Sensitivity Analysis for Photovoltaic Water Pumping Systems: Energetic and Economic Studies[1]

Imene Yahyaoui[1], Ahmad Atieh[2], Alvaro Serna[3] and Fernando Tadeo[3]*

[1]Technological center, University of Espirìto Santo, Brazil

[2]University of Jordan, Amman, Jordan

[3]Industrial Engineering School, University of Valladolid, Spain

e-mails: imene.yahyaoui@ufes.br, akatieh@hotmail.com, alvaro.serna@autom.uva.es
fernando@autom.uva.es

*Corresponding author: Imene Yahyaoui

E-mail address: imene.yahyaoui@ufes.br

Tel: 0034 983 184 859

Fax: 0034 983 423161

Abstract*— In agricultural remote areas where electrical energy is required to supply water pumping plants, photovoltaic modules are considered a good option to generate electricity. The reliability of autonomous Photovoltaic water pumping plants depends essentially on the system components size, which should meet the criteria related to the plant autonomy and the water volume required for irrigation. In this context, this research paper proposes an approach to size the elements of an autonomous photovoltaic system equipped with an energy storage device (a battery bank), and which is used to supply a water-pumping plant with electricity. The proposed approach determines the optimal surface of the photovoltaic modules, the optimal capacity of the battery bank and the volume of the water storage tank. The optimization approach takes into account the monthly average solar radiation, the fulfillment of the water needed for the crops' irrigation and the number of the days of autonomy. Measured climatic data of 10 ha situated in Northern Tunisia and planted with tomato are used in the optimization process, which is conducted during the tomato vegetative cycle (from March to July). The optimal results achieved for this farm are 101.5 m² of photovoltaic modules'*

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surface, 1680 Ah/12V of the battery bank and 1800 m³ of the volume of the water storage tank. Then, to verify the reliability of the proposed optimization approach, the results of the proposed sizing algorithm are compared with those of a commercial optimization tool named HOMER, which shows better results using the proposed approach. Finally, the economic reliability of the obtained size is studied and compared with systems that include a diesel generator, and a diesel generator- photovoltaic panels, respectively, using climatic and economic parameters in three countries: Tunisia, Spain and Jordan. The economic analysis for these water pumping systems showed that photovoltaic- batteries/ Pump system is the optimum solution in the three countries. However, the initial cost of the system can be recuperated faster in Spain than in Tunisia and Jordan due to high prices of the diesel these two countries.

Keywords— Photovoltaic energy; water pumping; system sizing; economic sensitivity.

1. Introduction

For remote agriculture areas, it is common to use diesel generators to supply autonomous installations. However, due to the instability of the diesel cost and the decrease in the photovoltaic (PV) technology costs, PV- batteries systems are best placed to generate electricity especially in these areas, where the continuous need for providing diesel is considered the most important disadvantage of systems that use diesel generators to generate electricity. Therefore, this renewable based solution should be reliable and economic. Thus, sizing and the energy optimization of PV- batteries installations must be properly performed, since they are affected especially by the energetic and climatic constraints, namely the intermittence of the climatic parameters [1, 2].

In fact, sizing of autonomous PV systems is considered a key factor that allows the PV energy generated to be optimized and the electrical power required to the loads supply to be produced during the needed days of autonomy [2, 3]. Consequently, the optimal sizing is indeed recognized as being crucial for the system to provide satisfactory power to the loads. More precisely, for agricultural applications, where water is used principally for crops irrigation, the size of PV- batteries systems must guarantee the water volume needed during the crops vegetative cycle [3]. In fact, the knowledge of the water volume required, the site' climatic parameters, the PV module and the batteries characteristics are crucial for the autonomous system design [1, 2]. Indeed, sizing optimization techniques must provide adequate values for the water pumping system components, especially the PV modules' surface, the batteries bank capacity and the reservoir volume.

In this context, researchers have established various methods to optimize the size of the PV installations' components [4- 6]. For instance, some research works have focused on developing analytical methods based on a simple calculation of the PV modules' surface and the battery bank's capacity using the energetic balance method, as it has been studied in [7- 9]. Other research works have concentrated on the cost versus reliability issue by studying the optimum sizing of the system elements from an economic point of view, as it has been reported by [10]. Moreover, some researchers have proposed sizing algorithms based on the minimization of cost functions using the Loss of Load Probability (LLP) concept [6, 11- 12]. Additionally, other researchers have combined the Artificial Neuronal Networks (ANN) and the Genetic Algorithms (GA) to determine the optimum size for autonomous PV systems, as it has been reported by [9, 13]. Deterministic methods and probabilistic approaches have also been used to analyze the impact of the geographic site on the PV modules and the energy storage design [14]. Moreover, multi-objective optimization approach based on Fuzzy logic has also been used to ensure the best comprise between two conflicting objectives, such as the system reliability and cost optimizations, as treated in [15].

Although the efficiency of these techniques in finding reliable sizing for the systems components, they may result in an oversized system for one location and an undersized one for another one [16]. Indeed, the oversized case results in high installation costs. Whereas for an undersized case, the installation is unable to supply the load with the needed energy [17- 18], as well as the installation lifetime is short due to excessive use of the batteries. Thus, the system size must be carefully selected for each specific application and location [1, 16].

Consequently, this research paper presents a continuation of previously published works by some of the authors [17, 18], where a sizing algorithm for a PV- battery installation destined for water pumping is proposed and evaluated. In fact, using the drip- irrigation technique for tomatoes, the pumped water is used here to irrigate an agriculture land situated in Northern Tunisia (latitude: 36.39º; longitude: 9.6º) during the crops vegetative cycle, which is from *March* to *July*. The system consists of PV modules, a battery bank, an MPPT/ charge regulator, an inverter and a water reservoir. The regulator is used to avoid the batteries damage due to overcharging. The MPPT tracks the Maximum Power Point (MPP) generated by the PV modules to have an efficient conversion for the solar energy to electricity. Fig. 1 shows the main components of the autonomous PV system used for the water pumping in this application.

The main contribution of this research paper is the comparison of the algorithm performances with those obtained using Homer [1]. Then, an economic study is developed by comparing the costs of the adopted system to those of two other possible water-pumping systems, which are the DG/ pump and the PV/ DG/ pump systems. Indeed, the economic study includes the components buying, maintenance and replacement costs. The study has been evaluated in three countries, Tunisia, Spain and Jordan.

The paper is organized as follows: Section 2 details the models used to describe the system components operating. The sizing algorithm principle is detailed in the third section. Then, a case study to test the sizing algorithm performance is described and explained deeply in Section 4. The achieved results are compared with those obtained by HOMER in Section 5. Then, Section 6 presents an economic comparison of three possible systems, which are the DG/ pump, PV/ DG/ pump and the PV/ batteries/ pump, where costs in three countries: Tunisia, Spain and Jordan are compared. Finally, the research paper is concluded in Section 7.

Fig.1 Block diagram of the PV water pumping system used for the crops irrigation

2. Modeling of the system components

2.1 PV module

A PV module is composed of PV cells connected in series. Then these modules are connected in parallel, which results in a PV array. Nowadays, the most common solution for crystalline PV technology is made of 60 cells in series [19]. Thus, modeling a PV module can be based on modelling a PV cell [19, 20]. In fact, a simple approach to model a PV module consists in using a matrix where the solar radiance G and the ambient temperature T_a of a particular location are linked, and used to determine the corresponding PV power P_{pv}, and therefore forming the matrix P_{pv} $(G;\ T_a)$ [21]. Despite the simplicity of this method, it remains practical only for the studied technology and the PV module, and therefore, it cannot be generalized. Moreover, some other researchers use non-linear models to characterize the PV modules. These nonlinear models use one diode or two diodes based model, which associates a current source in parallel with the diodes, to describe the PV current generated by the solar cell [22, 23]. In this model, losses related to the PV cells connection are presented by the series resistance R_s. However, losses caused by the charge carriers, namely, losses by diffusion, are modeled by a parallel resistance R_p [1, 23, 24].

Additionally, the yield based PV module model has also been used to characterize the PV module operation [1]. In fact, this model is evaluated using the solar cell parameters values, namely the Nominal Operating Cell Temperature (NOCT), as well as the temperature coefficient for the module yield and the module yield at the reference temperature. The yield model is simple to use, adaptable to the site characteristics and the PV module technology. Moreover, it has experimentally been validated in a previous published work [1]. Therefore, in this research paper, the yield model is chosen to model the PV modules. It is described by the following equations [1, 36]:

$$\eta_{pv}(t) = \eta_r \left(1 - \beta_{pv}\left(T_c(t) - T_{ref}\right)\right) \tag{1}$$

where:

η_r : the module efficiency at the reference conditions, STC (Standard Test Conditions),

β_{pv} : the temperature coefficient for the module yield ($°C^{-1}$),

$T_c(t)$: the PV cell temperature (ºC),

T_{ref} : the temperature of the PV cell reference (°C).

