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A novel algorithm for optimal sizing of stand-alone photovoltaic pumping systems

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ABSTRACT

Pumping water is one of the most popular technologies of solar energy for irrigation or drinking water supply. Its performance depends on the characteristics of the site (sunlight, ambient temperature, geographical obstacles), on the performance of the modules, as well as, on the characteristics of other equipment (converter and pump). The optimal sizing of a photovoltaic water pumping system makes it possible to guarantee the satisfaction of the water demand throughout the irrigation period and to model the electrical energy needs to supply the pump to irrigate the crops and water livestock. This paper proposed a novel algorithm for dimensioning the elements of an autonomous photovoltaic system equipped with irrigation water storage. The proposed algorithm determines the optimal surface area of the photovoltaic modules and the electrical power necessary to satisfy the water requirement for irrigation in the observed time. The results obtained from the proposed algorithm for optimal sizing are compared to calculation scenarios to show better results. A case study from the Fez-Meknes region in Morocco has been selected for applying the optimal sizing algorithm.

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1. INTRODUCTION

Photovoltaic solar pumping over the sun is an efficient solution, in terms of energy, for the supply of water in the absence of the electricity grid. This type of system is well suited to applications where a constant volume of water must be pumped daily from a water source to the application or storage of water, as it's well simply because it consists of a direct coupling between the photovoltaic generator and the pump, and it is intended for pumping time throughout the day. In this case, the system can store energy or water to store the excess energy generated on days when solar energy is above average, either by storing extra electricity generated in batteries [1], or by pumping extra water and storing it.

One of the major issues facing solar irrigation systems is the seasonal demand pattern for crops and the diversity of solar power generation. To cope with this problem, several photovoltaic systems use batteries to accumulate the electrical energy produced by the photovoltaic system to match energy production and demand [1]. However, the batteries have several disadvantages because they are heavy, expensive, fragile, and require maintenance of the battery. Therefore, batteries are also introducing some degree of efficiency loss from about 20% to 30% of energy production [2], it causes increased system investment costs, space to store batteries, and environmental concerns related to battery disposals [3].

Several approaches have been proposed for a self-contained, direct-pumped photovoltaic irrigation system that pumps water directly to the irrigation distribution network instead of storing it in a reservoir. Moreover, to match energy production with irrigation demand [3], [4]. Adapting the production of photovoltaic energy to the demand for crop irrigation and also the livestock's demand for storing pumped water in reservoir storage remains the most relevant solution in terms of the availability of water in the worst monthly average of solar radiation.

The simplicity of the solar photovoltaic pumping system faces the problem of load adaptation since the direct coupling doesn't allow the generator to deliver its maximum power for a full day. It is, therefore, necessary to operate these generators at their optimum power. The approach to the problem is to insert between the generator and the receiver a static converter (chopper or inverter) to perform the optimal transfer of power. Furthermore, direct-pumping stand-alone photovoltaic irrigation systems that pump water directly to the asking location can cause problems where the water demand will not be sufficient in the critical time. This is why we have proposed a system to combine direct irrigation and irrigation through the storage tank. This solution meets the need at any given moment.

The main objective of this work is to develop a novel algorithm to provide optimal dimensions for the components of photovoltaic (PV) pumping systems to ensure that the water demand is met throughout the irrigation duration. This algorithm was applied to stand-alone PV pumping systems to irrigate tomato farmland located in the Fez-Meknes region of Morocco during the most critical month of the culture cycle vegetative, which runs from April to August. The system consists of PV modules, a DC/DC converter, livestock watering, and a water tank. Figure 1 shows the principal components of the standalone photovoltaic system used to pump water in this application.

