Design and Evaluation of a Renewable Water Pumping System

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Abstract: The design and evaluation of a stand-alone photovoltaic system for well pumping in agricultural application is presented. Given environmental (irradiance and ambient temperature), system (PV and battery technology, array geometry) and load (monthly daily demand) data, the optimal size of main components of PV systems are obtained by a sizing algorithm; specifically the output are: the surface of PV array and the battery pack capacity. The decision is made based on the estimated power generation, the required power for the load, the water needed by the crops and the battery requirements. The proposed design is then evaluated using yearly simulations, on hourly base, performed by a specialized commercial software, named PVSyst, to show that the proposed optimal size ensures also a high reliability evaluated by two indices: number of autonomous days (NAD) and Loss of Load Probability (LOLP).

Keywords: photovoltaic panels; algorithm; sizing; pumping; PVSyst.

INTRODUCTION

The main components of a stand-alone photovoltaic (PV) system, that supplies a given load are: a PV array, a battery pack, an MPPT/ charge regulator. The MPPT/charge regulator must be used to operate correctly with both PV modules and batteries. This appliance performs not only the charge and discharge of the batteries in order to avoid damage or poor energy performance but also the maximum power point tracking (MPPT) in such a way to have an efficient PV conversion.

Sizing the components of these PV installations affect their autonomy and cost [1, 2]. Hence, it is necessary to fix during the design adequate values for the components sizes, such as the photovoltaic panel surface and the battery capacity [3, 4]. In fact, for agricultural applications, during the crops vegetative cycle, the photovoltaic installation size selected must guarantee the water volume needed for the crops irrigation, the system autonomy and the battery bank safe operating [3]. Indeed, knowing the water volume needed for irrigating the crops, the site characteristics, the solar radiation and the photovoltaic panel type, sizing aims to provide the adequate values of the panel surface, battery capacity and (in some instances) the reservoir volume. In this sense, researchers have established various methods to optimize photovoltaic installations components [5]. For instance, some works have focused on developing analytic methods based on a simple calculation of the panels surface and battery bank capacity using the energetic balance [6-8]. Other works have concentrated on the cost versus reliability question [9]. Moreover, some researchers have proposed sizing algorithms based on the minimization of cost functions, using the Loss of Load Probability (LLP) concept [10-14]. This LLP approach has also been combined with artificial neuronal networks and genetic algorithms [9, 10].

However, these methods may result in an oversized system for one location and an undersized one for another location [15]. The oversized case results in high installation costs. Whereas, an undersized case, the installation is unable to supply the load with the energy needed [16, 17]. Moreover, the installation lifetime is shorter, due to the excessive use of the batteries. For these reasons, the sizes must be carefully selected for each specific application and location [15].

In [18], the deterministic method and the probabilistic approach are used to analyze the impact on design the PV system and the battery storage for three geographic sites in Italy, characterized by different values of sun radiation and ambient temperature. To find the best comprise between two conflicting obiecjetives (reliability and costs) a fuzzy logic based multi-objective optimization approach was used in [19].

This paper presents a continuation of previous published works by some the authors [16, 17], where an a sizing algorithm has been presented. Here, the algorithm is detailed and validated by means of hourly probabilistic simulations, that spans one year, using a widely used general software for the study of PV systems (Grid-connected, stand-alone or hybrid), named PVSyst [20] (Figure 1).

I.SIZING ALGORITHM PRINCIPLE

A good sizing must fulfill the electrical demand of the load [15]. Hence, the main objective is to ensure the load supply throughout the day, while charging the battery with the excees of the energy and guaranteeing the water volume needed for the irrigation. The scheme of the proposed approach is presented in Figure 1 [16, 17]. The algorithm depends on:

- the water volume needed,
- the site characteristics,
- the panel characteristics.

