Performances assessment of the first grid-connected photovoltaic micro power in Africa: The PVGIS approach

Abdelfettah BARHDADI*

Laboratoire de Physique des Semi-conducteurs et de l'Energie Solaire (P.S.E.S.)
Ecole Normale Supérieure, P.O. Box: 5118, Takaddoum, Rabat 10000, Morocco
Unité de Formation et de Recherche en Physique de la Matière Condensée et Modélisation Statistique des Systèmes, Faculty of Sciences, University Mohammed V-Agdal, Rabat, Morocco
&
The Abdus Salam International Centre for Theoretical Physics, P.O. Box 586, Trieste, Italy
And

Ashraf Saber ZAKEY

The Abdus Salam International Centre For Theoretical Physics
Earth System Physics Section
Physics of Weather and Climate Group
Strada Costiera 11, P.O. Box 586, 34014 Trieste, Italy

Abstract: In this paper, we apply the PVGIS method for estimating the performance of the first grid-connected PV micro-power plant in Africa and we present the preliminary results obtained on this subject. PVGIS approach provides analysis and assessment of in-site solar energy resources and predicts with good accuracy the potential of PV systems in term of electricity production. We find that annual total power generation of the micro-power is slightly higher than that initially expected at the installation stage and actually measured. The yearly predicted and measured power production values agree to about 2 %. However, individual monthly production can have larger discrepancy. The present preliminary work will be developed very shortly through the integration of new components notably predictions from the radiation scheme in the ICTP-regional climate model (RegCM). The attenuation of the solar radiation in the atmosphere will then be also assessed and taken into consideration.

Keywords: Solar energy resources, Photovoltaic energy prediction, Grid-connected power plant, Simulation.

** Corresponding author (Senior Associate of the Abdus Salam ICTP)*
Phone: (212) 37 75 12 29 or (212) 37 75 22 61 or (212) 64 93 68 15
Fax: (212) 37 75 00 47
E-mails: barhdadi@ictp.it or abdelbar@fsr.ac.ma

I- Introduction

It is well known that performances of a given Photovoltaic (PV) system are strongly dependent on the climate conditions at the system setting. The most important parameters influencing these performances are the solar radiation impinging at the surface of the PV modules and the ambient temperature that affect losses from these modules. The precise nature of this influence depends mainly on the PV technology used. A number of studies have been made to determine how the efficiency varies for different PV technologies [1,2]. The result is a set of approximate expressions for module performance for given climatic characteristics. This is useful for a general appraisal of the technology. However, for a given PV installation obtaining the necessary climatic data is a non-trivial task, and so detailed performance evaluations become difficult. Yet the deviation of the conversion efficiency under real conditions from that obtained at Standard Test Conditions (STC) is large enough to have an influence on the economic feasibility of PV installations. Therefore it is important to be able to estimate the average performance of PV systems in sites where long-term detailed climatic data are not available. For this end, Suri et al [3-5] have developed at the Joint Research Centre of the European Commission their well established open source software named PhotoVoltaic Geographical Information System (PVGIS) which combines a long-term expertise from laboratory research, monitoring and testing with geographical knowledge. PVGIS is used as a research tool for the performance assessment of PV technology in geographical regions, and as a support system for policy-making in the European Union. A web interface was developed to provide interactive access to the data, maps and tools to other research and education institutes, decision-makers, PV professionals and system owners as well as to the general public.

The purpose of this paper is to apply PVGIS approach to the first African grid-connected micro-power PV plant recently built in Morocco; with the aim to provide an analysis of in-site solar energy resources and to illustrate the preliminary results of PV electricity production from this station on the base of radiation predication and irradiative heat transfer.

II- Methodology

PVGIS method uses the Geographical Information System (GIS) GRASS to combine geospatial data with known correlations for estimation

of the performance of crystalline/thin film silicon modules under varying irradiance and temperature over large regions. The method has been successfully applied on the European and African continents, on the Mediterranean basin and on the South-West Asia region.

Applying this approach, the PV performance can be estimated for any geographical location in the area under investigation. Combined with a system for accessing the data interactively via the Internet, the results are made available for those interested.

The details of the PVGIS methodology and development can be found in key reference papers [6,7]. We propose in the section to recall the essential.

