface (considering also terrain shadowing);
- electricity generation from fixed and tracking PV systems;
- display of local horizon;
- optimum inclination and orientation of fixed PV modules to maximize solar energy yield;
- cumulative yearly and seasonal histograms showing probability distribution of daily global radiation.

Besides the above mentioned climatic data, the system also contains other geographical data, such as digital elevation model, Global Land Cover 2000 [11], and basic vector layers of administrative boundaries, cities, and rivers. These data were also used for preparing maps to facilitate location and selection of a suitable site for solar energy systems, using the online web tools.

3 ONLINE TOOLS FOR SOLAR ELECTRICITY ESTIMATIONS

To provide access to the PVGIS data and software over the Internet we have developed a set of interactive applications. The web interface is designed to give information on solar radiation and PV electricity generation in the form of maps, graphs and tables for any location in the region. A location can be chosen either by browsing/zooming and clicking on a map, choosing a country and a settlement from the list, or directly by setting latitude/longitude values. The output data are displayed in a separate window. The elevation and landcover maps, as well as climatic and PV-potential maps provide an overview of the spatial variability of the data. The web interface is organized into three separate applications.

3.1 Querying maps of solar irradiation and related climatic data

This application provides long-term monthly and yearly averages of global irradiation at horizontal and inclined surfaces, as well as Linke turbidity, ratio diffuse/global irradiation and the estimation of optimum inclination angle of the PV modules to maximize yearly energy yield. For a chosen location, an estimation of the relative deficit in yearly horizontal irradiation due to terrain shadowing is also displayed. The data displayed represent a grid cell with 2-km spatial resolution.

Upon request, the application generates on-the-fly cumulative probability distribution of daily global horizontal irradiation for the whole year as well as for March, June, September and December. As these data are processed at lower spatial resolution (grid cell 15-arc minutes), the histograms outline the distribution of values within a larger area and do not take into account local differences in the terrain elevation and shadowing.

3.2 Estimation of the average daily variation of global irradiance

For a chosen inclination and orientation of a module, the user can request an average daily profile of clear-sky and real-sky irradiances for a chosen month. As an option the system can also display the daily irradiance profile received by a 2-axis sun-tracking system. The calculation of the daily variation in solar irradiance is performed on request by a separate program running on the server. The calculation also takes into account the shadowing by local terrain features (at the 2-km data resolution).

3.3 Estimation of potential solar electricity generation

This application calculates the yearly potential electricity generation E [kWh] from a PV system with fixed-mounted modules at chosen inclination/orientation, and alternatively for 2-axis tracking systems, using the formula:

$$E = 365\, P_k\, r_p\, H_{h,i}$$

where P_k (kW) is the peak power installed, r_p is the system performance ratio (a typical value for a system with modules from mono- or polycrystalline silicon is 0.75) and $H_{h,i}$ is the monthly or yearly average of daily global irradiation on the horizontal or inclined surface. The system performance ratio of 0.75 assumes system losses 25% as default, where 9% is assumed as an 'average' loss due to temperature effects and the remaining 16% can be modified by the user.

Upon request, the calculator calculates the optimum inclination/orientation of the PV modules to harvest maximum electricity over the whole year. It also provides estimates for 2-axis tracking systems. For the chosen location, the system outputs a graph of the local horizon outline (based on the 2-km digital elevation model).

3.4 Other technical aspects

At present, the interactive system communicates in five languages – English, French, German, Italian and Slovak. For all three applications the maps have been calculated beforehand while the calculations for a single (user-defined) location are performed upon request. Since these calculations are rather computing-intensive, a number of steps have been implemented to optimize their speed. Calculations are performed by stand-alone programs written in the C language on the web server, thus the calculation times do not depend on the speed of the users' computer. This makes it much faster than if the program was written in one of the scripting languages for the web (such as PHP or Perl). The data are stored in binary form with a constant record length for each grid point. In this way, the reading of input data is an O(1) operation, independent of the size of the data set.

The total amount of database is approximately 7 GB for the present dataset with ~20 million grid points. Apart from the programs calculating the irradiance and irradiation, most parts of the web applications are written using server-side scripting, primarily PHP. The use of client-side scripting (JavaScript) is kept to a minimum to enable access also to users with limited computing resources.

4 APPLICATION OF PVGIS

Although the original HelioClim-1 data are accessible from the SoDa web site, the PVGIS database and the map-based approach provides an improved understanding of the spatial variability of the solar energy resource and PV performance in regions.