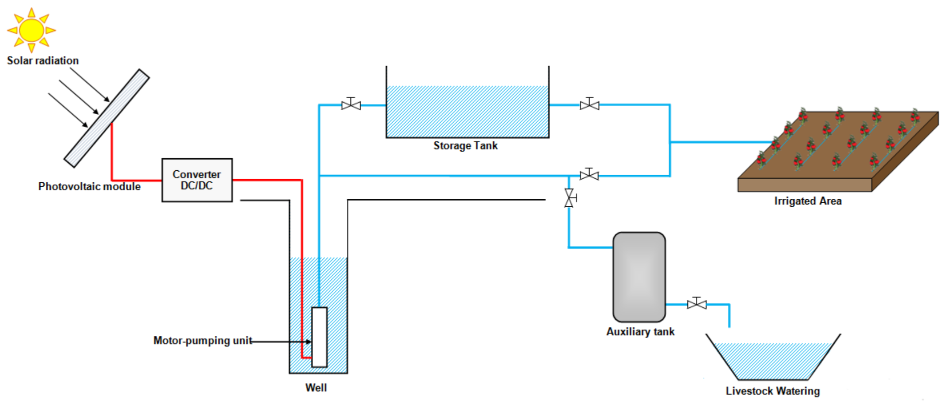

Figure 1. Synoptic scheme of stand-alone PV pumping system

This paper presents three sections. The first section (section 2) is the modeling of the parts of electrical and hydraulic energies: solar radiation and global irradiation calculation model, optimal position of the panel, photovoltaic array model, and motor-pump unit model. The second (section 3) is about the water requirement for irrigation, livestock, and irrigation water storage sizing. The third section (section 4) presents the methodology of the proposed algorithm. Then, a case study to test the performance of the sizing algorithm and compared results which are described and explained in section 5. The conclusion is given in section 6.

2. SYSTEM MODELLING

To dimension the elements of the system, it is necessary to model the components of the installation. This modelling includes both electric and hydraulic parts which are presented in this section.

2.1. Photovoltaic modules

Global solar radiation is a function of the composition and thickness of the atmosphere traversed by the light rays during the day. The total daily solar radiation $G_s(\alpha, \beta)$ in a tilted panel is evaluated by changing the hour angle corresponding to the length of the day. It is expressed by (1) [5].

$$G_s(\alpha,\beta) = R_d I_h + D_h \frac{(1+cos\beta)}{2} + Alb\frac{(1-cos\beta)}{2} G_h \quad (1)$$

Where I_h is the direct normal irradiance, D_h is the diffuse horizontal irradiance, $G_h$is the global horizontal irradiance, Alb is the albedo of the soil, β is the module tilt angle and R_d is the ratio of direct radiation on the inclined panel and direct radiation on the horizontal panel.

To model a photovoltaic pumping system, it's first necessary to model the photovoltaic cells. There are several mathematical models [5], [6] like one-diode and two-diode models, which describe the photovoltaic current as a function of the photovoltaic voltage, the multi-parameter I-V which is a non-linear equation. These photovoltaic models cell take into account the influence of the daily variation of global radiation and the junction temperature. The difference between these models is the calculation method, the number of intermediate parameters to calculate the I-V characteristic, and the accuracy of the results.

The model used in this paper is a single model (Figure 2), which is an analytical model that has given a great accuracy and can be suitably used for power system planning purposes [7], [8]. The I-V characteristic of the PV module is given by [5]–[9].

$$I_c = I_{ph} - I_s\left(exp(\frac{V_c + I_c R_s}{V_t}) - 1\right) - \left(\frac{V_c + R_s I_c}{R_p}\right) \quad (2)$$

Where R_p is the parallel resistance of the PV module and R_s is the serial resistance of the PV module. The panel yield model is expressed by [5]–[10].

$$\eta_{pv} = \eta_r\left[1 - \beta_{pv}(T_c - T_{ref})\right] \quad (3)$$

Where η_r is the panel yield at the reference temperature, β_{pv} is the temperature coefficient for the panel yield, T_c is the cell temperature, and T_{ref} is the reference temperature. The cell temperature is varying in the function of solar radiation and the ambient temperature. It can be calculated as [11].

$$T_c = T_a + (\frac{NOCT - 20}{800}) \cdot G_s(\alpha,\beta) \quad (4)$$

Where T_a is an ambient temperature, $NOCT$ is the Nominal Operating Cell Temperature and $G_s(\alpha,\beta)$ is the solar radiation on the tilted panel. η_r, β_{pv} et $NOCT$ depend of the type of photovoltaic array considered. Eventually, the PV power can be assessed by [12].

$$P_{pv} = S \cdot G_s(\alpha,\beta) \cdot \eta_{pv} \quad (5)$$

Where S is the panel surface.

