A SIMPLE BUT EFFECTIVE APPROACH TO THE SITE ASSESSMENT FOR PV PLANTS: THE SIMULATINO PROGRAM SUNSIM

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ABSTRACT: Nowadays, many programs for the site assessment of PV plants are available on the market. Many of them are quite powerful and reliable but in some cases their use is complex and may require many data to be introduced. On the opposite, other programs are very simple but they do not take into account many important aspects, for instance the shadowing and the effects of the albedo. Therefore, a question raises: it is possible to develop a program, easy to understand, which in less than a couple of minutes may assess the productivity of a site by taking into account the PV geometry (tilt and azimuth of PV modules), the shadowing (obstructions), the surrounding landscape (albedo) and the maximum angle of incidence of the sun beam on the front glass? The program SunSim is the result of an effort aimed to meet these requirements and therefore all the operations (with the exception of the filename typing) may be performed by using only the mouse. The data base for the sun radiation includes 173 sites of Italy, Europe and North Africa. The graphical approach allows to select the tilt and azimuth of PV modules by moving the mouse on the sun-path diagram. In the last release the program allows the calculation of the energy yield for double-axes tracking systems

1 INTRODUCTION

The site assessment for PV plants can be a time-consuming experience, especially if the site geography is far from ideal, the site is large and the horizon line cannot be considered homogeneous. Furthermore it is often necessary to know what happens if one or more parameters change, for instance tilt and azimuth of PV modules or their reciprocal distance.

The methodology used by the program SunSim is based on the rigorous application of the trigonometric equations and atmosphere related equations that can be considered significant for energy calculations.

Raw solar data are pre-treated in order to reproduce trends of value for average days.

Furthermore, it is generally recognized that mono-crystalline, multi-crystalline and thin-film PV modules have a different behavior when the angle of incidence of the solar radiation (cosϑ) is close to 90°. This is valid not only for the direct radiation but also for the diffuse radiation. Therefore, simulation programs should cut-off this portion of solar radiation that cannot be converted to energy.

The program proposed in the paper considers an innovative approach to the problem by giving the opportunity to choose all relevant input data and, in particular, considering the sun diagram as a dashboard where to rotate and incline PV modules. The energy yield changes accordingly and it is displayed on the same window as a table of values.

2 CALCULATION METHOD

2.1 General approach

The program SunSim performs simulations in the time dominium. Results are obtained by a construction of solar paths for each month of the year and by a calculation of the effects on the specific site for each time step. Partial results are thus added in order to obtain final results.

The simulation approach gives the possibility to take into account various parameters that may affect the result, mainly the shadowing and the atmospheric turbidity. On the other side this approach requires a certain amount of calculations (with a time step of 10 minutes, about 1600 calculations of solar radiation in different conditions are needed to obtain a single result). Anyway, this massive utilization of the CPU is not evident to the user also because of the efficient code which is written in C++ language.

2.2 Sun path diagram and shadowing

The sun path diagram is the fundamental part of the program. It is composed by a working area with a white background, a X-scale from 0 to 360 degrees for the azimuth and a Y-scale from 0 to 90 degrees for the solar elevation (see figure 1).

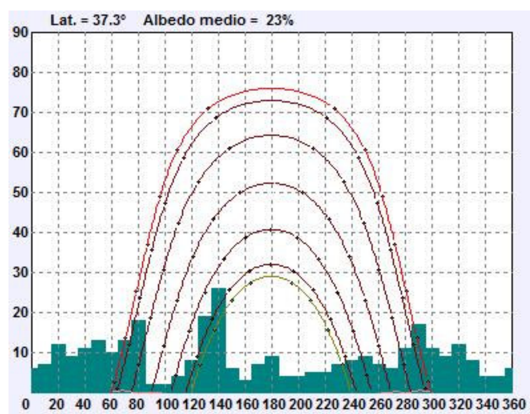

Figure 1: Example of sun path diagram

The number of solar paths in the diagram is 7, the lower one refers to December 21, the higher one refers to June 21 and the other 5 refer to the couples November-January, October-February, September-March and April-May.

