Estimation of Solar Radiation, Management of Energy Flow and Development of a New Approach for the Optimization of the Sizing of Photovoltaic System; Application to Algeria

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Abstract- The design of photovoltaic systems is an important step, its optimization, as well as the optimization of different parameters, is a crucial operation. In our work, after estimating hourly solar radiation, we developed, thanks to the concept of solar usability, energy flow models for the produced photovoltaic electricity. Then, we used a genetic algorithm to develop our own computer program (with Python) for finding the best configuration (total surface of the panels, PV efficiency and total capacity of batteries) among those that meet our needs. We applied our study to a region in southern Algeria, Bechar.

Keywords—Photovoltaic; Algeria; Optimization; Genetic Algorithm; Solar usability.

1. Introduction

Solar energy is available everywhere on Earth. It theoretically represents 900 times the global demand for energy term [1]. Algeria, thanks to its geographical position, is one of the largest solar farms in the world [2], which makes it suitable for the installation of conversion systems of solar energy, particularly photovoltaic systems.

For optimal use of photovoltaic energy, a good knowledge of all the data describing the solar potential of the area where we want to install our systems is important. When these data are missing, we often go through mathematical models to generate them.

Sizing of photovoltaic systems is an important operation. Its optimization, as well as the optimization of various system components, is a crucial step. Many studies have been carried out to optimize the design of photovoltaic systems [3-11] in relation to the cost of installation as well as the influence of meteorological variables. In our study, after presenting a method for generating digital data of the solar radiation, we have developed a methodology to optimize three parameters of the system: total surface of the panels, PV panel's efficiency and total capacity of batteries. We will choose the cheapest configuration.

Based on the concept of solar usability [12], we have developed a model for managing energy flows involved in the production and consumption of photovoltaic electricity, and we used a genetic algorithm to develop our own computer program (with Python [13]) to find the best configuration among those that meet our needs. We applied our study to a region in southern Algeria, Bechar.

2. Solar Radiation on Inclined Surface

For sizing a photovoltaic system or any other system that uses solar energy to convert it into electricity or thermal energy, it is essential to have data relating to solar radiation. In this case, we detail a complete method to generate numerically hourly data of solar radiation on a surface inclined with an angle β over the horizon.

2.1. Position of the Sun

2.1.1. Solar declination

Solar declination is the angle of the sun to its maximum stroke (solar noon) compared to the equatorial plane [14]:

$$\delta = 23.45 \sin\left(2\pi \frac{284+n}{365}\right) \quad (1)$$

n represents the day of the year.

2.1.2. Hour angle of the sun

The hour angle of the sun is its movement around the polar axis in the east-west running, compared to the local meridian [15]:

$$\omega = 15(T_{sv} - 12) \quad (2)$$

T_{sv} represents the value of the solar time [12]:

$$T_{sv} - T_{std} = 4(L_{st} - \lambda) + T \quad (3)$$

T is the time equation:

$$T = T_0(T_1 + T_2 - T_3 - T_4 - T_5) \quad (4)$$

With:

$T_0 = 229.2$

$T_1 = 0.000075$

$T_2 = 0.001868 \cos(z)$

$T_3 = 0.03077 \cos(z)$

$T_4 = 0.014615 \cos(z)$

$T_5 = 0.04089 \cos(z)$

In addition:

$$Z = \frac{2\pi}{365}(n-1) \quad (5)$$

The hour angle of sunset is [12]:

$$\omega_s = cos^{-1}(-tan(\psi)\, tan(\delta)) \quad (6)$$

ψ represents the latitude, T_{std} is the standard time, L_{st} the local meridian and λ the longitude.