There are many simple models to calculate the cell temperature $T_c(t)$, starting from the ambient operating conditions, the one that is based only on the thermal parameter, NOCT, provided by the PV modules manufacturer is the following [1, 25, 36]:

$$T_c(t) = T_a(t) + H_t(t,d)\frac{NOCT - T_{a\,ref}}{800} \tag{2}$$

where:

T_a : the ambient temperature (°C),

$H_t(t,d)$: the solar radiation on a tilted PV module (W/m²),

NOCT: the Normal Operating Cell Temperature (ºC),

$T_{a\,ref}$: the reference ambient temperature (°C).

Finally, the PV power $P_{pv}(t)$ can be evaluated as follows, where only the thermal losses have been considered; the optical, mismatch and joule losses of the PV array will be considered with separated efficiencies [1, 36]:

$$P_{pv}(t) = S\,H_t(t,d)\,\eta_{pv}(t) \tag{3}$$

where S is the PV module surface (m²).

2.2 Battery bank

The intermittence of the solar radiation and the generation of the PV power only during the daytime make using storage energy components namely the batteries, necessary. Thus, battery bank is generally used to supply the required power to the load on one hand and to store the PV energy generated in excess, on the other one [1, 24]. In this research paper, a non-linear model, based on the battery bank' current and voltage, is used to model the battery operation. The model performance is evaluated by the batteries depth of discharge (*dod*), which is expressed as follows [1, 24, 26, 36]:

$$dod_{(k)} = 1 - \frac{C_{R_{(k)}}}{C_p} \tag{4}$$

where the stored charge in the battery C_R is given by [36]:

$$C_{R(k)} = C_{R(k-1)} + \frac{\partial k}{3600} I_{bat_{(k)}}{}^{k_p} \tag{5}$$

where:

∂k : the time between instant *k*-1 and *k*,

k_p : the Peukert coefficient,

C_p : the Peukert capacity (Ah),

$I_{bat_{(k)}}$: the battery bank current, which is considered constant (A).

2.3 Water volume for Tomatoes irrigation

In this research paper, the PV water pumping system is used to pump water for tomatoes irrigation. Hence, it is necessary to study the need for water of the crops based on the climatic and the site parameters.

In fact, Tomatoes is harvested in Tunisia during the summer period. Indeed, they are sown in nursery plants during February. The seedlings are transplanted in *March* in the fields. Eight to ten weeks after sowing, flowering occurs in the middle of *May*. At the end of this month and at the beginning of *June*, fruits ripening occur. In *July*, the fruits are ready to be harvested [27]. Hence, the growing steps of Tomatoes will be considered here as a base to determine the optimum system sizing for the PV installation components, which must provide the water volume required for the crops irrigation, by taking into account of the optimal frequency and timing of irrigation, which correspond to a specific irrigation schedule [28]. Indeed, parameters related to the crops are used here to model the water volume needed for the crops irrigation, namely the reference crop evapotranspiration (ET_o) and the rainfall r_m , which can be expected for a given 10-days period [29, 30]. In fact, in the literature, many models have been used to describe Tomatoes' evapotranspiration. For instance, some researchers used the Penman Method, which depends essentially on the net radiation at the crop surface, the mean air temperature, and the wind speed [31]. Other works presented the evapotranspiration as a function of the sunlight duration and the air temperature [1, 32]. For instance, the Blaney-Criddle model for the evapotranspiration modelling includes the seasonal crop coefficient k_c , in addition to the ratio of the mean daily daytime hours for a given month to the total daytime hours in the year *p* and the mean monthly air temperature *T* of the corresponding month [27]. There by, this model provides good patterns of the water volume required for Tomatoes' irrigation [27]. Hence, in this research, it is used to describe the Tomatoes' evapotranspiration [27]:

$$ET_o = K\ p(0.46T + 8.13) \tag{6}$$

where *K* is the correction factor, which is expressed by:

$$K = 0.03 + 0.24K \tag{7}$$

To obtain the necessary gross water, it is essential to estimate the irrigation losses. Thus, an additional water volume must be pumped, to compensate the possible losses. Consequently, the final water volume *V* needed to irrigate Tomatoes is given by [1, 27, 33]:

$$V = k_c ET_o - r_m \left(1 + \frac{1 - l_f (1 - L_R)}{l_f (1 - L_R)} \right) \tag{8}$$

where:

r_m : the average monthly rain volume (m³),

l_f : the leaching efficiency coefficient as a function of the irrigation water applied (%),

L_R : the leaching fraction given by the humidity that remains in the soil expressed in (%) and given by:

$$L_R = \frac{EC_w}{5EC_e - EC_w} \tag{9}$$

where:

EC_w : the electrical conductivity of the irrigation water (dS. m^{-1}),

EC_e : the crop salt tolerance (dS. m^{-1}).

3. Sizing Algorithm Principle

A good optimization of the water pumping system should fulfill the electrical power required to supply the water pump during the necessary pumping duration [34]. Hence, the main objective of the sizing algorithm is to ensure that the pump is supplied throughout the day, while protecting the battery bank against deep discharge or excessive charge, and guaranteeing the water volume needed for tomatoes' irrigation. The inputs, outputs, objectives and criteria of the sizing algorithm are presented in Fig. 2. Indeed, the algorithm depends on:

- the water volume V needed to irrigate tomatoes,
- the site characteristics, including the solar radiation G and the ambient temperature T_a ,
- the battery' depth of discharge *dod*,
- the PV module characteristics, such as the PV power, current and voltage.

Fig. 2 Principle of the proposed sizing algorithm

The proposed sizing approach aims to provide the optimum PV modules' surface (S_{opt}), the number of batteries ($n_{bat_{opt}}$) and the reservoir volume V that guarantees the installation autonomy. In fact, the idea consists in searching the optimal components sizes that ensure the energetic balance between the energy (E_c) charged in the battery bank, and the energies E_{AM} and E_{PM} extracted from it during the AM and PM times, respectively, as it is shown in Fig. 3. Indeed, the battery bank supplies the pump when the PV modules do not generate the sufficient electrical power for the pump power supply, and it is charged with the PV energy generated in excess. The energy balance can be expressed as follows (Fig. 3):

$$E_c \approx E_{AM} + E_{PM} \tag{10}$$

Fig.3 Diagram of the energy balance principle

The proposed sizing approach is composed of two main algorithms. In fact, in Algorithm 1, the optimum sizes of the PV system components are evaluated for each month *M* of the Tomatoes vegetative cycle (from *March* to *July*) as it is described in Fig. 4. These results are used in Algorithm 2 which evaluates the final value of the system components sizes, as it is described in Fig. 5. These two algorithms are detailed in the following subsections.

3.1 Algorithm 1: Evaluation of the monthly PV modules' surface and the batteries' number

Algorithm 1 finds the PV module surface (S_M) and the number of batteries (n_{bat_M}) for each month *M* during the crops' vegetative cycle. The algorithm has the following process:

Step 1 Estimation of the diffused radiation ($H_d(t,d)$) and direct radiation ($H_b(t,d)$) using the mean value of monthly global solar radiation (*H*) on a horizontal PV module as follows [1, 24, 35]:

$$H_d(t,d) = \frac{\pi}{24} \frac{cos\ w - cos\ w_s}{sin\ w_s - w_s\ cos\ w_s} \left(1.391 - 3.56\ \overline{K}_t + 4.189\ \overline{K}_t^{\,2} - 2.137\ \overline{K}_t^{\,3}\right)\overline{H} \tag{11}$$

$$H(t,d) = \frac{\pi}{24} \frac{cos\ w - cos\ w_s}{sin\ w_s - w_s\ cos\ w_s} (a + b\ cos\, w)\overline{H} \tag{12}$$

$$H_b(t,d) = H(t,d) - H_d(t,d) \tag{13}$$

where:

$$a = 0.409 + 0.501\, sin\left(w_s - \frac{\pi}{3}\right) \tag{14}$$

$$b = 0.6609 + 0.4767\, cos\left(w_s - \frac{\pi}{3}\right) \tag{15}$$

w: the angle of the sun at a specific hour,

w_s: the angle of the sun at sunset,

K_t: the clearness index.