The values of the solar elevation θ_h and of the azimuth angle θ_a ate calculated on the basis of the latitude Φ and solar declination δ (different curves have different solar declinations). Each curve is therefore drawn by varying the hour angle ω in the following formulas.

$$\cos\theta_h = \sin\delta\cdot\sin\Phi + \cos\delta\cdot\cos\Phi\cdot\cos\omega$$

$$\cos\theta_a = \frac{\sin\theta_h\cdot\sin\Phi - \sin\delta}{\cos\theta_h\cdot\cos\Phi}$$

Where:

$$\delta = 23{,}45\cdot\sin\left(360\cdot\frac{284+n}{365}\right)$$

$$\omega = 15\cdot t + \Delta\omega - 180$$

As showed in figure 1, in the area occupied by the sun path diagram it is represented also the shadowing diagram, in order to highlight the periods of the year and the time of the day when the direct solar radiation is obscured.

The innovation introduced by the program SunSim consists in the use of the same working area, i.e. the sun path diagram, to vary tilt and azimuth of PV modules. This means an intuitive and fast procedure for the introduction of these important data. Furthermore, it is sufficient to move the cursor to see the effect on the energy yield caused by a different exposition. Every variation in tilt or azimuth of the PV module surface is traduced in a new calculation of direct, diffuse and reflected energy for each month of the year. These value are displayed on the left side of the sun path diagram along with their totals (per rows and per columns).

2.3 Calculation of the direct radiation

The calculation of the direct solar radiation I_B is performed by taking into account the solar path of each month. Each path is considered as composed by a number of points and for every point the program calculates the direct radiation on the PV module surface on the basis of the following factors [1]:

- Direct solar data
- Angle θ betwen the solar beams and the normal to the PV module plane
- Turbidity of the atmosphere

The direct solar data are those previously chosen and referred to the site, while the θ angle is calculated by means of the following equation:

$$\begin{aligned}\cos\theta = &\sin\delta\cdot\sin\Phi - \sin\delta\cdot\cos\Phi\cdot\sin\beta\cdot\cos\alpha\\ &+\cos\delta\cdot\cos\Phi\cdot\cos\beta\cdot\cos\omega\\ &+\cos\delta\cdot\sin\Phi\cdot\sin\beta\cdot\cos\alpha\cdot\cos\omega\\ &+\cos\delta\cdot\sin\beta\cdot\sin\alpha\cdot\sin\omega\end{aligned}$$

The turbidity of the atmosphere is calculated by the Linke equation:

$$I_B = I_0\cdot e^{-\delta_{CDA}\cdot T_L\cdot am}$$

By means of the Linke equation it is possible the calculation of the direct solar radiation I_B from the extra atmospheric radiation I_0. This equation takes into account the value of the air mass am, set as $1/\sin\theta_h$ and the Linke turbidity coefficient, which may vary according to the site and the period of the year, but that for reasons of simplicity has been set equal to 3. As regards the parameter δ_{CDA} there are different expressions, but in this case the equation proposed by Kasten [2] has been chosen, because it is valid for a wide range of am.

$$\delta_{CDA} = \frac{1}{9{,}4 + 0{,}9\cdot am}$$

As already mentioned, every the single point of the paths that concur to calculate the energy yield is considered valid only if it does not intersect the shadowing diagram, otherwise the program set the corresponding value to zero.

In case of 2-axes tracking system simulation, the program assumes that the PV modules follow perfectly the sun paths, therefore the θ angle is always set equal to zero.

2.3 Calculation of the diffuse radiation

The calculation of the diffuse radiation on the PV module surface I_D takes into account the tilt angle β and uses the following equation:

$$I_D = I_{D0}\cdot\frac{1+\cos\beta}{2}$$

It is however necessary to consider the shadowing effect on the site along with the tilt angle β because on the rear of the PV module the tilt angle can be higher of the obstruction angles. For this reason the space around the PV module plane has been divided in 2 portion, each of 180° wide on the horizontal plane. The first one is the front portion and in this case the effect of obstruction angles is simply weighted on the whole space. The second portion is the rear portion, where the program evaluates if the tilt angle is predominant on the obstruction angle. Thus the calculation considers, for every slice of the horizon, the higher angle between tilt and obstruction.