2.1.3. Incidence angle

For a surface oriented face south without solar tracking system, the value of the incidence angle is [12]:

$$cos(\theta) = cos(\psi - \beta)\, cos(\delta)\, cos(\omega) + sin(\psi - \beta)\, sin(\delta) \quad (7)$$

The zenith angle [12] is also a very important parameter:

$$cos(\theta_z) = sin(\delta)\, sin(\psi) + cos(\delta)\, cos(\psi)\, cos(\omega) \quad (8)$$

2.1.4. Sunrise and sunset

To calculate the time of sunrise and the sunset, the following steps are followed [16]:

- Calculate the approximate time:

$$t = n + \left[\frac{\left(6 - \left(\lambda/_{15}\right)\right)}{24}\right] \qquad (sunrise) \quad (9)$$

$$t = n + \left[\frac{\left(18 - \left(\lambda/_{15}\right)\right)}{24}\right] \qquad (sunset) \quad (10)$$

- Calculate the sun's mean anomaly:

$$S_{ma} = (0.9856 - t) - 3.289 \quad (11)$$

- Calculate the sun's true longitude:

$$L = 282.634 + (0.020\, sin(2S_{ma})) + (1.916\, sin(S_{ma})) + S_{ma} \quad (12)$$

L potentially needs to been adjusted into the range [0,360] by adding/subtracting 360.

$$L_{quad} = \left(floor\left(\frac{L}{90}\right)\right) 90 \quad (13)$$

- Calculate the sun's right ascension:

$$S_{ra} = tan^{-1}(0.91764\, tan(L)) \quad (14)$$

S_{ra} potentially needs to been adjusted into the range [0,360] by adding/subtracting 360.

$$S_{ra,quad} = \left(floor\left(\frac{S_{ra}}{90}\right)\right) 90 \quad (15)$$

- Right ascension value needs to be in the same quadrant as L:

$$S_{\grave{ra}} = S_{ra} + (L_{quad} - S_{ra,quad}) \quad (16)$$

$$S_{\grave{ra},h} = \frac{S_{\grave{ra}}}{15} \quad (17)$$

- Convert ω_s into hours:

$$\omega_{s,h} = \frac{(360 - \omega_s)}{15} \qquad (sunrise) \quad (18)$$

$$\omega_{s,h} = \frac{\omega_s}{15} \qquad (sunset) \quad (19)$$

- Calculate local mean time of rising/setting and adjust back to UTC (Coordinated Universal Time):

$$UT = \omega_{s,h} + S_{ra,h} - \frac{\lambda}{15} - 6.622 - 0.0657t \tag{20}$$

- Convert UT value to local time zone:

$$S_{rise}(or\ S_{set}) = UT + L_{offset} \tag{21}$$

L_{offset} is the local offset.

2.1.5. Extra-terrestrial radiation

The extra-terrestrial radiation H_0 is the solar radiation before it passes through the atmospheric layer. For a horizontal surface and a day n, it is given in J/m^2 by [17]:

$$H_0 = \frac{86400 G_{sc}}{\pi}\left(1 + 0.033\cos\left(\frac{360n}{365}\right)\right) \times \begin{pmatrix} \cos(\psi)\cos(\delta)\cos(\omega_s) \\ + \frac{\pi\omega_s}{180}\sin(\psi)\sin(\delta) \end{pmatrix} \tag{22}$$

G_{sc} is the solar constant and its value is 1367 W/m². The hourly normal extra-terrestrial is [12]:

$$I_{0,n} = G_{sc}\left(1 + 0.033\cos\left(\frac{360n}{365}\right)\right) \tag{23}$$

2.1.6. Hourly direct, diffuse and global radiation

First, for the day n, we should calculate the daily diffuse radiation on horizontal surface H_d using the correlation of Erbs [18]:

- If $\omega_s < 1.4208\ rad$:
  - For $K_T < 0.715$:

$$\frac{H_d}{H} = 1 - 0.2727K_T + 2.4495K_T^2 - 11.9514K_T^3 + 9.3879K_T^4 \tag{24}$$

  - For $K_T \geq 0.715$:

$$\frac{H_d}{H} = 0.143 \tag{25}$$

- If $\omega_s \geq 1.4208\ rad$:
  - For $K_T < 0.722$:

$$\frac{H_d}{H} = 1 - 0.2832K_T + 2.5557K_T^2 - 0.8448K_T^3 \tag{26}$$

  - For $K_T \geq 0.722$:

$$\frac{H_d}{H} = 0.175 \tag{27}$$

K_T is the daily clearness index:

$$K_T = \frac{H}{H_0} \tag{28}$$

Using the formula of Liu and Jordan, we calculate the hourly diffuse radiation I_d [12, 19]:

$$I_d = H_d\left(\frac{\pi}{24}\frac{\cos(\omega) - \cos(\omega_s)}{\sin(\omega_s) - \frac{\pi\omega_s}{180}\cos(\omega_s)}\right) \tag{29}$$