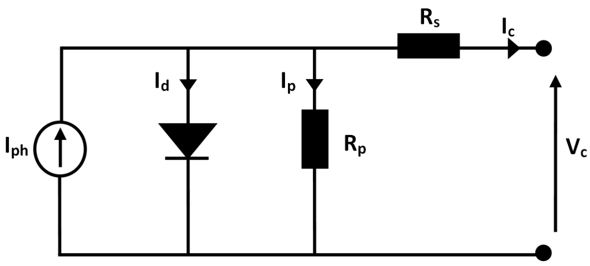

Figure 2. Photovoltaic cell model

The sun turns from the east, where it rises, to the west, where it sets every day. This varies during the seasons. It varies all the more as the latitude of the place of observation is high. During the summer season, the sun rises to the south-east of the sky and lies to the south-west. On the other hand, during the winter season, the sun rises approximately northeast of the sky and sets to the north-west. So, in order to maximize the power output of a photovoltaic system, it is necessary to orient the modules optimally in order to capture a maximum of solar radiation. Indeed, the direction of the sun is important.

There are many methods of sun-tracking that have been proposed to facilitate the tracking of the sun's position with a high degree of accuracy [13]–[16]. The panels can absorb the maximum energy in the noontime, where the rise of the sun is at zenith and the values of the solar radiation are maximum. Furthermore, for the trackers and in order to meet the energy needs and optimize the overall efficiency of the system, the sensor field must keel its surface perpendicular to the rays emitted by the sun.

To calculate the optimal position of the panel described by the two angles (inclination β and orientation α), we must look for these two angles from the radiation incidence angle (6), for which the angle of incidence γ will be zero ($\beta = 90 \ \ - \alpha$) and the module azimuth angle equal to the sun's azimuth angle ($\alpha = a$).

$$cos(\gamma) = cos(\beta)sin(h) + sin(\beta)cos(h)cos(\alpha - a) \tag{6}$$

Where h is the sun elevation angle, α is the surface azimuth angle and a is the solar azimuth angle.

$$\begin{cases} \gamma = 0 \ \ \rightarrow cos(\gamma) = 1 \\ \beta = 90 \ \ - \alpha \\ \alpha = a \end{cases} \tag{7}$$

In the practical case, it's very difficult to implement these methods because of the number of panels and the exorbitant cost generated depending on the mobile support. In addition, they will have to be maintained regularly and may be more likely to be damaged by high winds; so fixed systems are generally cheap and require the least maintenance. In these methods, the solar panels are installed at an inclination β and a fixed orientation α. The latter is chosen towards the south or the north, according to the geographical situation of the considered site compared to the equator. For the case of Morocco, it is located in the northern hemisphere, so the orientation of the panels is towards the south. For inclination, the modules must be tilted at the latitude ± 15 (+ for the summer, - for the winter) [17] of the site to produce the largest annual solar radiation and hence the highest annual output power at that location.

Photovoltaic modules could be oriented to the east or west to maximize energy production in the morning or afternoon as needed. It is also possible to tilt the photovoltaic modules at an angle greater than the latitude angle if the need for water pumping is higher in winter or throughout the year. On the other hand, they could be inclined at an angle less than the latitude angle if the pumping requirements are higher in summer.

2.2. Pump modelling

Each pump features a flow rate and total head. The typical head consists of a static component and a dynamic component [18]. The static head is the vertical distance from which the water must be pumped. It is the height difference in feet between the pumping level in the well and the pressure tank (static head = H_c + H_u). The total dynamic head (TDH) is the sum of the static head, the draw-down distance (the water level drops), and the distance equivalent to the friction losses in the pipe; it can be expressed by [19].

$$TDH = H_c + H_u + H_r + F_l \tag{8}$$

Where H_c is the vertical rise, (H_u + H_r) is the pumping level and F_l is the friction loss.