The algorithm aims to find the panels surface S_{opt} and the battery capacity $C_{bat_{opt}}$ that guarantee the installation autonomy when supplying the pump. Hence, the idea consists in searching the optimal components sizes that ensure the balance between the charged and the extracted energies E_c and E_e, respectively. In fact, the battery bank supply the load by E_{bat} when the panel does not generate the sufficient energy E_{load}, and is charged with a part of the PV energy produced E_{pv} (Figure 2). The balance between the accumulated and the extracted energies does not guarantee the autonomy, due to the fluctuation in the solar radiation and the energy losses. Thus, to ensure the autonomy and provide the energy demanded by the load, the algorithm is performed by adopting an efficiency coefficient η (slightly greater than 1). Hence, the energy balance can be expressed as follows:

$$E_c \approx \eta \, E_e \tag{1}$$

The sizing algorithm is performed using two sub algorithms during the vegetative cycle: the Algorithm 1 determines the sizes of the panel surface S_M and the battery capacity C_{bat_M} for each month *M*. Then, Algorithm 2 is performed to deduce the final sizes based on the sizes determined for each month and the available components, providing the numbers of panels and batteries needed. Algorithm 1 is detailed now following Figure 4.

a) Algorithm 1: Determination at each month of the minimum panel surface and battery bank capacity

Step 1 Estimation of the diffused and direct radiation.

Step 2 Deduction of the hourly daily solar radiation distribution $H_t(h,d)$ in a tilted panel [17].

Step 3 Estimation of the hourly cell temperature $T_c(h)$ [16].

Step 4 Deduction of the hourly panel efficiency $\eta_{pv}(h)$ [17].

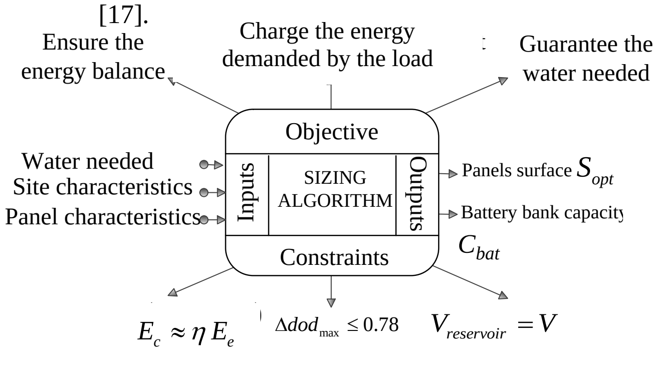

Fig. 1 Planning of the proposed sizing algorithm

Step 5 Calculation of the water needed *V* [16, 17]:

$$V = \left(k_c E_{To} - r_m\right)\left(1 + \frac{1 - f_i\left(1 - L_R\right)}{f_i\left(1 - L_R\right)}\right) \tag{2}$$

where:

k_c : crop growth coefficient for month *M*,

E_{To} : reference evapotranspiration average for month *M*,

r_m : average rain volume for month *M*,

f_i : leaching efficiency,

L_R : leaching fraction given in the soil.

Step 6 Calculation of the pumping duration [17]:

$$\Delta t = \frac{V}{Q} \tag{3}$$

where Q is the water flow (m²/h).

Step 7 Calculation of the minimum panel surface S_i and the initial battery capacity C_{bat_i} using equations (4) and (5) respectively:

$$S_i = \frac{P_{pump} \, \Delta t}{W_{pv} \, \eta_{bat}^{\,2} \, \eta_l \, \eta_{pv} \, \eta_{reg} \, \eta_{inv} \, \eta_{opt\,ther} \, \eta_{matching}} \left(1 + \frac{d_{aut}}{d_{rech}}\right) \tag{4}$$

$$C_{bat_i} = \frac{E_d \, d_{aut}}{V_{bat} \, \Delta dod_{\max}} \tag{5}$$

with:

P_{pump} : pump power (W),

d_{aut} : requested days of autonomy,

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

W_{pv} : average daily radiation (Wh/ m^2 / day),

η_{bat} : electrical efficiency of the battery bank,

η_l : electrical efficiency of the rest of the installation (includes ohmic wiring and mismatching wiring losses),

η_{pv} : efficiency of each photovoltaic panel,

η_{reg} : regulator performance,

η_{inv} : inverter performance,

$\eta_{optther}$: panel performance - optical and thermal effects (%),

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

E_d : daily energy consumption (Wh),

V_{bat} : battery voltage (V),

$\Delta dod_{\max}$: maximum permitted variation of the depth of discharge dod .