Using the Collares Pareira and Rabl formulas, the hourly value I of global radiation is calculated [12, 19]:

$$I = H\left[(a + b\cos(\omega))\left(\frac{\pi}{24}\frac{\cos(\omega) - \cos(\omega_s)}{\sin(\omega_s) - \frac{\pi\omega_s}{180}\cos(\omega_s)}\right)\right] \tag{30}$$

With:

$$a = 0.409 + 0.5016\sin(\omega_s - 60) \tag{31}$$

$$b = 0.6609 + 0.4767\sin(\omega_s - 60) \tag{32}$$

Direct hourly radiation component is:

$$I_b = I - I_d \tag{33}$$

2.2. Hourly radiation on inclined surface

The hourly radiation on tilted surface area, I_t, is considered as the sum of three components: direct, diffuse from the sky and the reflection radiation on the ground [12]:

$$I_t = I_b R_b + I_{d,t} + I\rho\left(\frac{1 - \cos(\beta)}{2}\right) \tag{34}$$

ρ is the ground albedo and R_b is given by [7, 10]:

$$R_b = \frac{A}{B} = \frac{max(0, \cos(\beta))}{max(\cos(85°), \cos(\theta_z))} \tag{35}$$

The diffuse component $I_{d,t}$ of the radiation on inclined surface was the subject of several studies to propose models that can generate fairly realistic values. However, many analysts suggest that the model of Perez [20], despite his complexity, gives in most cases the best results.

$$I_{d,t} = I_d(1 - F_1)\left(\frac{1 + \cos(\beta)}{2}\right) + I_d F_1 \frac{A}{B} + I_d F_2 \sin(\beta) \tag{36}$$

F_1 and F_2 are, respectively, the circumsolar and brightness of the horizon components:

$$F_1 = max\left[0, \left(f_{11} + f_{12}\Delta + \frac{\pi\theta_z}{180}f_{13}\right)\right] \tag{37}$$

$$F_2 = f_{21} + f_{22}\Delta + \frac{\pi\theta_z}{180}f_{23} \tag{38}$$

The parameters $f_{11}, f_{12} \ldots f_{23}$ are obtained from [20] according to the values of the coefficient of sharpness ε:

$$\varepsilon = \frac{\frac{I_d + I_{b,n}}{I_d} + 5.535\times10^{-6}\theta_z^3}{1 + 5.535\times10^{-6}\theta_z^3} \tag{39}$$

With [12]:

$$I_{b,n} = \frac{I_b}{cos(\theta_z)} \tag{40}$$

Δ is the brightness coefficient:

$$\Delta = \frac{I_d}{I_{0,n} cos(\theta_z)} \tag{41}$$

3. Electrical Power Generation

3.1. Operating diagram

We adopt the scheme of figure 1 for an autonomous photovoltaic system.

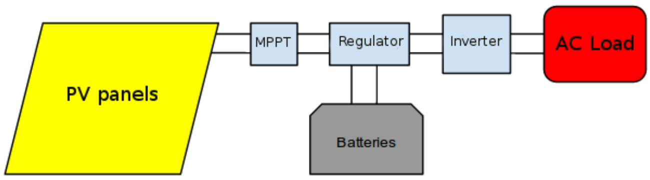

Fig. 1. General scheme of the system.

The photovoltaic system must operate optimally such that at each time *t* of the year, load demand $E_L(t)$ must be satisfied by one of the following options:

- The energy produced by photovoltaic panels and injected directly into the load.
- The energy stored in batteries.
- The energy produced and injected directly in addition to the energy stored in the batteries.

If the options just mentioned cannot meet the load demand, we have a deficit of energy, that is to say, the energy required by the different loads is greater than the energy produced by the panels and/or stored in batteries.

3.2. Usability function

In the field of solar energy, usability function is the fraction of the total incident radiation on a surface that exceed a level called "critical level" [12]:

$$\phi(t) = \frac{(I_t(t) - I_c(t))^+}{I_t(t)} \tag{42}$$

The sign + is the fact that we only take positive values. If $(I_t(t) - I_c(t))$ is negative, the value of usability will be equal to zero.