A larger pipe size must be uses in photovoltaic pumping systems than would be used with conventional water systems to maintain friction losses as low as possible [20]. It is important to match the discharge capacity of the well and the pumped water, i.e. the power of the PV pumping system must be synchronized in this sense. As a result, it is necessary to introduce a limitation on the daily pumping of water from the well in the period i, with the following equation [4]–[12].

$$Q(i) \leq Q_{max} t_i \tag{9}$$

Where i assumes the values 1 to N_T (N_T is the total number of time stages, decades), $Q(i)$ is the mean daily pumped water (m^3/day), Q_{max} is the maximum discharge capacity of borehole (m^3/h), t_i is the mean daily insolation (h).

3. WATER REQUIREMENT

Determining the total amount of water needed per day should be the first step in sizing the system. In our case, we have two parts to determine its need for water: irrigation and livestock watering.

3.1. Crop water requirement

The crop water requirements correspond to how much water to bring to the plant. Water requirements vary mainly depending on the type of plant, soil, climate, and weather conditions. The balance between the inputs (rain, watering, groundwater, and the residual moisture of the soil) and the losses which are modelled in the form of evapotranspiration is made to know the quantity of water to be brought. It can be represented by [21].

$$V_n = ET_c - P_e - \Delta SF - \Delta W \quad (10)$$

Where V_n is the net water requirements, ET_c is the culture evapotranspiration, P_e is the effective precipitation, ΔSF is the water which arrives at the root zone by capillary ascent from the phreatic level, and ΔW is the variation of residual soil moisture.

According to [22], evapotranspiration is a parameter that depends on the climate, the type of plant, and its state of development. It can be expressed as (11).

$$ET_c = K_c ET_0 \quad (11)$$

Where K_c is the crop coefficient, which depends on the characteristics of the crop itself (growth period, degree of water supply of crops during the vegetation period, and climate conditions of the area), and ET_0 is the amount of water that plants may use from the soil and the surface of plant organs under optimum cultivation conditions [21]. It is essential to estimate the irrigation losses to obtain the total water requirement, which represents: i) evaporation losses at ground level; ii) losses by runoff or deep percolation; iii) soil washing, when more water is needed to keep the salts in the soil away from the roots; and iv) inhomogeneous water distribution, which means bringing more water to the most favorable areas to ensure that the most unfavorable areas receive a sufficient amount. For this, total water requirements during the time stage evaluated by [21].

$$V_{ri} = \frac{ET_c - P_e}{W_e} \quad (12)$$

Where W_e is the watering efficiency.

3.2. Livestock requirement

The water requirements for livestock depend on the type and quantity of animals. These needs vary with air temperature, age, herd size, gestation, breastfeeding, animal weight, type of diet, and size of livestock. It should be taken all of these variants into account when determining the minimum volume of water that the solar pumping system must provide each day. Water requirements correspond closely to the amount of food or feed ingested; as intake increases, the level of water requirements increases [18]. Hence, the daily water requirement per day (G_w) can be calculated as [23]–[25].

$$G_w/Item = Q_L * R_g/Item \quad (13)$$

Where Q_L is the quantity and R_g is the required gallons of water per day which is 3.78541 liter of water per day.

3.3. Irrigation water storage

Pumping over the sun makes it possible to have a photovoltaic system that is simpler, more reliable, and less expensive than a system with a battery. A water storage tank is an essential component of a solar-powered water pumping system and is economical. The storage is done hydraulically, the water being pumped, when there is enough sunlight, and the temperature of the solar cells, in a tank above the ground. It is then distributed by gravity as needed (livestock and irrigation). The reservoir can often be built locally, and the storage capacity can vary from one to several days. This tank doesn't require complex maintenance and is easy to repair locally. For stand-alone systems, the storage tank must have sufficient volume to accommodate peak demands, to compensate for cloudy days and nights. For this reason, the required volume of the storage tank is determined by (14) [5].

$$V_{storage} = \eta_{storage}(V_l + V_{ri}) \quad (14)$$

Where $\eta_{storage}$ is the water losses in the storage tank, V_l is the water volume leaked or in excess, and V_{ri} is the total water requirements for irrigation.