Step 2 Calculation of the solar radiation $H_t(t,d)$ for a tilted PV module using the model given by Collares Pereira et Rabl (16) [1, 24, 35]. This model for the solar radiation modelling is chosen since it is easy and can be applied for whatever geographic site by adopting the site' latitude and longitude:

$$H_t(t,d) = R'_b\ H_b(t,d) + \left(\frac{1+\cos\beta}{2}\right) H_d(t,d) + \rho\left(\frac{1-\cos\beta}{2}\right) H(t,d) \quad (16)$$

where:

ρ : the albedo of the soil,

β : the PV module tilt angle (°),

R'_b : the ratio of direct radiation on tilted PV module and direct radiation on horizontal PV module expressed by [36]:

$$R'_b = \frac{\cos\theta}{\cos\theta_z} \quad (17)$$

where:

θ : the radiation incidence angle (°) that fulfills the following expression:

$$\begin{aligned} \cos\theta &= \sin\delta\ \sin\varphi\ \cos\beta - \sin\delta\ \cos\varphi\ \sin\beta\ \cos\gamma + \cos\delta\ \cos\varphi\ \cos\beta\ \cos w \\ &+ \cos\delta\ \sin\varphi\ \sin\beta\ \cos\gamma\ \cos w + \cos\delta\ \sin\beta\ \sin\gamma\ \sin w \end{aligned} \quad (18)$$

θ_z : the zenith angle of the sun (°) given by:

$$\cos\theta_z = \sin\delta\ \sin\varphi + \cos\delta\ \cos\varphi\ \cos w \quad (19)$$

Step 3 Calculation of the cell temperature ($T_c(t)$) using equation (2) [1, 36].

Step 4 Calculation of the module yield ($\eta_{pv}(t)$) using equation (1) [1, 36].

Step 5 Evaluation of the water (*V*) required for Tomatoes irrigation using equations (6)- (9) [1, 24, 36].

Step 6 Evaluation of the pumping duration (Δt) using the water flow (*Q*). The pump flux is assumed constant. Thus, Δt can be evaluated by [1, 24, 36]:

$$\Delta t = \frac{P_{pump}}{Q} \quad (20)$$

Step 7 Calculation of the minimum PV modules' surface (S_i) and the number of batteries (n_{bat_i}) using equations (21)- (23) [1, 24, 36]:

$$S_i = \frac{P_{pump}\Delta t}{W_{pv}\,\eta_{bat}{}^2\eta_l\eta_{pv}\eta_{reg}\eta_{inv}\eta_{opt\,ther}\eta_{matching}}\left(1+\frac{d_{aut}}{d_{rech}}\right) \tag{21}$$

Knowing that $E_c = E_{tot}\,\Delta dod_{max} = E_d\,d_{aut}$ (22)

Hence, the initial battery bank number is obtained using equation (23) [36]:

$$n_{bat_i} = \frac{E_d\,d_{aut}}{V_{bat}\,C_{bat}\,\Delta dod_{max}} \tag{23}$$

where:

P_{pump} : the water pump power (W),

Δt : the water pumping duration (h),

d_{aut} : the number of days of autonomy,

d_{rech} : the number of days needed to recharge the battery,

W_{pv} : the average daily radiation (Wh/m²/ day),

η_{bat} : the electrical efficiency of batteries bank (%),

η_l : the electrical efficiency of installation that includes Ohmic wiring losses (%),

η_{reg} : the regulator performance (%),

η_{inv} : the inverter performance (%),

η_{opt} : the module performance due to optical effects (%),

$\eta_{matching}$: the module matching performance (%),

E_d : the daily energy consumption (W.h),

V_{bat} : the battery voltage (V),

Δdod_{max} : the maximum *dod* variation (%),

C_{bat} : the nominal capacity of a battery (Ah).

Step 8 Evaluation of the PV module power ($P_{pv\,i}$) that corresponds to minimum module surface (S_i) using equation (24) [1, 24, 36]:

$$P_{pv\,i} = \eta_{pv}\,\eta_{opt\,ther}\,\eta_{reg}\,\eta_{matching}\,H_t\,S_i \tag{24}$$

where:

H_t : the solar radiation on tilted PV module (W/m²),

S_i : the initial PV module surface (m²).

Step 9 Calculation of the expected energies to be stored and extracted from the batteries bank for each day by evaluating the area (E_c) and (E_e), respectively.

Step 10 The algorithm increases the PV module surface by the minimum increment value of PV modules' size when discharged energy is higher than charged energy. The algorithm also looks for the best configuration that guarantees the balance between the required and the generated energies by ensuring the equality between the energies charged and extracted, E_c and E_e respectively, from the batteries bank, as it is described in equation (10). The new PV modules' surface must match the PV models surface commercially available.

The balance between the charged and the extracted energies does not guarantee the system full autonomy due to fluctuations in the solar radiation and to energy losses in installation components. Thus, the algorithm adopts an efficiency coefficient (η), which allows the full system autonomy to be ensured and the battery bank to be protected against deep discharges. As a result, the variation in the *dod* (Δdod) has to be less than Δdod_{max} .

Thus, by introducing the error factor η in equation (10), it becomes:

$$E_c \approx \eta\left(E_{AM} + E_{PM}\right) \tag{25}$$

Moreover, the previous condition is performed considering 10 % of PV energy produced in leak, to ensure the continuity in the pump supply.

Step 11 Deduction of the number of batteries using equation (26) [1, 36]:

$$n_{bat} = \frac{E_c}{C_{bat}{}^{k_p}} \tag{26}$$

where:

E_c : the energy charging batteries bank (W.h),

C_{bat} : the nominal capacity of the battery bank (A.h).

3.2 Algorithm 2: Deduction of the final values of PV modules' surface and the number of batteries

The final values of the PV modules' surface (S_{opt}) and the number of batteries ($n_{bat_{opt}}$) are deduced using algorithm 2. S_{opt} corresponds to the maximum value of modules' surface obtained during the months of Tomatoes' vegetative cycle. The optimum batteries' capacity (C_{opt}) corresponds to the obtained value of S_{opt} as shown in Fig. 5.

Fig. 4 Principle of the system sizing using Algorithm 1 for each month *M* of Tomatoes vegetative cycle [1]

Fig.5 Algorithm 2: deduction of the optimum components sizes of the PV water pumping installation

3.3 Determination of the reservoir volume

The calculation of the reservoir volume, which must ensure the system installation autonomy, depends on the possible leaking water volume, the number of the consecutive cloudy days n_c and the possibility of having discharged battery bank. Indeed, the maximum number of cloudy days per month n_{c_i} and the amount of clouds per day A_{c_i} are evaluated for each month *M* to determine the days of autonomy. They are calculated using (27)– (28) [1]:

$$n_{c_i} = \frac{n_{M_i}\left(W_{pvc_i} - \overline{H}_{t_i}\right)}{\left(1 - DA_i\right)W_{pvc_i}} \tag{27}$$

$$A_{c_i} = \frac{W_{pvc_i} - \overline{H}_{t_i}}{W_{pvc_i}} \tag{28}$$

where:

n_{M_i} : the days number in the month *M*,

W_{pvc_i} : the solar energy for the month *M* using the clear sky model (Wh) [1, 37],

$\overline{H}_{t_i}$: the solar energy for the month *M* (Wh),

DA_i : the ratio between diffuse and global daily solar radiation.

Therefore, the water volume leaked or in excess is evaluated using equation (29) [1, 36]:

$$V_{leaked\,/\,excess} = V_{pumped} - \frac{n_c}{f_i} V \tag{29}$$

where:

V_{pumped} : the possible pumped water volume (m^3),

n_c : the number of cloudy days,

f_i : the irrigation frequency,

V: the water volume needed for irrigation for specific month *M*.

The required volume of the reservoir is determined by equation (30):

$$V_{reservoir} = \eta_{reservoir} \left(V_{leaked\,/\,excess} + V \right) \tag{30}$$

where $\eta_{reservoir}$ is the water losses in the reservoir (%).

4. Application of the system sizing algorithms to a case study

The proposed sizing algorithm is applied to calculate the components' sizes of a case study of an actual tomato farm (10 ha) during its vegetative cycle months (*March* to *July*). The farm is located at Northern Tunisia: latitude: 36.39°, longitude: 9.6°. The components parameters shown in Table 1 are used to execute Algorithm 1 and Algorithm 2, which are proposed for the sizing approach. The measured crops' data, namely the growth coefficient and the daily evapotranspiration, in addition to the daily rain volume are shown in Fig. 6. The measured data of the site characteristics such as the solar radiation and the ambient temperature are also used in the sizing approach of the farm. Fig. 7 illustrates the measured hourly average solar radiation and the ambient temperature for each month *M* of the vegetative cycle for the farm investigated.