The critical level is [15]:

$$I_t(t) = \frac{E_L(t)}{S\ \eta_{pv}(t)\ \eta_w\ \eta_{mppt}\ \eta_{inv}\ \eta_r} \tag{43}$$

$E_L(t)$: energy directly called by the load.
S: the total surface of the photovoltaic panels.
$\eta_{pv}(t)$: the efficiency of panel at the time t
η_w: takes into account the electricity transmission losses through the power cables (we chose a value of 0.99).
η_{mppt}, η_{inv} and η_r are, respectively, the MPPT system performance (0.95, Maximum Power Point Tracker), the performance of the converter (0.97) and the charge controller performance (0.98).

$\eta_{pv}(t)$ is calculated as [15]:

$$\eta_{pv}(t) = \eta_{ref}\left[1 - \beta_p\left(T_c(t) - T_r\right)\right] \tag{44}$$

η_{ref}: the reference efficiency of the panels
β_p : the temperature coefficient for the efficiency of panels
T_r : the reference temperature (25°C)
$T_c(t)$ represents the temperature of solar cells [15]:

$$T_c(t) - T_a(t) = (219 - 823K_T)\frac{NOCT - 20}{800} \tag{45}$$

NOCT is the nominal operating cell temperature, $T_a(t)$ the ambient temperature and K_T is the clearness index.

3.3. Energy available for batteries

Each time t, the energy that can been used to recharge the batteries is:

$$E_b(t) = E_{pv}(t)\eta_w\eta_{mppt}\eta_r\phi(t) \tag{46}$$

$E_{pv}(t)$ is the energy produced by the photovoltaic panels:

$$E_{pv}(t) = I_t(t)\eta_{pv}(t)\ S \tag{47}$$

3.4. Directly available energy for load

Every hour t, the energy transferred to the load is:

$$E_d(t) = E_{pv}(t)\eta_w\eta_{mppt}\eta_r\eta_{inv}(1 - \phi(t)) \tag{48}$$

4. Energy Management

The available energy in the batteries is controlled according to the following relationship:

$$B_c(t) = B_c(t-1)(1-\sigma) + \left(E_b(t)\ \eta_{b,ch}\right) - L(t) \tag{49}$$

$B_c(t)$: total battery capacity at time t
$B_c(t\text{-}1)$: total battery capacity at time $t\text{-}1$
σ: hourly rate of self-discharge batteries (we take it equal to 0.005/hour).
$\eta_{b,ch}$: charging battery efficiency (we take it equal to 0.80).

- If $E_L(t)\text{-}E_d(t) \geq 0$:

$$L(t) = \frac{E_L(t) - E_d(t)}{\eta_w \, \eta_r \, \eta_{inv}} \quad (50)$$

- Otherwise:

$$L(t) = \frac{E_L(t) - E_d(t)}{\eta_w \, \eta_{inv}} \quad (51)$$

For the control of energy, we have two possibilities:

- $B_c(t) < SOC_{min}$: energy deficit, the controller disconnects the load from the batteries.
- $Bc(t) \geq SOCmax$: the controller disconnects panels to stop charging.

SOC_{min} represents the minimum level of the total capacity, which must not be reached during the discharge process, and SOC_{max} represents the maximum level of the total capacity, which must not be exceeded during the recharge process. This regulation ensures the proper functioning of batteries.

5. Economic Evaluation

In our study, we consider only the cost of the purchase of photovoltaic modules and batteries. The cost of the group of batteries is:

$$C_b = N_b \times C_{b,u} \quad (52)$$

N_b is the number of batteries, $C_{b,u}$ is the unit price of batteries.

Total peak power is:

$$P_{peak,t} = S \; 1000 \; \eta_{ref} \quad (53)$$

The number of panels required is:

$$N_{pv} = \frac{P_{peak,t}}{P_{peak,u}} \quad (54)$$

$P_{peak,u}$ is the peak power of a single photovoltaic panel. The total price will be:

$$C_{pv,t} = N_{pv} \times C_{pv,u} \quad (55)$$

$C_{pv,u}$ is the price of a single photovoltaic panel.