4. PROPOSED ALGORITHM

The objective is to provide optimum component dimensions that can provide autonomy for the pump installation and pump a volume of water needed to irrigate crops and livestock. This algorithm depends on panel and site characteristics, including solar radiation, ambient temperature, and crop characteristics. The algorithm flowchart is presented in Figure 3. The algorithm is performed by Algorithm 1.

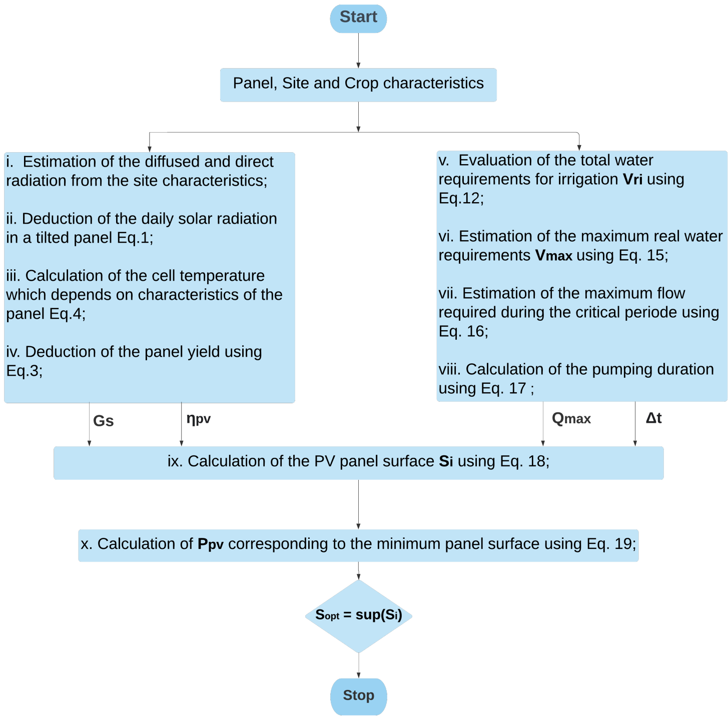

Figure 3. Main flowchart of optimal sizing of the photovoltaic pumping system for irrigation

Data: α, β, ET_o and P_e for the chosen site; η_r,β_{pv}, and $NOCT$ for the chosen panel; K_c for the chosen crop;
Result: Optimal PV panel surface S_{opt};
for i = *1* : N_T **do**
  Estimation of $G_s(\alpha,\beta)(i)$, $T_c(i)$ and $ET_c(i)$;
  Deduction of $\eta_{pv}(i)$;
  if $P_e(i) - ET_c(i) \leq 0$ **then**
    calculation of the total water requirements $V_{ri}(i)$: $V_{ri}(i) \leftarrow \dfrac{ET_c - P_e}{W_e}$;
    estimation of the maximum real water requirements volume:
    $V_{max}(i) \leftarrow sum(V_{ri}(i)) - V_{storage}$ (15)
    estimation of Q_{max}, the maximum flow required: $Q_{max} \leftarrow \dfrac{V_{max}(i)}{min(t_i)}$ (16)
    calculation of Δt, the pumping duration [1] :$\Delta t \leftarrow \dfrac{P_{pump}}{Q}$ (17)
  else
    pump water to storage tank: $V_{storage} \leftarrow \eta_{storage}(V_l + V_{ri})$;
  end
  calculation of the panel surface :$S(i) \leftarrow \dfrac{\Delta t.Q_{max}}{G_T.\eta_{mp}.\eta_c.\eta_{pv}}$ (18)
end
calculation of the photovoltaic power : $P_{pv} \leftarrow S_i G_s(\alpha,\beta)\eta_{pv}$ (19)
deduction of S_{opt}, the optimal panel surface : $S_{opt} \leftarrow sup(S_i)$;