Step 8 Calculation of P_{pvi} corresponding to the minimum panel surface S_i, using (6) [17]:

$$P_{pv\,i} = \eta_{pv} \, S_i \, H_t \tag{6}$$

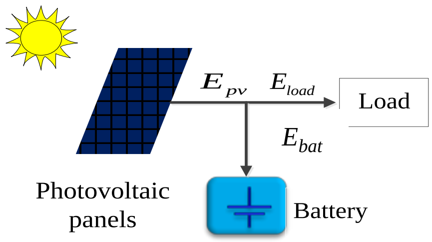

Fig. 2 Energy balance principle

Step 9 Calculation of the energies expected to be daily stored and extracted from the battery E_c and E_e .

Step 10 If the extracted energy is higher than the stored energy, the algorithm increases the panel surface by the minimum increment of the PVP size commercially available: the algorithm looks for the best configuration to guarantee the balance between the demanded and the produced energies, by equalizing the energies stored E_c and extracted energies E_e in the battery bank (1).

Step 11 Battery capacity C_{bat_M} deduction for month *M* [17]:

$$C_{bat_M} = \frac{E_c}{V_{bat}} \quad \textbf{(7)}$$

b) Algorithm 2: Calculation of the minimum panel surface and battery bank capacity for the whole vegetative cycle

Using Algorithm 2 (Figure 3), the final values of the panel surface S_{opt} and the battery bank capacity $C_{bat_{opt}}$, are deduced. S_{opt} corresponds to the maximum value of the panel surface obtained during the months. The final battery capacity is the corresponding value for S_{opt} , since it is the most critical.

II. Application to a Case Study

The proposed algorithm is applied now to evaluate the components sizes of a case study: the proposed algorithm is tested during the months that correspond to the vegetative cycle of tomatoes (*March* to *July*), using data of the target area (Northern of Tunisia: latitude: 36.39°, longitude: 9.6°).

Following Algorithm 2, the Algorithm 1 was first evaluated for all the months in the vegetative cycle: the solar radiation accumulated on a tilted panel is evaluated; then, the panel yield is calculated for each month; in parallel, the water needed *V* is evaluated depending on the vegetative cycle and the site [17]. Then, if the stored energy is higher than the extracted energy, the surface is increased by the minimum surface in the market (in our case, the increment is 0.5 m^2).

Algorithm 1 results are summarized in Table 1, which shows that the proposed strategy always ensures the water needs, respects the limits on the battery-bank' depth of discharge and the energy balance (1). This has been tested during the months of tomatoes vegetative cycle: the efficiency coefficient η is around the fixed values throughout all the considered months. For this value, Δdod_{max} is guaranteed to be equal to 0.78.

For instance, in *July*, the minimum η is 1.46, and the value obtained with Algorithm 1 η_1 is equal to 1.47. On the other hand, in *March*, the generated photovoltaic power during the morning supplies the pump together with the battery bank during the pumping duration. After that, the photovoltaic power generated charges the battery bank. The quotient between the cumulated and extracted energies is 1.66, which is near to target value 1.7. We must point out that for the energy balance, an error coefficient is used to consider the clouds. Hence, in our study, we take into account the possibility of having cloudy days. For example, in *April* the loss of energy each day is 23.23 %. The obtained results (Table 1) prove that the panels surface and battery bank capacity obtained using the proposed Algorithm 1 satisfy the energy balance. This is possible thanks to the calculation of the battery capacity, which is done by considering the same Δdod_{max} value that can be reached. Since July is the most critical month for irrigation, the system components sizing of July is selected. The obtained size allows the load to be supplied during the requested pumping duration Δt , and also provides the energy E_c needed to charge the battery bank.