Although the calculation of the diffuse radiation for a fixed PV plant does no require any simulation, in case of tracking systems tilt and azimuth are not constant and therefore a simulation based on sun paths is needed. The simulation criteria is quite similar to that used for the direct radiation but the number of points used is less.

2.4 Calculation of the reflected radiation

The calculation of the reflected radiation on the PV module surface I_R takes into account the tilt angle β and uses the following formula:

$$I_R = \rho\cdot(I_B + I_D)\cdot\frac{1-\cos\beta}{2}$$

The values of the albedo coefficient ρ, of the direct solar radiation I_B and of the diffuse solar radiation I_D vary month by month and may be introduced by means the window shown in figure 2.

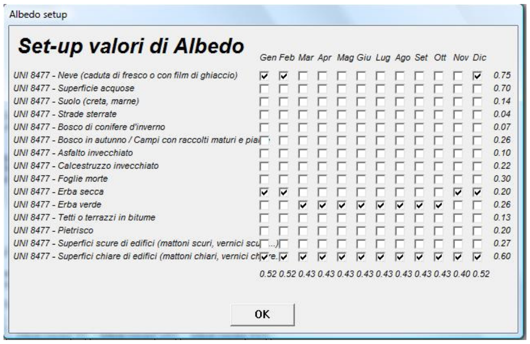

Figure 2: Introduction of the values of albedo for each month and in consideration of different conditions of the soil and the landscape

Although the calculation of the reflected radiation for a fixed PV plant does no require any simulation, in case of tracking systems the tilt is not constant and therefore a simulation based on sun paths is needed. The simulation criteria is quite similar to the criteria used for the direct radiation but the number of points used is less.

2.5 Maximum angle of incidence

A further innovative aspect of the program SunSim is the possibility to introduce a maximum angle of incidence (AOI) for the sun beams. The program considers that under this angle all solar radiation is collected by PV modules and above it the solar radiation is totally reflected. Usually this simple approach is different from reality, because the behaviour of sun beams at high angles of incidence shows a gradual decrement (see figure 3) [3].

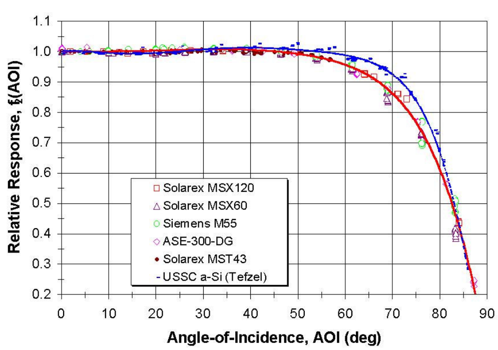

Figure 3: Measured effect of angle of incidence variation on the response (short-circuit current) of different commercial photovoltaic modules

However, for energy purposes, in most cases it is sufficient to consider an average value for the cut-off of power, provided its choice is well done. The program allows the introduction of the limit angle, defined as 90-AOI. This limit angle may be chosen in the range from 0° to 25°.

It has been observed that maximum angle of incidence concerns not only the direct solar radiation, but also the diffuse radiation. This effect is in most cases predominant and thus a particular care has been taken in its calculation.

The possibility of varying the maximum angle of incidence may be applied to the different behavior of the PV technologies as regard of this parameter and in particular when comparing c-Si and thin-film.

3 SOLAR RADIATION DATA

The program SunSim uses 2 different sources of data. The first one, taken from the Italian standard UNI 10349 [4] contains monthly data (direct and diffuse radiation) for 101 Italian sites (see table I). The second one, taken from the PVGIS site of the JRC of Ispra [5], contains the same type of monthly data for 72 European sites (see table II). However a few Italian sites are also included in the list of PVGIS data.