Algorithm 1. Optimal sizing algorithm of the photovoltaic pumping system

5. STUDY CASE

For a case study of the proposed algorithm, a specific simulation of an area of 0.5 hectares in the Fez-Meknes region, Morocco (latitude: 33 53'36 "North, longitude: 5 32'50 "West) cultivated tomatoes focus on Figure 1. For this reason, the tilt angle must be fixed at 33 and facing to the south. To use a PV pumping system to irrigate the crops and water livestock, given the significant solar radiation during the growing season in the site, unlike a complicated diesel engine. In the Fez-Meknes region, in general, farmers use furrow or drip irrigation, which is a principal method for irrigating tomatoes, thanks to its economic advantages in terms of saving water and increasing production.

We have chosen the RECOM RCM-345-6MA mono-crystalline photovoltaic module for the characteristics of the panel, which are presented in Table 1. For the data input Table 2 contains climate data, photovoltaic pumping system, well, and crops data. The decade average daily values of solar radiation G_T, insolation t_i, air temperature T_a, evapotranspiraton ET_o, and total effective precipitation P_e were obtained from CROPWAT program. T_c cell temperatures were recalculated according to (4). The sizing algorithm was implemented during the growing season from the first decade of April to the last decade of August. Table 3 shows the water requirements for livestock watering. The water requirements of these animals vary little from one season to another, increasing slightly in summer and decreasing slightly in winter. We can assume that the daily water needs will be the same.

Table 4 represents the real evapotranspiration $ET_c(i)$, the total required water quantities for irrigation (V_{ri}), the panel yield η_{pv}, and the pumping duration Δt. Table 5 describes the results of the proposed algorithm, the value of the surface of the panel S_i as well as the photovoltaic energy P_{pv}, which are calculated for the three scenarios:

- Scenario 1: optimal sizing using the proposed algorithm.
- Scenario 2: optimal sizing using the proposed algorithm without storage tank, which means direct irrigation from the pump.
- Scenario 3: sizing without optimisation.

Table 1. Characteristics of the panel

PV module	RCM-345-6MA	PV module type	Mono-crystalline
Peak power(P_{max})	345 Wp	Efficiency	17:78 %
V_{oc}	46:6 V	V_{mpp}	38:1 V
I_{sc}	9:48 A	I_{mpp}	9:06 A
Operating temperature	−40 + 85 C	Coeff./P_{mpp}	−0:40 C
Coeff./V_{oc}	−0:32 C	Coeff./I_{sc}	0:048 % C
NOCT	45 C	Dimensions	1956*992*40 mm

* Electrical data of PV module measured at STC (G_s = 1000W=m^2, T_c = 25 C, Air mass (AM) = 1:5)

According to Table 2, the most critical month is $July$, with precipitation of 2 mm and evapotranspiration of 5.84 mm/day or 175.2 $mm/month$. This month requires more water for irrigation, about 204.7 mm/m. Hence, the dimensioning of the $July$ system components is selected as the system dimensioning. The total water requirement is illustrated in Figure 4 and also the culture evapotranspiration and the effective precipitation for the growing cycle of the crop. The first scenario presents the results of our proposed algorithm. We obtained the surface of the panel S_i as well as the photovoltaic power P_{pv} using (18) and (19). Hence, we can deduce that the optimum surface of the PV panel that satisfies the requirements of consumers during the observed period is $S_{opt} = sup(S_i) = 33.1\ m^2$.

The results obtained are compared to the two scenarios (using the proposed algorithm without having the tank and the other dimensioning without optimization) to verify the accuracy of the proposed dimensioning algorithm. As we see, in the same critical month of July, the necessary surface of the modules obtained for the second scenario is 38 m^2, and for the third scenario is 93 m^2. By comparing these results with the ones obtained using the proposed algorithm, it can be seen that the optimal values of the surface panel, obtained by the novel proposed of optimization algorithm are lower than those obtained by the compared scenarios. The precision of the obtained results depends mainly on all relevant elements, from the photovoltaic pumping system, the well, the microclimate, the soil, the crops, the storage tank, to the irrigation system. To obtain the optimum sizing of the irrigation PV pumping system, the proposed algorithm performs well under the conditions of the subject and satisfies the need in the observed period.