The total cost is:

$$C_i = C_{pv,t} + C_b \quad (56)$$

6. Genetic Algorithm

A genetic algorithm is an evolutionary algorithm. We use it as optimization technique in mathematics. The goal is to mimic the natural genetic selection process and apply artificial intelligence to find solutions to optimization problems.

6.1. Steps of algorithm

During the execution of a genetic algorithm, it goes through the following steps:

- Initialization: creating a first generation (randomly) with a specific number of probable solutions.
- Selection: based on an objective function, representing the merits of each individual to be closer to the optimal solution, a selection among the individuals of the first generation occurs.
- Crossover: from the population of survivors (step 2), a cross will be such that each two individuals (parents) who have successfully passed the selection stage will exchange "chromosomes" (characteristics) to give birth to new individuals (children) who will form the next generation. This exchange of chromosomes (coupling) depends on a probabilistic parameter of the genetic algorithm.
- Mutations: as a stage spanning, the characteristics of new individuals can mutate (genes in chromosomes). In this case, the probability that these mutations occur must be low in order not to waste time in finding the optimal.

These steps are repeated until reaching the stop condition set by the user.

6.2. Objective function

The objective function *OF* is a function that we will use as a criterion to determine the optimal solution to our optimization problem.

The year contains 8760 hours. Every hour of the year in which $B_c(t) < SOC_{min}$ will be counted as time deficit (T_{fail}). We define the loss-of-load probability as follows:

$$LLP = \frac{T_{fail}}{8760} \quad (57)$$

When the value of *LLP* is very low, the PV system is reliable and its design is optimal. Note that for a system accepting no loss-hours during the year $LLP = 0$

Therefore, by setting the value of *LLP*, the optimal solution will be one that will produce at least a certain minimum value of the objective function defined as:

$$OF = \frac{1}{LLP} = \frac{8760}{T_{fail}} \quad (58)$$

7. Simulation and Results

7.1. Site and data used

To test the developed methodology, we chose to apply it to an Algerian southern region known for its strong solar radiation: Bechar (31°37′N, 2°13′W) (see figure 2).

Fig. 2. Location of Bechar within Algeria.

For daily solar irradiation H we have recovered data from [21] for a period from 1983 to 2004. These data have helped us to build a profile for a typical meteorological year.

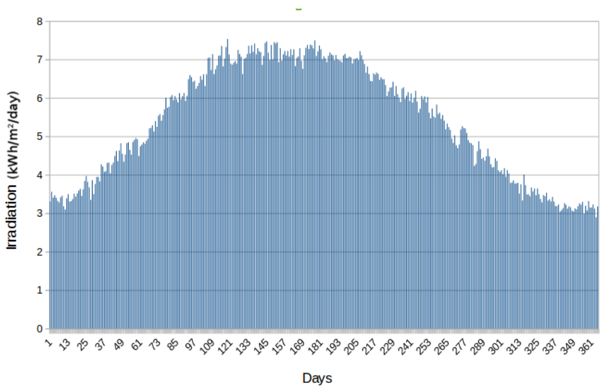

Fig. 3. Irradiations H for a year.

For the temperatures [22], see figure 4.

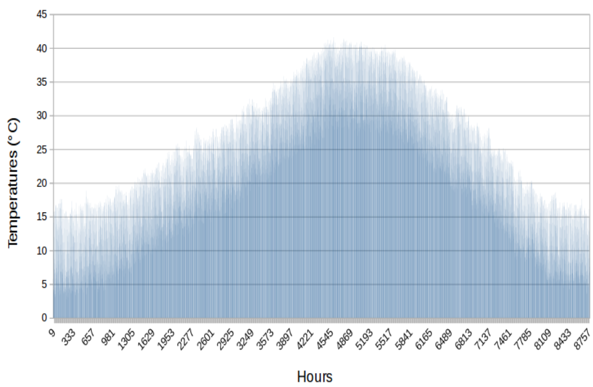

Fig. 4. Hourly temperatures over the year.

For the load demand, we divided the year into three periods:

- Hot period: May, June, July, and August.
- Cold period: November, December, January, and February.
- Half season period: March, April, September, and October.