Table 1 Parameters used for the components sizing of the PV water pumping

Fig. 6 Crops characteristics for each month *M* of the vegetative cycle

Fig. 7 Measured hourly solar radiation for each month *M* of Tomatoes vegetative cycle in the farm investigated

Algorithm 1 is first performed for all the months of the vegetative cycle as described earlier. The solar radiation accumulated on the tilted PV panel is evaluated using equation (16). Then, the panel yield η_{pv} is calculated for each month *M* using (1), as shown in Table 2. At the same time, the water volume required for Tomatoes' irrigation *V* is evaluated for each month *M* depending on the crops vegetative cycle and the site characteristics using (8). Also, the pumping duration Δt is evaluated using (20).

Table 2 Climatic parameters, panel efficiency and irrigation parameters used in the case study

The following parameters are described in Table 3. The maximum number of cloudy days n_{c_i} per month M, the clouds rate per day A_{c_i} per month *M* and the number of days of the batteries discharging and charging d_{aut} and d_{rech}, respectively. The irrigation frequency for each month is defined as the day number in each 10 days on which irrigation occurred. For example, in the month of *March* and during the first 10 days, the crops are irrigated every third day (1, 4, 7, 10). On the other hand, the batteries are charged over a period of few days, as listed in Table 3. However, the battery' bank autonomy days; where they are discharged, is the irrigation day. The PV energy is evaluated using the clear sky model [37]. The initial values of the PV module surface S_i and the battery number n_{bat_i} used in Algorithm 1 are also shown in Table 3. These values are used in evaluating the condition given by (25). In fact, when the charged energy E_c is higher than the extracted energy E_e, the PV modules' surface is increased by the minimum surface value available in the market for PV module technology (in this case, it is equal to 0.5 m²). The efficiency coefficient values throughout the vegetative cycle guaranteed that Δdod_{max} equals to 0.78 as specified in battery datasheet of a local Tunisian manufacturer.

Algorithm 1 results are summarized in Table 4. It is shown that in the month of *March*, the required pump electricity is supplied by the PV panels in conjunction with the battery bank during the morning period. After the water pumping duration of 2.5 hours as described in Table 2, the generated power of the PV modules is used to charge the batteries bank. The quotient between the cumulated energy and extracted energy is 1.66, which is close to the target value of 1.7. Table 4 also shows that *July* is the most critical month for irrigation because it requires more water volume for irrigation. Therefore, the system components sizing of *July* are selected as the sizing of the system. The achieved components' size allows the load to be supplied during the requested pumping duration, the battery bank to be operated safely, and the water volume required to irrigate tomatoes to be pumped. The required daily water needed and actual pumped water volumes are illustrated in Fig. 8 for the crop vegetative cycle. Table 5 shows that the leaked water volumes in *May* and *July* are 1314.6 m^3 and 963 m^3, respectively. It is clear that the month of *May* has the maximum leaked water. Therefore, the water volume corresponds to *May* is chosen to for the reservoir. Hence, using equations (27)- (30), and considering $\eta_{reservoir} = 80\%$, the final value of the reservoir volume that ensures the system autonomy for this farm is 1800 m^3. This volume ensures an autonomy of 10.22 consecutive days in *May* and 5.62 in *July* with no need to pump water to the reservoir. These values are sufficient to provide water even when the sky is cloudy (9 days in *May* and 4 days in *July*) and the PV modules are not producing electricity and the batteries are fully discharged. This is an excellent result which proves that the system is totally autonomous for both electric energy and water considerations.

Fig. 8 Daily needed (*V*) and pumped (V_{pumped}) water volumes during tomatoes vegetative cycle for the case study

Table 3 Parameters used in executing Algorithm I including initial values of PV module surface and batteries number

Table 4 Algorithm 1 results summary

Table 5 Frequency of cloudy days and water volume needed for irrigation

5. Results comparison with HOMER tool

In order to check the accuracy of the proposed sizing approach, its results are compared with those obtained using HOMER commercial software. In fact, using Homer, the needed modules surface obtained is

142 m², and the battery number is 14 batteries (210 A.h/ 12V). While, S_{opt} was 101.5 m² and $n_{bat_{opt}}$ was 8 batteries of 210 A.h/ 12 V as obtained using proposed approach. The simulation results using HOMER software are presented in Fig. 9 and Fig. 10. The PV modules’ size suggested by HOMER is higher than the surface obtained by the proposed algorithm. This can be explained because HOMER gives huge importance to the day autonomy and includes when calculating the battery bank capacity.

Fig. 9 The hourly inverter output power in kW in each month of vegetative cycle averaged over months’ days using HOMER

Fig. 10 Batteries bank state of charge for each month of the vegetative cycle at each hour in a day averaged over months’ days using HOMER

6. Economic viability of PV/ batteries/pump and diesel only/pump options

In this section, the total water pumping system cost including initial investments and operational costs are compared for three different system implementations. The first system is composed of a diesel engine only which supplies electricity to the water pump. In the second system, the pump is supplied by both PV modules and a diesel engine. Finally, the third system is a fully renewable option in which the electricity is supplied to the pump by PV modules and batteries bank. The option composed of PV/ Batteries/ DG is not studied here since it is assumed that the water pumping will be only performed during the day.

6.1 Costs analysis of water pumping plants

The total cost of water pumping installation plant is calculated for the different options assuming it has N parts. The total cost includes initial investment, maintenance and parts replacements costs [38].

6.1.1 Cost of diesel water pumping system

This system is composed of a diesel generator which supplies electricity to the water pump. Hence, its cost $cost_{s1}$ can be evaluated using equation (31):

$$cost_{s1} = n_{diesel}\left(C_{t\_diesel} + \left(n_y - 1\right)M_{diesel}\right) \tag{31}$$

where:

n_{diesel} : number of diesel engines used.

C_{t_diesel} : investment price of the diesel engine (€/ for n_y years of operating).

n_y : number of years of system operation.

M_{diesel} : diesel generator maintenance cost (€/ module per year).

The evaluation of the diesel cost C_{t_diesel} includes fuel and engine oil costs. It is evaluated as follows:

$$C_{t\_diesel} = C_{diesel} + C_{fuel} * \Delta t_{diesel} * V_{fuel} + n_{oil} * C_{oil} * V_{oil} * n_y \quad (32)$$

where:

C_{diesel} : diesel generator price (€/ module for n_y).

C_{fuel} : cost of the fuel (€/ l).

Δt_{diesel} : time duration of operation (h/ day).

V_{fuel} : volume of fuel consumption (l/ h).

C_{oil} : cost of engine oil (€/ l).

n_{oil} : number of oil changing times by year.

6.1.2 Cost of PV/ diesel water pumping system

This system is composed of PV modules and diesel generator to supply water pump with electricity. In this case, the diesel generator is used when the power generated by the PV modules is insufficient to operate the water pump. The cost $cost_{s2}$ of this system can be evaluated as [38]:

$$\begin{aligned} cost_{s2} &= n_{pv}\left(C_{pv} + n_y M_{pv}\right) + n_{chop} C_{chop}\left(y_{chop} + 1\right) + M_{chop}\left(n_y - y_{chop} - 1\right) \\ &+ C_{inv}\left(y_{inv} + 1\right) + M_{inv}\left(n_y - y_{inv} - 1\right) + n_{diesel}\left(C_{t\_diesel} + \left(n_y - 1\right) M_{diesel}\right) \end{aligned} \quad (33)$$

where:

n_{pv} : number of PV modules,

C_{pv} : PV module cost (€/ module for n_y).

M_{pv} : PV module maintenance cost (€/ module per year).

n_{chop} : number of choppers.

C_{chop} : chopper cost (€/chopper for n_y).

y_{chop} : number of times the chopper is replaced during n_y years.

M_{chop} : maintenance cost for one chopper (€/ chopper per year).

C_{inv} : cost of inverter (€/ inverter for n_y).

y_{inv} : number of inverters replaced during n_y years.

M_{inv} : maintenance cost for one inverter (€/ inverter per year).

6.1.3 Cost of PV/batteries bank water pumping system

This system is composed of PV modules and a batteries bank which supply the water pump with electricity. In this case, the batteries bank supplies the water pump when the PV power generated is insufficient to operate it. The cost $cost_{s3}$ of this system can be evaluated by [38]:

$$cost_{s3} = n_{pv}\left(C_{pv} + n_y M_{pv}\right) + n_{bat}\left(C_b + y_b C_b + \left(n_y - y_b - 1\right)M_b\right) + n_{chop}C_{chop}\left(y_{chop} + 1\right) + C_{inv}\left(y_{inv} + 1\right) + M_{inv}\left(n_y - y_{inv} - 1\right) \quad (34)$$

where:

n_{bat} : number of batteries.