II-1- Performance of crystalline silicon PV systems

Most of terrestrial PV systems are made from mono-crystalline or poly-crystalline silicon materials. For these materials studies have been performed to calculate the system performances under varying conditions of irradiance and temperature. The starting point for performing this calculation is the set of semi-empirical formulas for the voltage V and current I of PV modules at maximum power point, given in [1] and used in modified form in [2]. From these we can calculate the relative conversion efficiency of the module (η_{rel}), i.e. the efficiency relative to the efficiency η_0 measured at STC:

$$\eta_{rel}(G_i,T_m) = \frac{I_m V_m}{I_{mSTC} V_{mSTC}} = \frac{G_i}{G_0}\left[1+\alpha_i\left(T_m - T_0\right)\right] \times \left[1 + c_1 \ln\frac{G_i}{G_0} + c_2\left(\ln\frac{G_i}{G_0}\right)^2 + \beta_v\left(T_m - T_0\right)\right] \quad (1)$$

Here I_m and V_m are respectively the real current and voltage values of the module at maximum power point at in-plane irradiance G_i and module temperature T_m. $I_{m,STC}$ and $V_{m,STC}$ are the corresponding values, at STC of in-plane irradiance G_0 = 1 kW/m^2 and T_0=25°C, at which the reference efficiency η_0 of PV modules is normally measured. The other parameters are empirical and were already determined experimentally in reference [2]. For mono-crystalline silicon modules which are the case of PV system considering in this work, the values of these parameters were found as: $\alpha_i = 1.20\ 10^{-3}$ °C, $\beta_v = - 4.60\ 10^{-3}$ °C, $c_1 = 3.3\ 10^{-2}$ and $c_2 = - 9.2\ 10^{-3}$. Different values would be needed for other PV technologies.

Since the module temperature T_m is not known a priori, the following approximate relation between T_m, the ambient temperature T_{amb} and the nominal operating cell temperature T_{noct}, provided by the module supplier, has been employed:

$$T_m = T_{amb} + \left(T_{noct} - 20\right)\frac{G_i}{800} \quad (2)$$

For modules in a free-standing configuration, an approximate value for Tnoct is normally given as T_{noct}=48°C.

Given these relationships between PV module performance and meteorological conditions, we can calculate the power output of a given grid-connected crystalline silicon PV system with nominal peak power P_{nom} as:

$$P\left(G_i, T_m\right) = P_{nom}\ \eta_{rel}\left(G_i, T_{amb}\right)\frac{G_i}{G_0} \quad (3)$$

From equation 3, we see that in order to estimate the performance of a system at a given geographical location it is necessary to estimate both the irradiance in a given plane (in-plane irradiance) G_i and the ambient temperature T_{amb} at any given time during the day. This estimate must then be integrated over the day for a sufficient number of days during the year to obtain a good yearly average.

II-2- Solar radiation database

The construction of high spatial resolution data sets for solar radiation has been previously reported [3,4]. A brief description should therefore be sufficient here.

The computational approach is based on a solar radiation model *r.sun*, and the spline interpolation techniques *s.surf.rst* and *s.vol.rst* that are implemented within the open-source GIS software GRASS [8]. The *r.sun* model algorithm uses the equations published in the European Solar Radiation Atlas [9]. The model estimates direct, diffuse and reflected components of the clear-sky and real-sky global irradiance and/or irradiation for horizontal or inclined surfaces. The total daily irradiation (Wh/m^2) is computed by the integration of the irradiance values (W/m^2) that are calculated at a time step of 15 min from sunrise to sunset. For each time step, the computation accounts for sky obstruction (shadowing) by local terrain features, calculated from the digital elevation model.

The necessary input components for calculating average monthly and yearly irradiation were:

- Monthly averages of daily sums of global irradiation available at the meteorological ground stations [9];
- Monthly averages of the ratio of diffuse to global irradiation at the same ground stations (for irradiation on inclined planes);
- Monthly values of the Linke atmospheric turbidity [10, 11];
- Digital Elevation Model (DEM) derived from SRTM-30 data [12].