For each period we have adopted a single daily profile for hourly load demand (see figure 5).

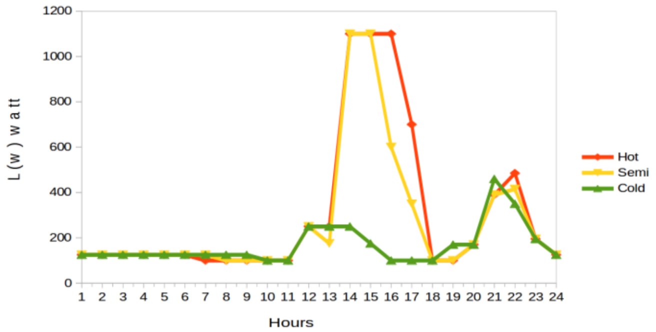

Fig. 5. Hourly load demand.

$L(w)$ is the load demand.

7.2. Initialization of solutions

A population of potential solutions will represent each generation. Each solution will be in the form of a vector containing three values:

$$[S,\ \eta_{ref}, B_c]$$

We chose three types of panels with three different η_{ref} (table 14).

Table 1. Considered photovoltaic panels [23].

Model	Peak power	NOCT	ηref	βp	Price
70W poly	70 W	45°	12%	-0.369%/°C	94.29$
90W mono	90 W	45°	13%	-0.37%/°C	115.17 $
145W poly	145 W	45°	14%	-0.369%/°C	175.79 $

Since the surface S depends on the performance η_{ref}, our method considers this point in the generation of random solutions. For each day of the year, an area A is calculated:

$$A = \frac{L_t}{H\eta_{ref}\ 0.80\ \eta_w\ \eta_{vr}\ \eta_{inv}\ \eta_{mppt}}$$

We take the value of the inclination equal to the latitude of the location, and the value of the albedo of the soil has been set equal to 0.02.

Buresch [24] introduced the 0.80 factor. L_t represents the demand for daily load. We calculate S by averaging the two extreme values of A:

$$S = \frac{A_{max} + A_{min}}{2}$$

Battery capacity is expressed in Wh by:

$$B_c = 12\ to\ 15 \times L_{max}$$

L_{max} is the value of maximum hourly load.

7.3. Results

During the execution of our algorithm, we suppose that the maximum number of days that the photovoltaic system is not able to produce enough energy to power the entire load demand is 7 days. The objective function will be:

$$OF \approx 52.20$$

All solutions that produce values of $OF \geq 52.20$ will be considered as optimal. Our goal is to determine which one will give us a low installation cost Ci

The price of batteries has been set at 150$ per unit. Assuming we choose batteries with 1.4 kW capacity each, N_b will be:

$$N_b = Total\ Capacity / 1.4$$

We have developed our own computer program to model, simulate and optimize photovoltaic system based on the developed methodology with the Python programming language. To study the influence of the number of generations and possible solutions, we analyse nine cases summarized in the table 2:

Table 2. Results of the optimization.

Model	Peak power	NOCT	η_{ref}	β_p	Price
70W poly	70 W	45°	12%	-0.369%/°C	94.29$
90W mono	90 W	45°	13%	-0.37%/°C	115.17$
145W poly	145 W	45°	14%	-0.369%/°C	175.79$

From the results, we can infer that increasing the number of generations used in the search of the optimal solution cannot always have a positive influence. However, the more optimal solutions, the greater the overall cost of the installation C_i is reduced. To save simulation time and ensure that we have the best optimal solution, we suggest reducing the number of generations and increase as much as possible the number of optimal solutions in order to choose the best solution according to the established criteria.

8. Conclusion

We developed a comprehensive methodology to optimize the design of a photovoltaic system. We began by establishing key relationships to generate solar radiation values. Then, thanks to the hourly usability function, we established strategy for energy flow management. We applied our study to the region of Bechar, south of Algeria.

In a second step, and with a genetic algorithm, we optimize the sizing of the system. The results showed that the more probable solutions tested, the more we get closer to the ultimate optimal solution.

As prospects of this work, we propose reducing calculation time (the larger the number of solutions/generation is, the larger the calculation takes time), and the addition of other constraints on the choice of the final solution.

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