Table I: Italian sites from UNI 10349

Agrigento	Genova	Pistoia
Alessandria	Gorizia	Pavia
Ancona	Grosseto	Potenza
Aosta	Imperia	Ravenna
Ascoli Piceno	Isernia	Reggio Calabria
L'Aquila	Crotone	Reggio Emilia
Arezzo	La Spezia	Ragusa
Asti	Lecco	Rieti
Avellino	Lodi	Roma
Bari	Lecce	Rimini
Bergamo	Livorno	Rovigo
Belluno	Latina	Salerno
Benevento	Lucca	Siena
Bologna	Macerata	Sondrio
Brindisi	Messina	Siracusa
Brescia	Milano	Sassari
Bolzano	Mantova	Savona
Cagliari	Modena	Taranto
Campobasso	Massa-Carrara	Teramo
Caserta	Matera	Trento
Chieti	Napoli	Torino
Caltanissetta	Novara	Trapani
Cuneo	Nuoro	Terni
Como	Oristano	Trieste
Cremona	Palermo	Treviso
Cosenza	Padova	Udine
Catania	Parma	Varese
Catanzaro	Perugia	Verbania
Enna	Pescara	Vercelli
Ferrara	Piacenza	Venezia
Foggia	Pisa	Vicenza
Firenze	Pordenone	Verona
Forlì	Prato	Viterbo
Frosinone	Pesaro e Urbino	

Table II: European sites from PVGIS

Belfast (UK)	Bruxelles (B)	Catania (I)
Birmingham (UK)	Amsterdam (NL)	Cosenza (I)
Edinburgh (UK)	Luxembourg (L)	Firenze (I)
London (UK)	Berlin (D)	Genova (I)
Manchester (UK)	Frankfurt (D)	Milano (I)
Dublin (IRL)	Freiburg (D)	Napoli (I)
Reykjavik (IS)	Hamburg (D)	Roma (I)
Oslo (N)	Munchen (D)	Venezia (I)
Stockholm (S)	Warszawa (PL)	Ljubliana (SLO)
Helsinki (SF)	Praha (CZ)	Zadar (HR)
Kobenhavn (DK)	Bern (CH)	Beograd (SRB)

Vilnius (LT)	Innsbruck (A)	Bucaresti (R)
Riga (LV)	Wien (A)	Sofija (BG)
Tallin (EST)	Budapest (H)	Tirana (AL)
Moskva (RU)	Barcelona (E)	Athina (GR)
Minsk (BY)	Bilbao (E)	Thessaloniki (GR)
Kiev (UA)	Granada (E)	Istanbul (TR)
Bordeaux (F)	Madrid (E)	Valletta (M)
Lyon (F)	Sevilla (E)	Nicosia (CY)
Marseille (F)	Zaragoza (E)	Casablanca (MA)
Nice (F)	Lisboa (P)	Algier (DZ)
Paris (F)	Porto (P)	Tunis (TN)
Rennes (F)	Bari (I)	Tripoli (LAR)
Strasbourg (F)	Cagliari (I)	Cairo (ET)

4 EXAMPLE OF APPLICATION

This example considers the possibility to erect a PV plant on a flat site at ground level where a water tank casts a narrow but significant shadow on the area. The main input data are the followings:

Solar data: UNI 10349 – Piacenza
Ave. albedo: 25%
Limit angle: 10° (Max AOI = 80°)

The figure 4 shows the South view from the site and the figure 5 shows the result of the landscape profile applied to the sun path diagram. The water tank has an azimuth of 250° (70° W from South) and an obstruction angle of 21°.