The data from 566 meteorological ground stations are monthly averages of measurements over the period 1981-1990. Monthly averages of the clear-sky irradiation were calculated using the *r.sun*. Based on clear-sky irradiation and the ground station values of average real-sky solar irradiation, the clear-sky index was calculated for the ground station positions. Interpolating the clear-sky index and the ratio of diffuse to global irradiation makes it possible to

develop spatial (GIS) databases of the average monthly real-sky irradiation on an arbitrarily inclined plane.

The grid resolution of DEM was chosen 1x1 km for two reasons. First, a higher-resolution DEM makes it possible to take account of the elevation in calculating the clear-sky irradiation. Secondly, when calculating the daily sum of irradiation, it becomes possible to take into account shadows from nearby terrain features. In mountainous regions this can be very significant.

Using *r.sun*, and taking into account shadowing effects from nearby terrain, we have obtained an estimate of the monthly and yearly averages of global irradiation/irradiance values at any inclination for any location. The relative RMS error of the developed database for monthly horizontal irradiation is within the interval of 3.2 to 7.8 % and the yearly average is 3.7 %. For more details of the calculation method we can see [3, 4].

II-3- Temperature database

Temperature data come from approximately 800 ground stations over the period 1995-2003. These stations provide temperature measurements at 6:00, 9:00, 12:00, 15:00 and 18:00 GMT. The spatial distribution of the stations is heterogeneous with the highest density in Western Europe. For each station, the monthly and yearly averages of the temperature at the measurement time have been calculated. To estimate the temperature between measurement times, the known temperatures were fitted to a 2^{nd} order polynomial. The coefficients of the polynomial were then interpolated separately over the geographical region using a multivariate regularized spline with tension *s.vol.rst*. The same grid resolution of the GIS data was used as for solar radiation (1x1 km). The RMS error from interpolation and fitting of monthly averages is in the range 0.5-0.7°C.

Thus, for any given point, coefficients of the polynomial to calculate the average temperature at any time during the day have been obtained. The methodology of developing the temperature database is described in detail in [5].

II-4- Efficiency of silicon module

Given the average monthly real-sky irradiation and the polynomials for the daytime temperature a modified version of *r.sun* is used which incorporates the relative efficiency given by Equations (1) and (2) to integrate the daily PV energy output variation for crystalline silicon modules at any given location using Equation (3).

One thing to note when integrating Equation 3 using this method is that the irradiance G_i used is the instantaneous irradiance for average meteorological conditions. For the linear term G_i/G_0 calculating G_i using the average conditions is sufficiently accurate. However, for the calculation of $\eta_{rel}(G_i,T_{amb})$ it becomes necessary to take into account the actual values of irradiance. Most of the energy from a PV system is produced when the irradiance is close to clear-sky values. We have therefore chosen to use the clear-sky irradiance, $G_{i,cs}$, in this expression, whereby the equation for the power output becomes:

$$P\left(G_i, G_{i,cs}, T_m\right) = P_{nom}\, \eta_{rel}\left(G_{i,cs}, T_{amb}\right)\frac{G_i}{G_0} \quad (4)$$

The clear-sky and the real-sky irradiances, as well as the instantaneous value of the ambient temperature are calculated directly by the modified version of *r.sun* at 15 min. time step, and the expression for P is integrated over the day from sunrise to sunset.

III- Identification of the first African PV micro-power plant

On June 2007, the "Office National de l'Electricité" (ONE), which is the Moroccan Power Utility, launched a micro-solar PV station in Tit Mellil near Casablanca, to be the first of its kind in Africa. Dubbed "Chourouk", which means Sunrise, this station would help the Moroccan government cut its fuel bill and make electricity bill cheaper for customers. This PV micro-power plant is part of an overall strategy set up by ONE to promote renewable energy forms and encourage people to use them. According to ONE project manager, two other pilot projects are underway. The first, to be launched in Errachidia (South), will target 1,000 households. The second will be established in Taroudant (South), where over 500 households are already equipped with solar kits.

The technical characteristics of the first African PV micro-power plant are summarized in table 1.