III. Validation using PVSyst

The installation size has been also tested using PVSyst, since the solar radiation, the ambient temperature and the load requirements of the target cite can be manually choosed. This tool allows determine and validate installations components sizes. In addition, it takes into account varios losses related with components or climatic parameters. Hence, PVSyst evaluate the size efficicency using the solar fraction (SF), which determines whether the panel surface is able to supply the load with the needed energy. Moreover, it performs a more detailed evaluation of the installation size: the system losses (Ls), the unused energy (Lu) and the energy supplied to the user (Yf). The PVSyst simulation shows that the adopted size (*S*= 101.5 m^2 and C_{bat} =1680 A.h) gives good results. In fact, Figures 5 and 6 show that during the crops vegetative cycle, the solar fraction (SF), which determine whether the solar installation provides the load with the sufficient energy, is pratically equal to one, except in *June* and *July*, in which it is equal to 0.962 and 0.934, respectively (Table 2). This leak of energy can be covered by considering an additional water volume in the reservoir.

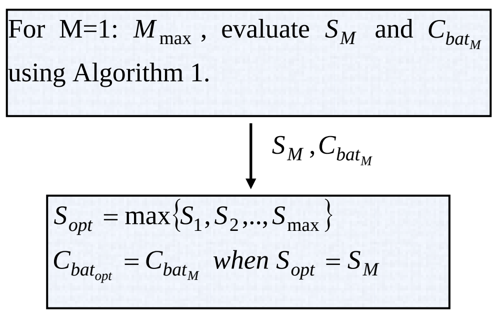

Fig. 3 Sizing Algorithm 2

Moreover, the obtained size is tested during the year (Figure 7), by taking into account all the possible losses related to the components or climatic parameters.

The results show that the choosen size allows supplying the load and having no more than 3.4 % of load losses, which represents a good result.