C_b : battery cost (€/ battery for n_y).

y_{bat} : number of times the batteries are replaced during n_y years.

M_{bat} : maintenance cost for one battery (€/ battery per year).

6.2 Cost comparison for different water Pumping Systems

The parameters used in the cost analysis for the different options calculated for the case studied farm in Tunisia are described in Table 6.

Table 6 Parameters used for costs analysis of different water pumping options [39]

The cost for options used diesel generators includes engine oil and fuel consumption costs, which are summarized in Table 7 for two options.

Table 7 Diesel generator parameters used for the cost analysis

The costs analysis of the different options are evaluated based on climatic and economic data in Tunisia using results obtained for the case studied farm which are S_{opt} = 101.5 m² and $n_{bat_{opt}}$ =8 batteries of 210 A.h/ 12 V). The total cost of these three systems are summarized in Table 8.

Table 8 Costs summary for the three water-pumping options for farm in Tunisia

It is noticed that system 2, which consists of PV/ DG / Pump, is the most expensive system. It is subject to relatively high price of diesel fuel in Tunisia (it is assumed that fuel price is constant during 20 years of operation). However, system 1, which uses DE, only have relatively close total cost to system 2. Finally, the cost of System 3 is the cheapest among the three systems for water pumping plant supply in Tunisia. It is necessary to mention that systems with DG requires continuous maintenance and need operator presence on regular bases to fuel and change oil to the engine which make them not practical solutions for supplying electricity to remote water pump systems.

6.3 Water pumping system cost analysis sensitivity to geographic conditions

It has been shown that the PV/ Batteries/ Pump system is the most economic system for water pumping plants in Tunisia. The cost analysis was done based on climatic, geographic and economic parameters in the country. In this section, the economic study is repeated for two more countries; Spain (latitude: 40.25°) and Jordan (latitude: 31°) to investigate the effect of geographic parameters variations on the final results. Hence, the cost of previously proposed options is recalculated for Spain and Jordan. These countries are chosen due to similarities in climatic condition (all are on the Mediterranean see). In addition, these countries were chosen because they have almost similar solar energy amounts compared of those of Tunisia. For instance, in

July, the solar radiation evaluated on a tilted PV module in Tunisia, Spain and Jordan are respectively: 9136.7 Wh/m², 9100 Wh/m² and 9121 Wh/m².

Similar calculations were done for sizing the PV/batteries bank for Spain and Jordan using the process mentioned in the proposed sizing algorithms of Section 3. Considering also that the crops water need is the same and using climatic data of these two countries, the final PV modules' surface area and the number of batteries are summarized in Table 9.

Table 9 Sizing of PV/ batteries/ pump system using climatic data of Tunisia, Spain and Jordan

Table 9 shows that there is a very large similarity in the system sizing for all three countries as expected. They have almost similar solar radiation amount and climatic parameters (Mediterranean climate). The total cost of water pumping system in the different countries are evaluated using updated fuel prices summarized in Table 10. It is shown in Table 10 that the fuel price in Spain is the most expensive compared to Tunisia and Jordan. Indeed, it is almost doubled. Hence, the total costs of the three options of implementing water pumping systems (DG/ Pump, PV/ DG/ Pump and PV/ Batteries/ Pump) are evaluated and presented in Table 11.

Table 10 Fuel prices in Tunisia, Spain and Jordan [40]

Table 11 Costs evaluation of the three systems options using data of Tunisia, Spain and Jordan

It is clear that the DG only/Pump system is the most expensive option for water pumping specially in Spain. This justifies the fact that Spanish government strategy is to encourage using renewable energy instead of fossil fuel. The cost analysis results showed that the PV/batteries/ pump system is the cheapest solution for water pumping systems in all three countries with similar climatic conditions.

The results shown in Table 8 also show that the cost of system 3, which is evaluated for 20 years, can be recuperated in about 15.5 years in Spain. Thus, the system will operate free of charge during 4.5 years. However, in Tunisia and Jordan, the number of years to recuperate the PV/batteries/pump cost is higher than the system lifetime. Thus, system 3 is still the optimum solution in Tunisia and Jordan but its price cannot be recuperated fast.

It is known that each liter of diesel has 720 g of CO_2 and requires 1920 g of O_2 to combust. As a result, a 20 kW DG would produce a pollutant of about 65117 Kg of CO_2 during 20 years [41]. Thus, the PV/batteries/Pump option is also preferable for lowing the pollution.

7. Conclusion

An algorithm for sizing the components of a water pumping installation is proposed and validated using measured climatic data of a 10 ha farm in Northern Tunisia. The sizing algorithm ensures the system autonomy, the safe operation of the system components and pumping the water volume needed to irrigate Tomatoes during its vegetative cycle (*March* to *July*). Moreover, a comparison of the components sizes with those obtained using HOMER proves the sizing algorithm reliability in optimizing the components size, while fulfilling the objectives related to saving energy and water.

The components sizing optimization is confirmed with the cost analysis for different water pumping options, including the Diesel Generator/ Pump, PV/ DG/ Pump and the PV/ batteries/Pump systems. The cost sensitivity of these options to climatic, geographic and economic parameters is analyzed for three different countries which are Tunisia, Spain and Jordan. The obtained results shows that the PV/ batteries/ pump system is the cheapest option for the three countries. Moreover, the cost of this system can be recuperated in 15.5 years in Spain due to the expensive fuel prices. Finally, CO_2 emission is eliminated when using PV/ batteries/ pump system, which makes it an environment friendly and cheap solution.

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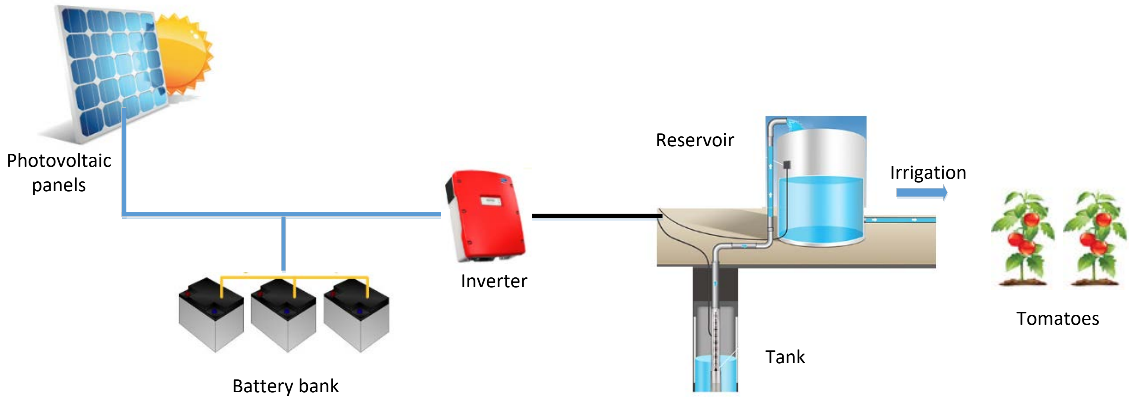

Fig.1. Block diagram of the PV water pumping system used for the crops irrigation