First African PV micro-power plant	
Location	Tit Mellil, Province of Mediouna, Grand Casablanca, Morocco
Latitude	33° 33' 28" North
Longitude	7° 29' 8" West
Elevation above	116 m
PV modules	1024 PV panels of 45 Wp each installed on the roof of ONE building that houses the Regional Direction of Rural Electrification
PV Technology	Crystalline silicon
PV system	Isofoton Maroc
Nominal power	46 kWp
Type of PV	Grid-connected
Operating date	June 14, 2007
Duration of	4 months

Estimated PV	10 %
PV power production expected	70 MWh per year which is the equivalent to the annual consumption of a village of 120 households (around 700 peoples)
PV power exploitation	Power production is exploited for domestic use in urban areas and the surplus is injected into the Moroccan network
Cost and financing	US $ 350,000 of which 140,000 funded by the German bank KFW
Estimated reduction of CO_2 emission	The micro-power should prevent the emission of 24 tons of carbon dioxide, or 720 tons over the project life.

Table 1: Technical characteristics of the first African PV micro-power plant

IV- Results

We have used the approach outlined above to estimate the annual PV performance of Chourouk micro-power plant. After providing the PVGIS software with all input parameters needed for performing the calculation, we obtained a large number of output results that we will expose and comment in the present section.

Even we have had the possibility to choose the inclination and orientation angle of Chourouk PV modules; we have preferred to let PVGIS calculating the optimal values for these parameters assuming fixed angles for the entire year. Table 2 summarizes the first results provided by PVGIS. We can see that the value of optimal inclination angle of the PV modules from the horizontal plane agrees perfectly with that of geographical latitude of Chourouk site. This is a good sign reflecting once more the accuracy of PVGIS calculation

Parameter	Value
Optimal inclination angle of the PV modules from the horizontal plane	30°
Optimal orientation angle of the PV modules relative to the south direction	0° (South)
Estimated losses due to temperature	9.5 % (using local ambient temperature data)
Estimated losses due to angular reflectance effects	2.6 %
Other losses (cables, inverter, etc.)	10 %
Combined PV system losses	22.1 %

Table 2: Optimal inclination/orientation of Chourouk PV modules and their estimated losses.

IV-1- Estimation of solar irradiation and daily temperature

Table 3 gives the estimated value of monthly (G_m) and daily (G_d) average sum of global irradiation per square meter received by the plane of Chourouk PV modules. It gives also the diffuse to global irradiation ratio D/G and the daily temperature T24h of the modules. The total yearly average value of the global irradiation at optimal inclination angle Gopt has been found to be about 1980 kWh/m^2. The shadowing by local terrain features can affect theses values. Some of these results are displayed in figure 1. We can easily see that G_m value of May is slightly higher than that of June. This is a little bit strange because usually the inverse should happen.

Month	Daily average sum of global irradiation G_d (kWh/m^2)	Monthly average sum of global irradiation G_m (kWh/m^2)	Average ratio of Diffuse to Global irradiation D/G	Average value of daily Temperature T_{24h} (°C)
Jan	4.12	128	0.41	12.7
Feb	4.57	128	0.41	13.4
Mar	5.70	177	0.37	15.7
Apr	5.97	179	0.38	16.4
May	6.31	195	0.36	18.9
Jun	6.37	191	0.35	21.8
Jul	6.44	199	0.35	23.5
Aug	6.39	198	0.35	23.9
Sep	6.00	180	0.35	22.3
Oct	5.10	158	0.39	20.0
Nov	4.07	122	0.43	16.2
Dec	3.92	121	0.42	14.0
Average values	**5.42**	**165**	**0.37**	**18.2**

Table 3: PVGIS estimates of daily, monthly and yearly averages of the global irradiation at optimal inclination angle, the diffuse to global irradiation ratio and the daily temperature.