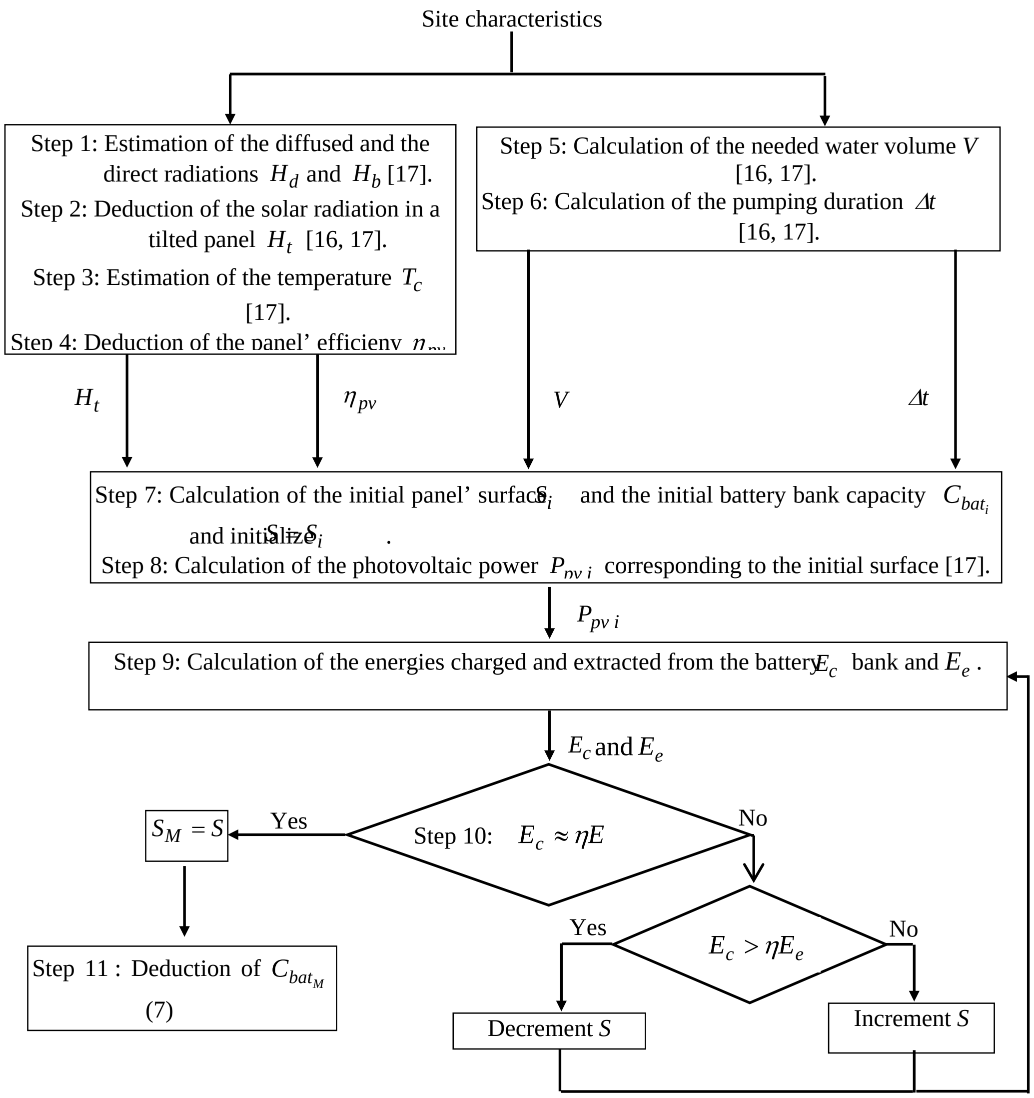

Fig. 4 Sizing Algorithm 1 for each month M

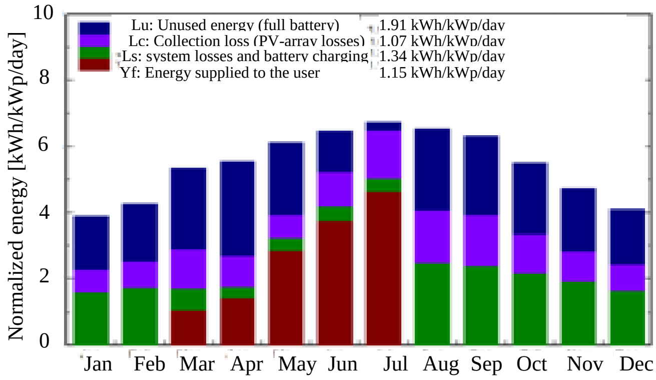

Fig. 5 Normalized production using PVSyst

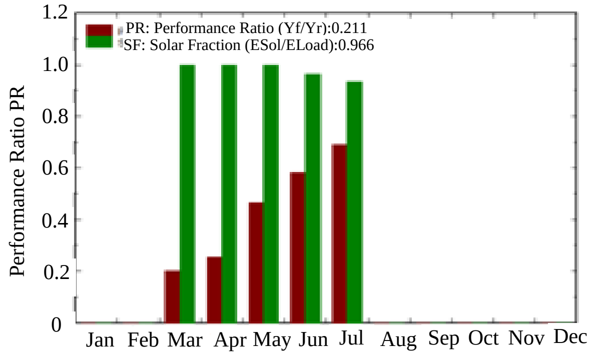

Fig. 6 Performance Ration and solar fraction using PVSyst

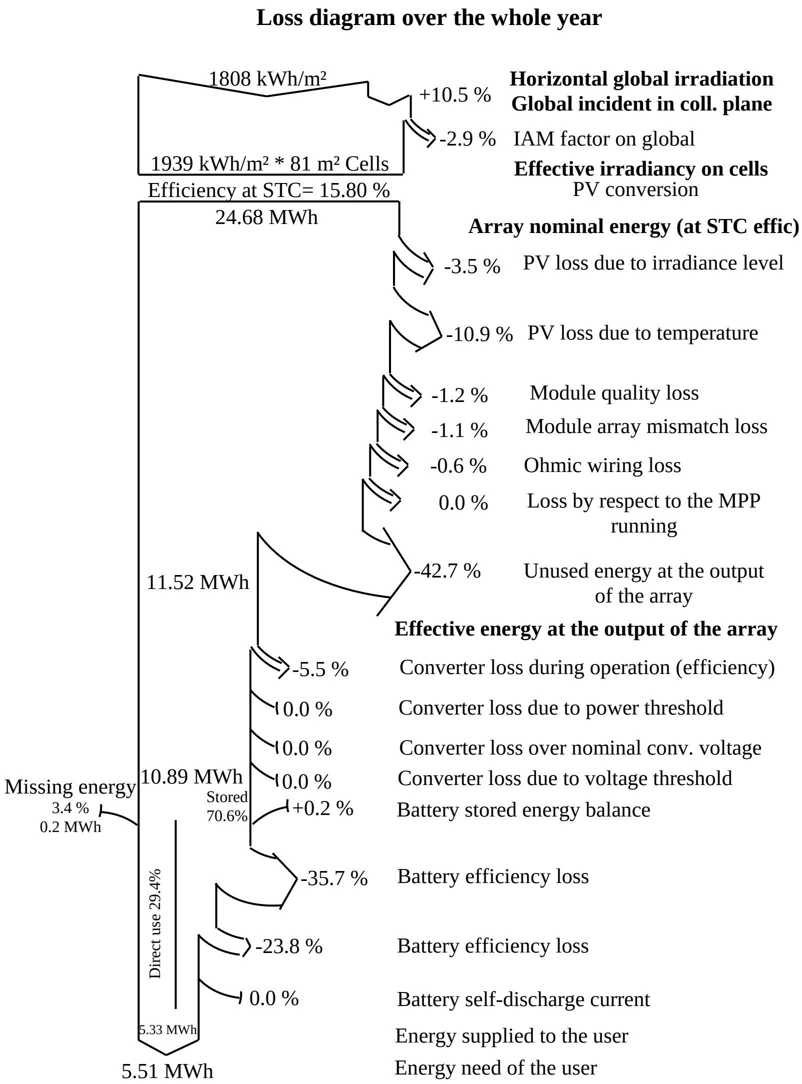

Fig. 7 Loss diagram over the whole year

IV. CONCLUSION

A sizing algorithm to decide on the sizing of the installation elements was presented and validated using PVSyst tool. The algorithm is tested for a 10 ha land surface in the northern of Tunisia. The sizing results ensures supplying the pump during the pumping period, the energy needed by the load and the needed water volume for crops irrigation.

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Table 1 Panel surface and battery capacity for each month *M*

Results \ *Months*	*March*	*April*	*May*	*June*	*July*
Cloud coverage A_c (%)	30.15	23.23	28.38	13.03	14.11
η_{error}	1.30	1.23	1.28	1.13	1.14
$S_M\left(m^2\right)$	**37.5**	**41.5**	**54.5**	**61.5**	**101.5**