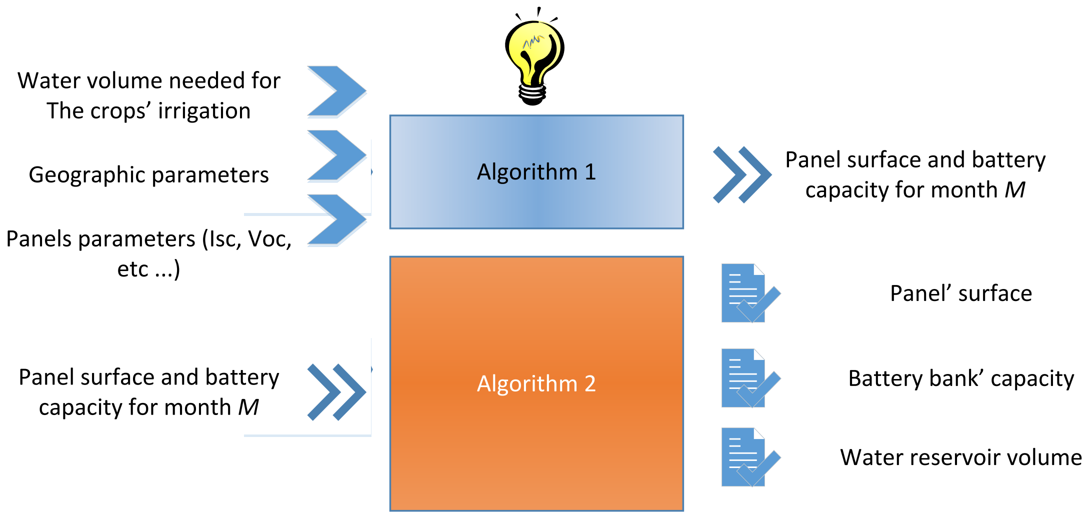

Fig. 2. Principle of the proposed sizing algorithm

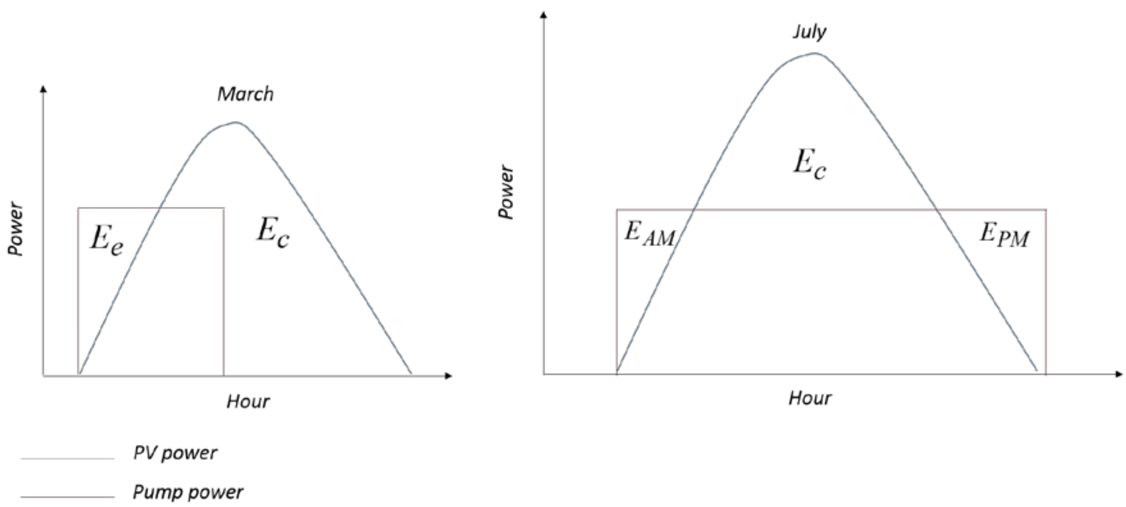

Fig.3. Diagram of the energy balance principle

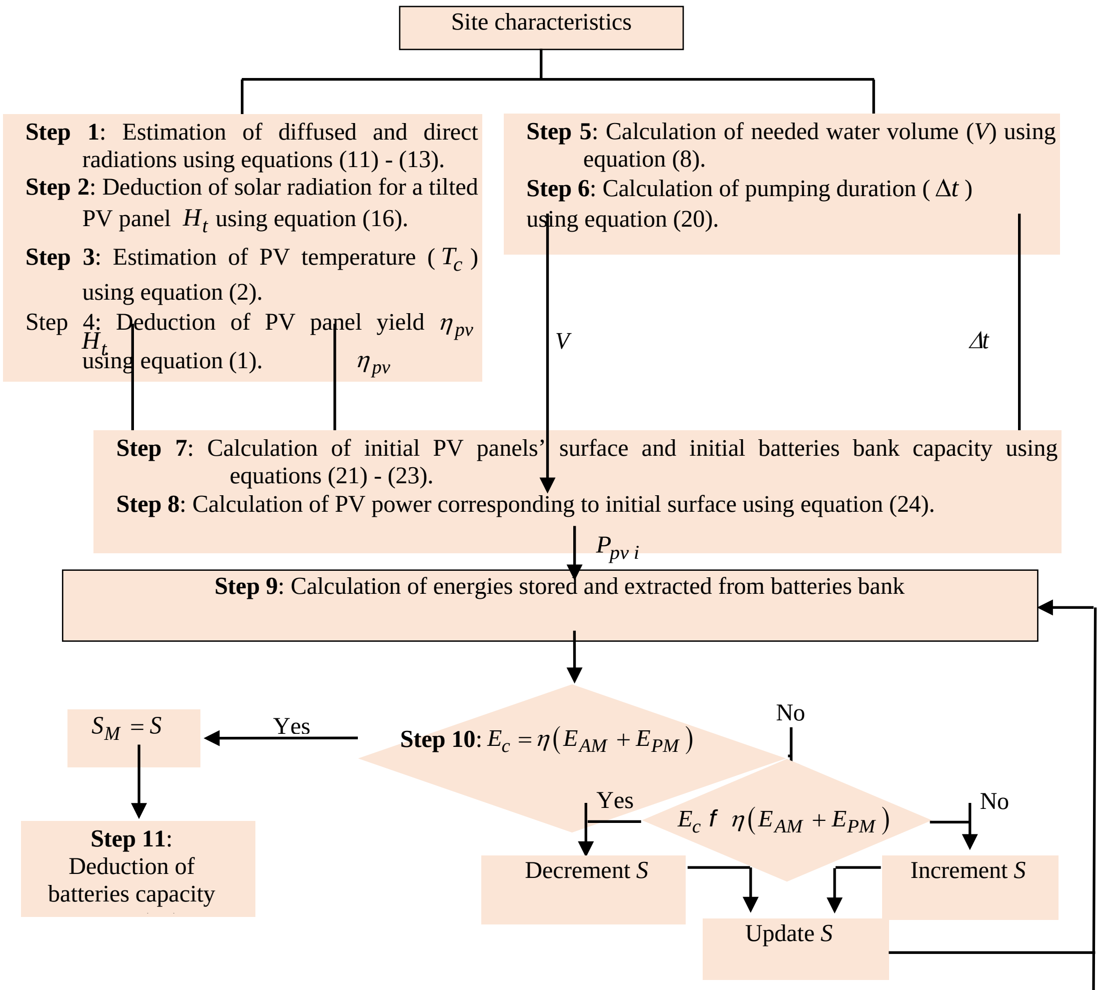

Fig. 4. Principle of the system sizing using Algorithm 1 for each month *M* of Tomatoes vegetative cycle [1]

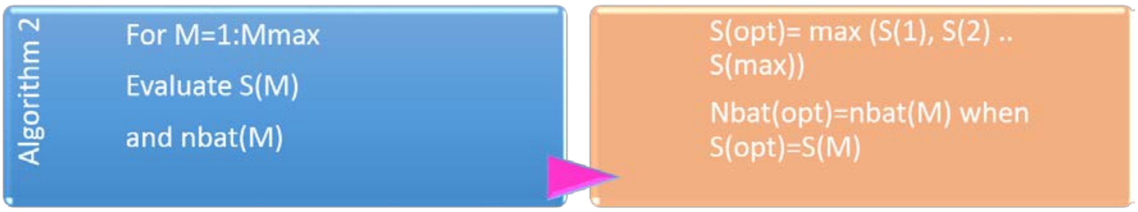

Fig.5. Algorithm 2: deduction of the optimum components sizes of the PV water pumping installation