Table 2. Data input for the Fez-Meknes region

Time stage i (Months)	Parameters				
	$G_T(Kwh{=}m^2{=}day)$	$t_i(hour)$	$T_a(\ C)$	$ET_o(mm{=}m)$	$P_e(mm)$
January	8.9	4.3	9.65	37.8	66.8
February	12	5.5	10.7	51.6	70.5
March	15.2	6.0	12.9	74.1	62.9
April	18.9	7.0	15	96.3	64.5
May	22.7	8.7	17.7	126.3	40
June	24.2	9.5	21.65	150	11.8
July	25.5	10.6	25.15	175.2	2
August	23.6	10.1	25.55	169.2	2
September	19.1	8.5	22.55	129.6	11.8
October	14	6.7	18.8	87.3	44.3
November	9.9	5.0	13.9	52.5	67.5
December	8	4.0	10.5	38.7	70.5

Table 3. Water requirements of cattle herd

Animal type	No. of animals	Daily requirement (gallon/day)
Horses	2	2*15=30
Sheep	20	20*2=40
Milk producing cows	5	5*15=75
calves	3	3*5=15
	Total	160 = 0.60 ($m^3{=}day$)

Table 4. Climatic and irrigation parameters and panel efficiency

Time stage i (months)	Parameters			
	$ET_c(mm{=}m)$	$V_{ri}(mm{=}m)$	$_{pv}(\%)$	$t(h)$
April	58.3	1.7	13.48	5.23
May	108	68.1	13.34	11.37
June	171.6	159.8	13.34	12.42
July	206.8	204.7	12.95	13.86
August	123	121.8	12.93	13.21

Table 5. Algorithm results for different scenarios

	Scenario 1		Scenario 2		Scenario 3	
Months	$S_i\ (m^2)$	$P_{pv}\ (Kwh)$	$S_{i2}\ (m^2)$	$P_{pv2}\ (Kwh)$	$S_{i3}\ (m^2)$	$P_{pv3}\ (Kwh)$
April	8.52	4.87	19.1	10.91	30.6	17.90
May	16.95	7.796	25.7	14.96	51.0	30.18
June	24.74	10.42	32.7	18.69	70.0	40.01
July	33.10	12.49	37.8	20.42	92.80	53.04
August	30.5	12.08	36.5	20.01	90	51.44

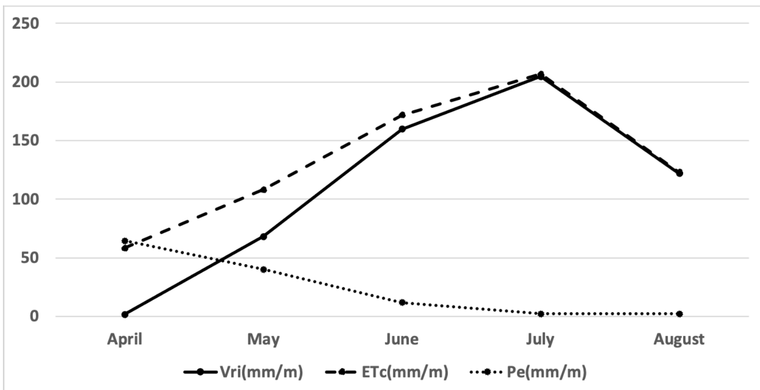

Figure 4. Total water requirements (V_{ri}), culture evapotranspiration ET_c and effective precipitation P_e chart

6. CONCLUSION

Solar energy is one of the highest solar insolation rates. In this sense, the use of photovoltaic water pumping for irrigation or drinking water supply to improve the socio-economic conditions of users, mainly in remote areas, becomes an attractive solution. For this reason, the development of optimal solutions taking into account the Energy-Water duo remains a major asset to have a considerable impact on the dimensions of sustainable development.