Figure 4: South view from the site

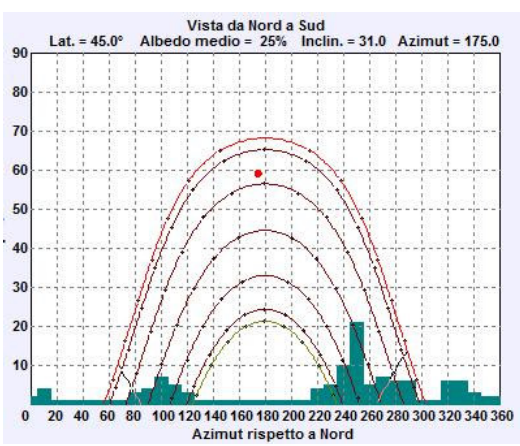

Figure 5: Landscape profile applied to the sun path diagram. The result of the optimization for tilt and azimuth of PV modules is also indicated

4.1 Simulation for a non-tracking PV system

By means of the program the research of the optimum tilt and azimuth for a non-tracking PV System is a matter of seconds and the results are:

Optimum tilt: 31°
Optimum azimuth: 175° (i.e. -5° from South)

The table III reports the energy yield as a result of the simulation.

Table III: Energy yield from the simulation for a non-tracking system [kWh/m^{2}g]

	Direct radiation	Diffuse radiation	Reflected radiation	Total radiation
Jan	1.19	0.58	0.02	1.79
Feb	1.78	0.85	0.03	2.66
Mar	2.63	1.24	0.06	3.93
Apr	3.40	1.60	0.09	5.10
May	3.67	1.87	0.11	5.64
Jun	4.14	1.94	0.12	6.21
Jul	5.01	1.73	0.13	6.87
Aug	4.39	1.60	0.11	6.10
Sept	3.65	1.31	0.08	5.05
Oct	2.42	0.97	0.05	3.43
Nov	1.31	0.63	0.02	1.97
Dec	0.93	0.51	0.02	1.45
Average	2.88	1.24	0.07	4.18

The figure 6 and 7 show respectively the daily trend of the direct and diffuse radiation. In the figure 6 it is possible to note that at 5:00 pm the direct radiation collapses in the period from October to March because of the presence of the water tank as shown in the diagram of figure 5.

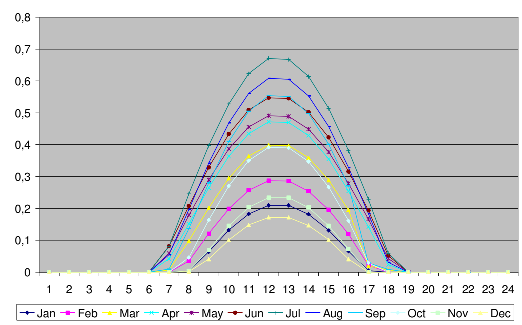

Figure 6: Trend of the daily yield for the direct radiation expressed in kWh/m^{2}h in case of a non-tracking system

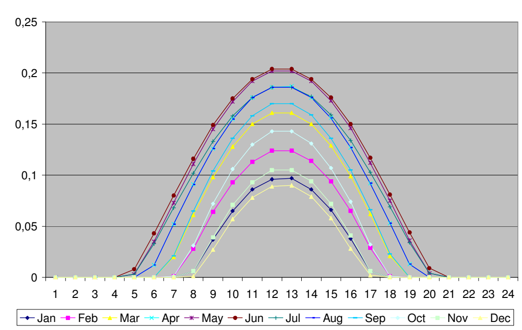

Figure 7: Trend of the daily yield for the diffuse radiation expressed in kWh/m^{2}h in case of a non-tracking system

4.2 Simulation for a 2-axes tracking PV system

If a 2-axes tracking PV system is chosen, the results are shown in table IV and figures 8 and 9. The comparison between table III and table IV shows a total increment of 29% of the energy yield for the tracker.