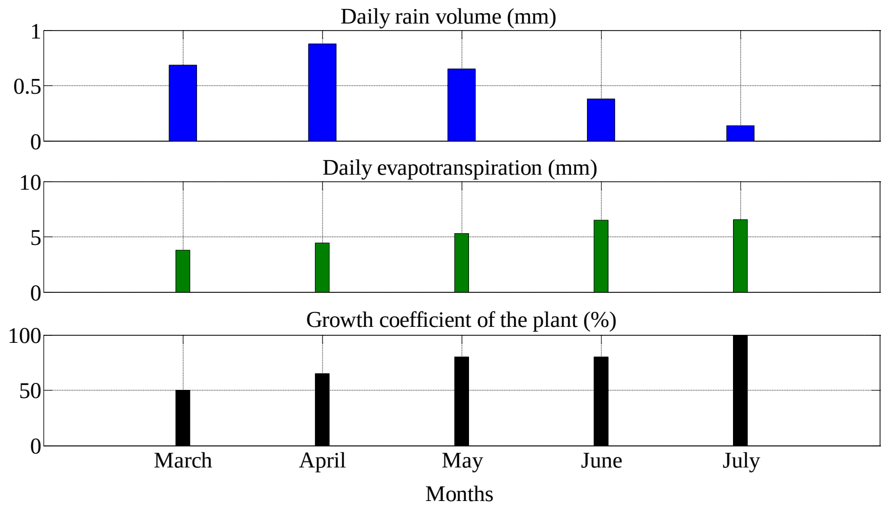

Fig. 6. Crops characteristics for each month *M* of the vegetative cycle

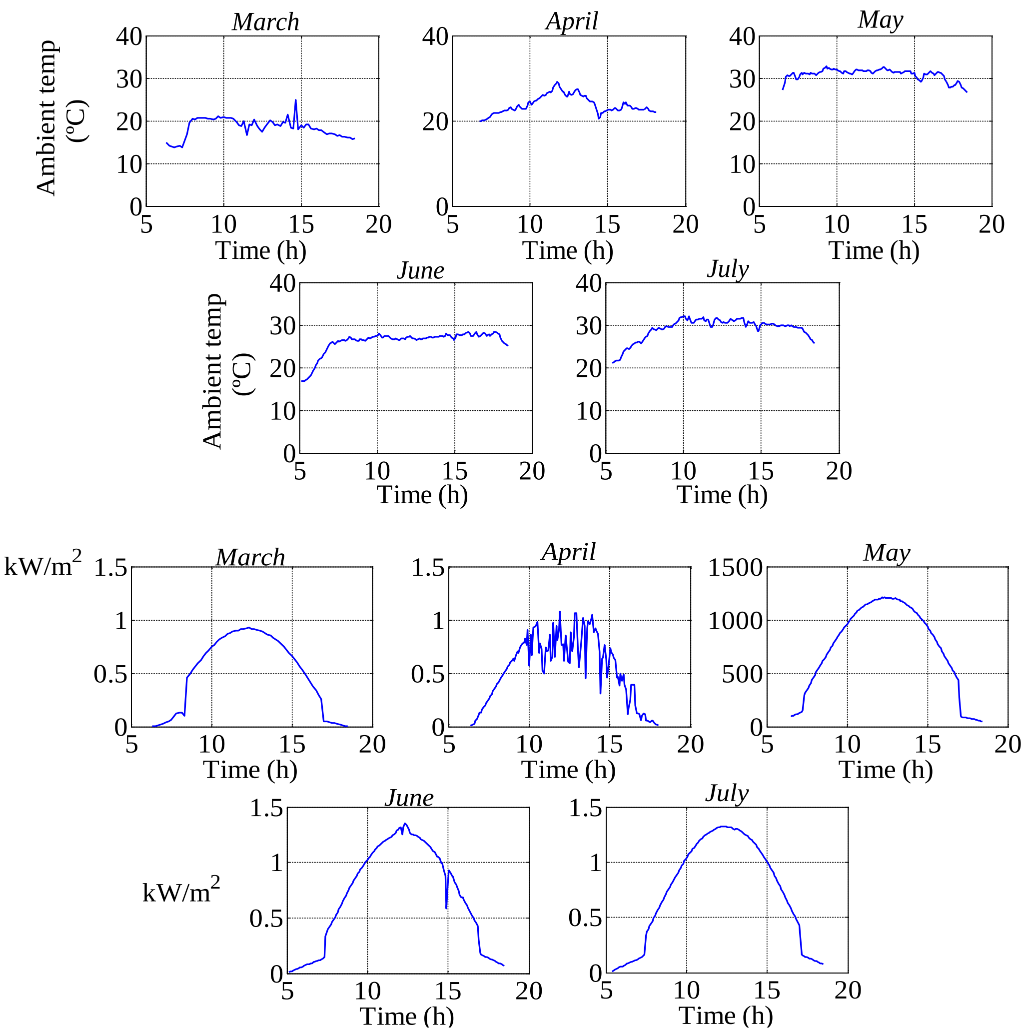

Fig. 7. Measured hourly solar radiation for each month *M* of Tomatoes vegetative cycle in the farm investigated

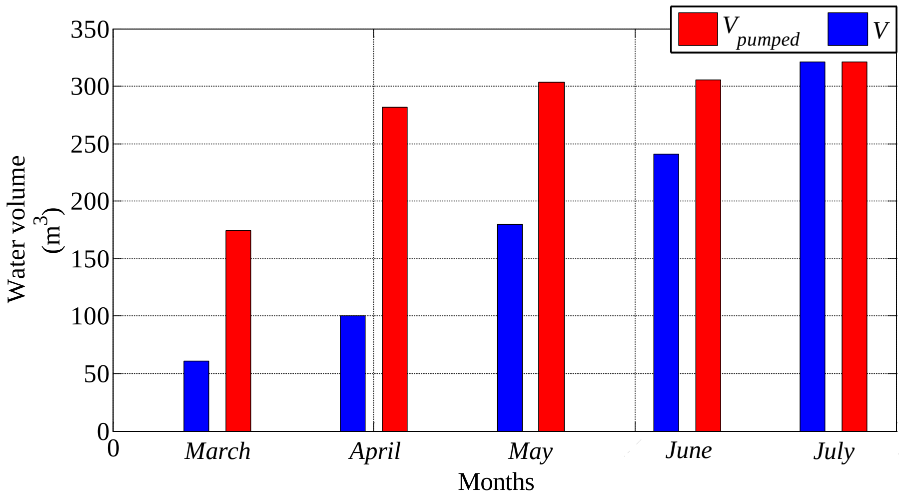

Fig. 8. Daily needed (V) and pumped (V_{pumped}) water volumes during tomatoes vegetative cycle for the case study

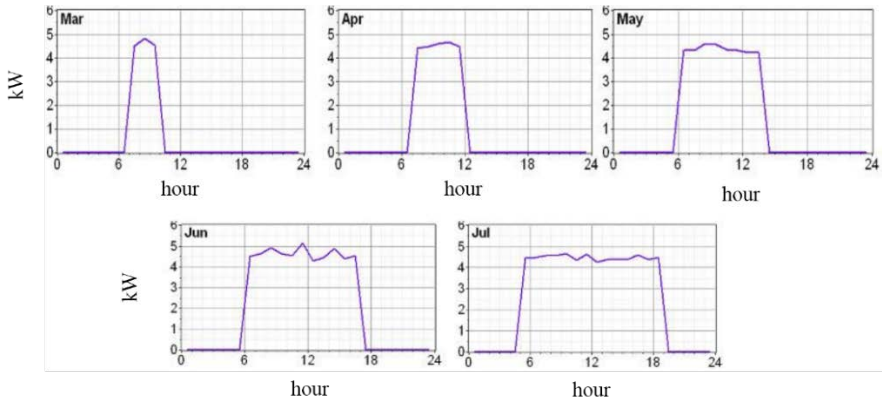

Fig. 9. The hourly inverter output power in kW in each month of vegetative cycle averaged over months' days using HOMER

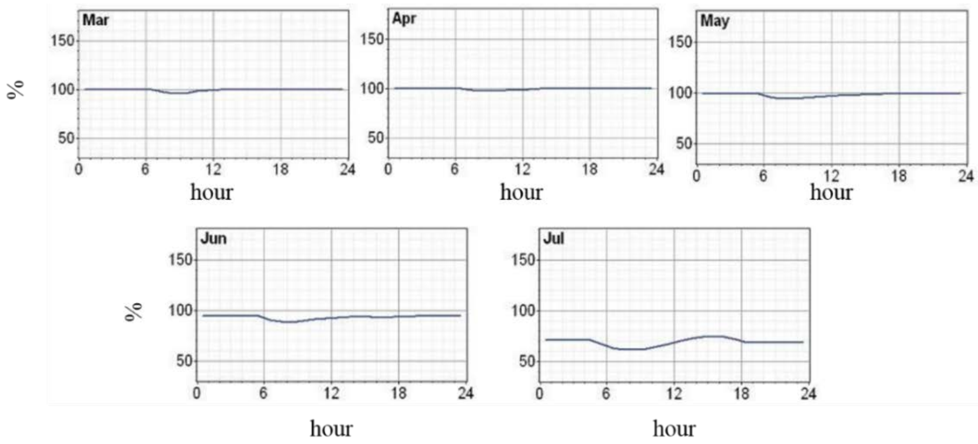

Fig. 10. Batteries bank state of charge for each month of the vegetative cycle at each hour in a day averaged over months' days using HOMER