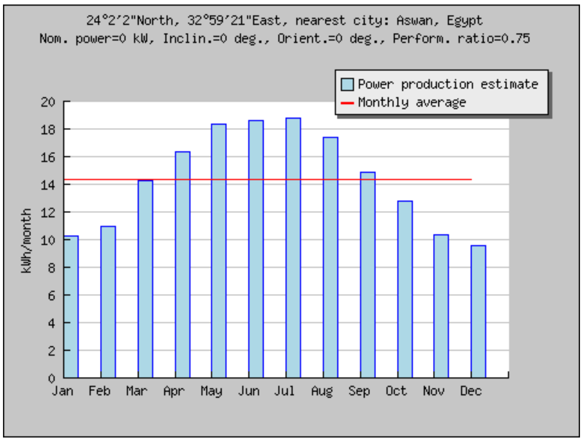


Figure 2: Seasonal variation of the monthly PV electricity generation from a 100 W_p system with modules in horizontal position in Aswan (Egypt; kWh)

Figure 1 shows that the latitudinal trends in global irradiation are modulated by patterns of atmospheric turbidity, cloud structures, and terrain elevation (including shadowing). There is a significant geographical and seasonal variation of global irradiation over the African continent and South West Asia, with values varying by almost a factor of 2. Thus, besides geographical latitude the variation is strongly determined by regional climatic features (compare to [12]). In dry regions, such as the Sahara and Kalahari deserts, or parts of the Arabian Peninsula, the irradiation is very high, while in the tropical rainforest regions (such as the

Congo River Basin) it is much lower, especially near the Western coast.

Monthly averages of daily global irradiation are used for the estimation of the PV electricity output (Figure 2). For example, assuming a small 100 W_p stand-alone PV installation with a battery and battery charger, together with a performance ratio of 0.75, the power production ranges from about 300 to 600 Wh per day in most locations in Africa and South West Asia, except in winter seasons in the extreme North and South. This energy is sufficient to drive 3 energy-efficient lights for 6 hours per day, or 3 energy efficient lights for 4 hours plus a radio, or a pump to deliver 3000 litres of water from a depth of 20 meters. Note that this calculation does not take into account possible losses due to the saturation of the battery capacity.

The seasonal variation of PV electricity is location-dependent. In regions with dry climate, the energy produced is generally higher but with higher seasonal variation, especially in the northernmost and southernmost latitudes. On the other hand, in humid equatorial climates, such as the Congo River Basin, the level of production is lower with low seasonal variation.

For design of stand-alone PV systems in a chosen location, the seasonal variation must be considered to avoid periods of insufficient power production. The cumulative probability distribution of daily irradiation, can be used to assess the probability of reaching the satisfactory level of irradiation input each month. As shown on the example (Figure 3), in Aswan the seasonal effects are well pronounced and it is much more likely that the daily irradiation will be near the maximum (clear-sky) irradiation in each season of year. In contrast, in Kinshasa very high irradiances are rare and the distribution of daily irradiation values within the year is rather broad with a very stable seasonal pattern.

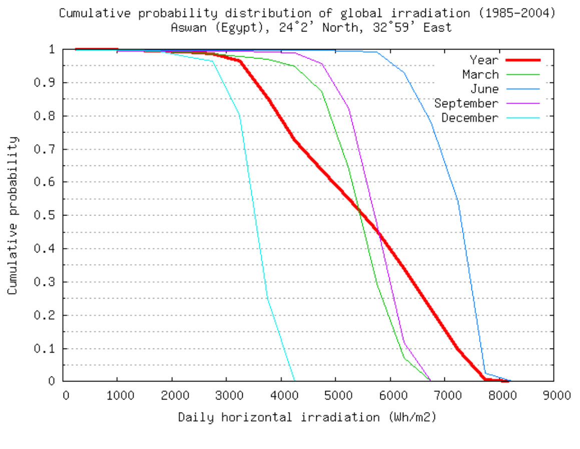


Figure 3: Cumulative probability distribution of daily global horizontal irradiation (Wh m^{-2}) in a year in Aswan (Egypt) in the period 1985-2004

The availability of daily irradiation values in the original HelioClim-1 database makes it possible to optimize PV system components. For example, assuming a certain daily energy consumption, it is possible to estimate the optimum size of the PV module and the size of the battery as demonstrated in a previous paper [7]. However this option of the system sizing is not yet accessible via the web interface.

6 CONCLUSIONS

PVGIS provides an interface to a geographical database and tools designed for the assessment of photovoltaic systems. The solar radiation data derived from satellite images and processed in GIS open new horizons to a better understanding of spatial and time variability of the solar energy resource and pathways of its exploitation for satisfying growing energy needs.

Enhancement of the original HelioClim-1 data and web access provides opportunities for improved optimization of the design of the stand-alone and grid-connected systems for any chosen location in the region. The tools can be used by decision-makers, local professionals, or international aid agencies to improve the use of the financial resources for rural electrification.

PVGIS provides only overview information about PV system performance. Those interested in more detailed system design, can use the PVGIS solar radiation data as an input into available software tools, such as RETscreen [13]. Professional applications need more detailed data analysis that can be requested at the SoDa web site [3].

More information on the methodology, accuracy, static maps and animations and other resources can be found on the PVGIS web site [14].

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