Table IV: Energy yield from the simulation for a 2-axes tracking system [kWh/m^{2}g]

	Direct radiation	Diffuse radiation	Reflected radiation	Total radiation
Jan	1.71	0.38	0.08	2.17
Feb	2.42	0.61	0.15	3.18
Mar	3.53	0.98	0.20	4.71
Apr	4.93	1.37	0.22	6.52
May	5.64	1.67	0.22	7.54
Jun	6.61	1.76	0.24	8.62
Jul	7.75	1.54	0.27	9.56
Aug	6.38	1.38	0.26	8.01
Sept	4.90	1.04	0.25	6.19
Oct	3.30	0.70	0.19	4.18
Nov	1.89	0.41	0.12	2.42
Dec	1.36	0.32	0.07	1.76
Average	4.20	1.01	0.19	5.40

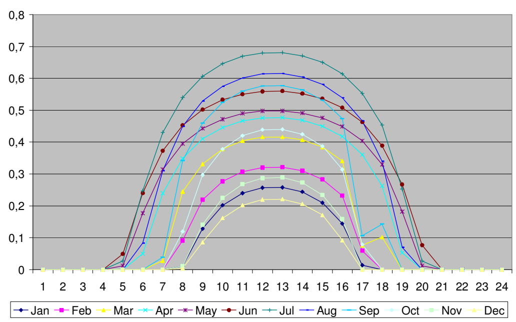

Figure 8: Trend of the daily yield for the direct radiation expressed in kWh/m^{2}h in case of a 2-axes tracking system

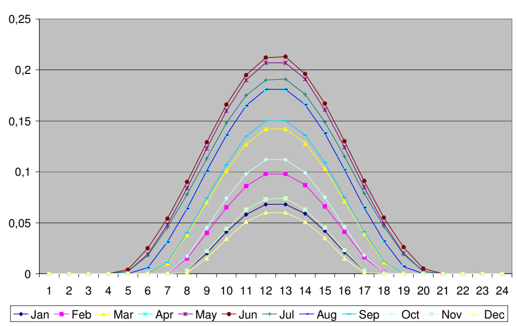

Figure 9: Trend of the daily yield for the diffuse radiation expressed in kWh/m^{2}h in case of a 2-axes tracking system

The 2-axes tracking of the PV system emphasizes the collapse of the energy yield when the PV modules are obscured by the water tank. This is particularly evident in the figure 8 at 5:00 pm for the curves that refer to the period from October to March.

It is interesting to note that the diffuse radiation has a trend quite different from the direct radiation. As shown in figure 9, the maximum collection of the diffuse radiation is in the middle of the day, when the tilt is low. On the contrary, at dawn and sunset the PV plane is close to vertical and therefore the collection of the diffuse radiation falls quickly.

Although the diffuse radiation is less for the simulated 2-axes tracking system, the reflected radiation is more than twice and passes from 1.7% to 5.4% of the total. The maximum yield is in the period from March to September, as shown in figure 10, when for a number of hours a high solar radiation corresponds to a high tilted surface.

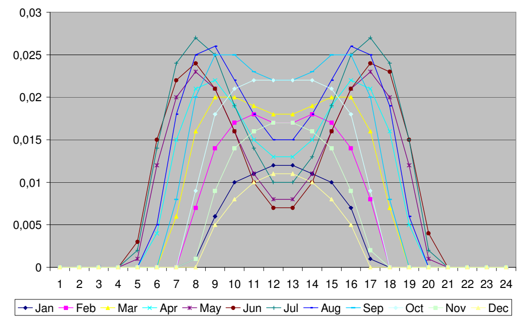

Figure 10: Trend of the daily yield for the reflected radiation expressed in kWh/m^{2}h in case of a 2-axes tracking system

5 CONCLUSIONS

The large diffusion of PV system need an effective and reliable approach to the assessment of sites. This phase is usually a time consuming practice, because it requires many considerations and calculations. The program SunSim was therefore developed with the aim of speed up the process of assessment and optimization of PV projects.

The most innovative aspects of his program are in particular the introduction of the tilt and the azimuth of PV modules by moving the mouse on the sun path diagram and the possibility to introduce a maximum angle of incidence for the solar radiation. This second characteristic is useful to differentiate the behaviour of different PV technologies (mono-crystalline Si, multi-crystalline Si, thin films) as regards the high angle of incidence of the direct and diffuse solar radiation.

6 REFERENCES

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