Nomenclature

A_{c_i}	Amount of clouds per day (%)	n_{diesel}	Number of diesel engines used
ANN	Artificial Neural Network	n_{M_i}	Days number in the month M
C_b	Battery cost (€/ battery for n_y)	n_{oil}	Number of oil changing times by year
C_{bat}	Nominal battery capacity (Ah)	n_{pv}	Number of PV modules
C_{fuel}	Cost of the fuel (€/ l)	n_y	Years number used for the systems costs evaluation
C_{inv}	Cost of inverter (€/ inverter for n_y)	NOCT	Nominal Operating Cell Temperature
C_{opt}	Optimum batteries' capacity (Ah)	PV	Photovoltaic
C_{oil}	Cost of engine oil (€/ l)	P_{pv}	Photovoltaic power (W)
C_p	Peukert capacity (Ah)	r_m	the rainfall (m³)
C_{pv}	PV module cost (€/ module for n_y)	R_s	Series resistance of the PV module (Ω)
C_R	Stored charge in the battery (Wh)	R_p	Parallel resistance of the PV module (Ω)
C_{diesel}	Diesel generator price (€)	R'_b	Ratio of direct radiation on tilted PV module and direct radiation on horizontal PV module
$cost_{s1}$	System 1 cost (€)	P_{pump}	Water pump power (W)
$cost_{s2}$	System 2 cost (€)	$P_{pv\,i}$	PV module power (W) at the minimum module surface S_i
$cost_{s3}$	System 3 cost (€)	S	PV module surface (m²)
d_{aut}	Number of days of autonomy	S_i	Minimum PV modules' surface (m²)
d_{rech}	Number of days needed to recharge the battery	S_M	PV module surface at month M (m²)
dod	Depth of Discharge	S_{opt}	Optimum module surface (m²)
E_c	Energy stored in the batteries (Wh)	T	Mean monthly air temperature
E_d	Daily energy consumption (W.h)	T_a	Ambient temperature at the panel surface (°C)
E_e	Energy extracted energy from the batteries (Wh)	$T_{a\,ref}$	Reference ambient temperature (°C)
E_{pump}	Energy needed by the pump (Wh)	$T_c(t)$	PV cell temperature (ºC)
E_{PM}	Energy extracted from the battery at pm (Wh)	T_{ref}	PV cell reference temperature (°C)
E_{PV}	Energy generated by the PV modules (Wh)	V	Water volume needed to irrigate Tomatoes
EC_e	Crop salt tolerance (dS. m^{-1})	V_{bat}	Battery voltage (V)
EC_w	Electrical conductivity of the irrigation water (dS. m^{-1})	V_{fuel}	Volume of fuel consumption (l/ h)
ET_o	Reference crop evapotranspiration	$V_{leaked\,/\,excess}$	Water volume leaked or in excess (m³)
f_i :	Irrigation frequency	V_{pumped}	Possible pumped water volume (m³)
G	Solar radiation (W/m²)	$V_{reservoir}$	Required volume of the reservoir (m³)
GA	Genetic Algorithm	*w*	Angle of the sun at a specific hour
H	Monthly global solar radiation (W/m²)	W_{pv}	Average daily radiation (Wh/m²/ day)

Table 1 Parameters used for the components sizing of the PV water pumping

Parameters	**Values**
η_{bat}	90 %
η_{inv}	92 %
η_{l}	95 %
$\eta_{matching}$	80 %
η_{opt}	90 %
η_{reg}	90 %
η_{r}	10.58 %
Δdod_{max}	78 %
P_{pump}	4500 W

Table 2 Climatic parameters, panel efficiency and irrigation parameters used in the case study

Months / ***Parameters***	*March*	*April*	*May*	*June*	*July*
T_a (°C)	14	17.25	20	22	30
$\overline{H}$ (Wh)(16)	4023.6	5512.3	5815.2	7392.2	7163.2
k_t (%)	54	51	54	61	64
W_{pv} (Wh) (3)	5908.6	7562.1	8030.9	9479.0	9136.7
η_{pv} (%) (1)	10.16	10.06	9.91	9.75	9.37
Water volume $m^3/10\,ha$ (8)	60.70	100.37	179.82	241.10	321.03
Pumping duration Δt (h) (20)	2.5	4.13	7.41	9.93	13.25

Table 3 Parameters used in executing Algorithm 1 including initial values of PV module surface and batteries number

Months / *Parameters*	*March*			*April*			*May*
	10 days	*10 days*	*11 days*	*10 days*	*10 days*	*10 days*	
W_{pvc_i} (Wh)	5760			7180			8120
Maximum number of cloudy days per month n_{c_i} (27)	9			7			9
Clouds rate per day A_{c_i} (%) (28)	30.15			23.23			28.38
Irrigation frequency f_i [1]	3	3	2	2	2	1	1
d_{aut}	1	1	1	1	1	1	1
d_{rech}	3	3	2	2	2	1	1
Initial panel surface S_i (m²) (21), (22)	61	61	68	89	89	107	203
Initial numbers of batteries n_{bat_i} (23)	4	4	4	5	5	5	10

Months / *Parameters*	*June*	*July*		
		10 days	*10 days*	*11 days*
W_{pvc_i} (Wh)	8500	8340		
Maximum number of cloudy days per month n_{c_i} (27)	3	4		
Clouds rate per day A_{c_i} (%) (28)	13.03	14.11		
Irrigation frequency f_i [1]	1	1	2	2
d_{aut}	1	1	1	1
d_{rech}	1	1	2	2
Initial panel surface S_i (m²) (21), (22)	234.5	337	168.5	168.5
Initial numbers of batteries n_{bat_i} (23)	14	18	18	18

Table 4 Algorithm 1 results summary

Parameters \ Months	*March*	*April*	*May*	*June*	*July*
η_{error}	1.30	1.23	1.28	1.13	1.14
$E_{AM} + E_{PM}$ (Wh/ day)	10991	14481	10239	12511	24046
E_c (Wh/ day)	18725	23035	16807	18033	35314
E_{pump} (Wh/ day)	11258	18615	33350	44716	59541
E_{PV} (Wh)	20371	29296	43378	55035	82802
S_M (m²)	**37.5**	**41.5**	**54.5**	**61.5**	**101.5**
$n_{bat\,M}$ (26)	**4**	**5**	**4**	**5**	**8**
η (25)	***1.66***	***1.57***	***1.64***	***1.44***	***1.46***
$\eta_1 = \dfrac{E_c}{E_{AM} + E_{PM}}$ (25)	***1.7***	***1.59***	***1.64***	***1.44***	***1.47***

Table 5 Frequency of cloudy days and water volume needed for irrigation

Parameters \ Months	*March*	*April*	*May*	*June*	*July*
Water volume $m^3/10\,ha$ (8)	60.70	100.37	179.82	241.10	321.03
Daily pumped water (m³)	274	281.6	291	321	321
Maximum number of cloudy days per month n_{c_i} (27)	9	7	9	3	4
Irrigation frequency f_i [1]	3 3 2	2 2 1	1	1	1 2 2
Leak water (m³) (29)	7 129	119.5 420	**1314.6**	417	**963** 321
Reservoir volume (m³) (30)			1793		1541

Table 6 Parameters used for costs analysis of different water pumping options [39]

Parameters	Name	Value
n_y (years)	the installation life time	20
C_{pv} (€/ module for n_y)	the PV module cost	265.81
M_{pv} (€/ module per year)	the PV module maintenance cost	2.66
C_b (€/ battery for n_y)	the battery cost	264
y_{bat}	the number of times the batteries are replaced during n_y years	4
M_{bat} (€/ battery per year)	the maintenance cost for one battery	2.64
n_{chop}	the number of choppers	1
C_{chop} (€/chopper for n_y)	the chopper cost	200
y_{chop}	the number of times the chopper is replaced during n_y years	0
M_{chop} (€/ chopper per year)	the maintenance cost for one chopper	2
C_{inv} (€/ inverter for n_y)	the cost of the inverter	1942
y_{inv}	the number of the inverter replaced during n_y years	0
M_{inv} (€/ inverter per year)	the maintenance cost for one inverter	19.42
C_{diesel}	the diesel generator cost	4475
M_{diesel} (€/ inverter per year)	the maintenance cost for the diesel	44.75

Table 7 Diesel generator parameters used for the cost analysis

Number of hours the diesel generator operates (h)	13.25 (DG only)	5 (DG/ PV)
Fuel consumption	4.7	l/h
Fuel price	0.48	€
Oil volume	8	l/ 3 months
Oil cost per liter	5.91	€

Table 8 Costs summary for the three water-pumping options for farm in Tunisia

System	System 1: DG/ Pump	System 2: PV/DG/ Pump	System 3: PV/Batteries/ Pump
Costs (€)	67044	69772	51263

Table 9 Sizing of PV/ batteries/ pump system using climatic data of Tunisia, Spain and Jordan

Results / **Country**	PV surface (m²)	Battery bank number
Tunisia	101.5	8
Spain	102.5	8
Jordan	102	8

Table 10 Fuel prices in Tunisia, Spain and Jordan [40]

Country	*Tunisia*	*Spain*	*Jordan*
Costs (€/l)	0.57	1.03	0.53

Table 11 Costs evaluation of the three systems options using data of Tunisia, Spain and Jordan

System / **Country**	*DG/Pump*	*PV/DG/Pump*	*PV/Batteries/Pump*	*Number of years to recuperate system cost*
Tunisia	67044	69772	51263	65
Spain	115330	75605	50306	15.5
Jordan	62845	81879	50147	79