C_{bat_M} (Ah)	**840**	**1050**	**840**	**1050**	**1680**
$\eta_1 = \frac{E_c}{E_{e\,AM} + E_{e\,PM}}$	**1.66**	**1.57**	**1.64**	**1.44**	**1.46**

Table 2 Energy balance and main PVSyst results

Results \ Months	GlobHor (kWh/ m^2)	GlobEff (kWh/ m^2)	E Avail (MWh)	E Unused (MWh)	E Miss (MWh)	E User (MWh)	E Load (MWh)	Sol Frac
January	78.0	117.8	1.221	0.630	0.000	0.000	0.000	1.000
February	89.1	116.0	1.185	0.608	0.000	0.000	0.000	1.000
March	140.0	161.3	1.587	0.959	0.000	0.419	0.419	1.000
April	164.1	161.8	1.708	1.089	0.000	0.540	0.540	1.000
May	208.1	183.6	2.055	0.855	0.000	1.116	1.116	1.000
June	225.0	187.0	1.966	0.466	0.056	1.429	1.485	0.962
July	237.0	201.8	1.973	0.099	0.129	1.824	1.953	0.934
August	208.0	196.7	1.891	0.968	0.000	0.000	0.000	1.000
September	166.0	184.2	1.767	0.905	0.000	0.000	0.000	1.000
October	128.0	166.7	1.661	0.851	0.000	0.000	0.000	1.000
November	89.9	138.6	1.412	0.724	0.000	0.000	0.000	1.000
December	75.1	123.8	1.266	0.649	0.000	0.000	0.000	1.000
Year	**1808.3**	**1939.5**	**19.692**	**8.801**	**0.185**	**5.328**	**5.513**	**0.966**