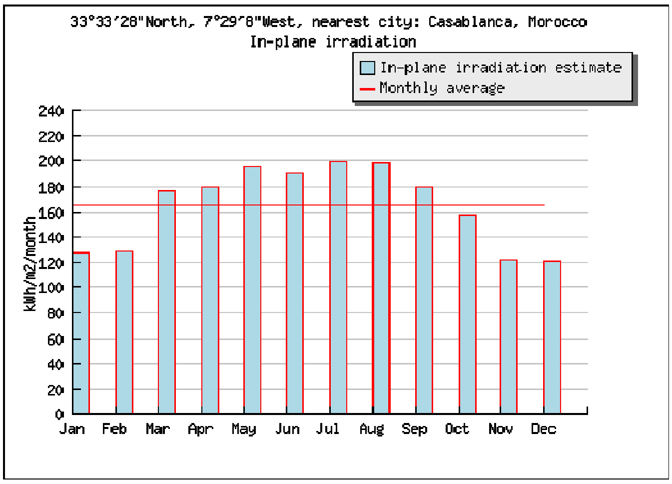

Figure 1: In-plane global irradiation estimated for the optimal inclination and orientation of Chourouk PV modules. The estimated monthly average value is also shown.

The values of irradiation and temperature obtained above are used to estimate and predict the amount of electricity production of Chourouk micro-power plant using the model and formulation described in the section II.

IV-2- Estimation of PV electricity production by Chourouk micro-power plant

Table 4 shows the estimated amount of electric power in kWh we can expect each day (E_d) and each month (E_m) from Chourouk micro-power plant with the parameters we inputted (at optimal inclination and orientation). It also shows the expected total PV power production par year. The electricity production for every month has been also plotted in figure 2 to show graphically the results. The power production ranges from about 4540 kWh in December to more than 7100 kWh in July. In December, the production is clearly much lower than other winter months because of the exceptionally rainy weather. The annual total estimated value of power production is about 71.875 MWh which is approximately the value initially expected and actually measured (70 MWh) as specified in table 1. The two values agree to better than 2.5%. This is within the typical 2 % uncertainty of the irradiance sensors and other error sources. The power production estimate for May is relatively higher than that for June. This unexpected result comes from the difference in G_m values noticed above between these two months. We can therefore conclude that the PVGIS prediction is valid over a long period of time such as one year but it seems less appropriate for single months because of some discrepancies between estimated and expected values.

Month	Average daily electricity production E_d (kWh)	Average monthly electricity production E_m (kWh)
Jan	155	4799
Feb	171	4780
Mar	208	6452
Apr	218	6536
May	228	7059
Jun	228	6834
Jul	229	7108
Aug	228	7061
Sep	215	6452
Oct	185	5738
Nov	151	4516
Dec	146	4540
Average values	**197**	**5990**
Total annual production (kWh)	**71875**	

Table4: Estimated power production of Chourouk micro-power plant at optimal inclination and orientation

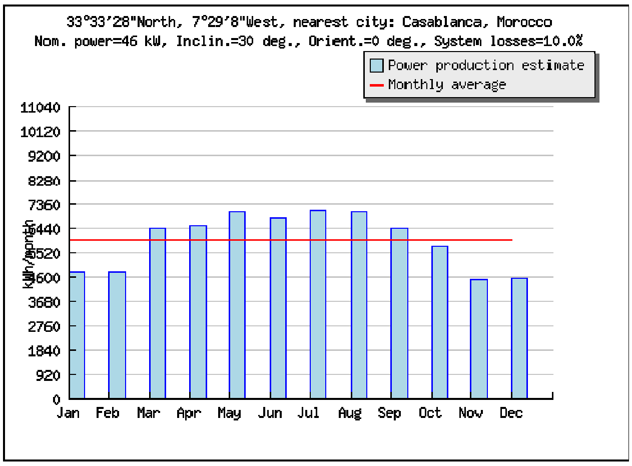

Figure 2: Estimated amount of electric power in kWh expected each month from Chourouk micr-power plant. The expected monthly average power production is also shown.

V- Conclusion

In this paper, we applied PVGIS approach to the first African grid-connected micro-power PV plant recently built in Morocco with the aim to provide an analysis of in-site solar energy resources and PV electricity production from this station. For the optimal inclination and orientation angles determined by the software itself, we found that annual total power generation of the micro-power is only slightly higher than that initially expected at the installation stage and actually measured. The yearly predicted and measured power production values agree to about 2% which is the typical uncertainty of the irradiance sensors and other error sources. For two consecutive months which are May and June, unexpected results have been found both in term of solar energy resources and electricity production. We can therefore conclude that the PVGIS prediction is valid over a long period of time such as one year but it seems less appropriate for single months because of some discrepancies between estimated and expected values.

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