This paper presents a systematic algorithm for sizing the improved PV pumping systems, considering all relevant elements, from the PV pumping system, wells, local climate, soil, to the irrigation system. As a result of this algorithm, the optimum size of the PV pumping system was presented, to meet the hydraulic power requirements in the best possible way during the entire observed period. The photovoltaic pumping system was designed to fulfill the irrigation water requirements of tomatoes cultivated near the Fez-Meknes region location and marked out by an irrigated area of 0.5 hectares and also the livestock watering. That work verifies that the electrical power of the photovoltaic generator is relatively lower than that obtained without optimization.

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REFERENCES

[1] I. Yahyaoui, M. Ammous and F. Tadeo, "Algorithm for Optimum Sizing of a Photovoltaic Water Pumping System," *International Journal of Computer Applications*, vol. 111, no. 6, 2015, doi: 10.5120/19544-1409.

[2] J. Royer, T. Djiako, E. Schiller, and B. S. Sy, "Photovoltaic pumping: course manual for engineers and technicians (in French: Le pompage photovoltaïque: manuel de cours à l'intention des ingénieurs et des techniciens)," Université d'Ottawa, 2002.

[3] R. López-Luque, J. Reca and J. Martínez, "Optimal design of a standalone direct pumping photovoltaic system for deficit irrigation of olive orchards," *Applied Energy*, vol. 149, pp. 13-23, 2015, doi: 10.1016/j.apenergy.2015.03.107.

[4] Z. Glasnovic and J. Margeta, "A model for optimal sizing of photovoltaic irrigation water pumping systems," *Solar Energy*, vol. 81, no.7, pp. 904-916, 2007, doi: 10.1016/j.solener.2006.11.003.

[5] I. Yahyaoui, *Specifications of photovoltaic pumping systems in agriculture: sizing, fuzzy energy management and economic sensitivity analysis*. Amsterdam, Netherlands: Elsevier, 2017.

[6] A. Oi, "Design and simulation of photovoltaic water pumping system," M.S. thesis, Department of Electrical Engineering, California Polytechnic State University, San Luis Obispo, USA, 2005.

[7] A. Hamidat, B. Benyoucef, "Systematic procedures for sizing photovoltaic pumping system, using water tank storage," *Energy Policy*, vol. 37, no. 4, pp. 1489–1501, 2009, doi: 10.1016/j.enpol.2008.12.014.

[8] V. Tamrakar, S. C. Gupta and Y. Sawle, "Single diode PV cell modeling and study of characteristics of single and two-diode equivalent circuit," *Electrical and Electronics Engineering: An International Journal (ELELIJ)*, vol. 4, no. 3, 2015, doi: 10.14810/elelij.2015.4302.

[9] S. S. Chandel, M. N. Naik and R. Chandel, "Review of solar photovoltaic water pumping system technology for irrigation and community drinking water supplies," *Renewable and Sustainable Energy Reviews*, vol. 49, pp. 1084–1099, 2015, doi: 10.1016/j.rser.2015.04.083.

[10] A.K. Daud, M.M. Mahmoud, "Solar powered induction motor-driven water pump operating on a desert well, simulation and field tests," *Renewable Energy*, vol. 30, no. 5, pp. 701–714, 2005, doi: 10.1016/j.renene.2004.02.016.

[11] M. Zegeye, T. Tadiwos, A. Aman, "Optimal sizing of solar water pumping system for small scale irrigation: Case study of Dangila," *International Journal of Renewable and Sustainable Energy*, vol. 3, no. 5, pp. 99-107, 2014, doi: 10.11648/j.ijrse.20140305.13.

[12] Y. Bakelli, A. H. Arab and B. Azoui, "Optimal sizing of photovoltaic pumping system with water tank storage using LPSP concept," *Solar Energy*, vol. 85, no. 2, pp. 288-294, 2011, doi: 10.1016/j.solener.2010.11.023.

[13] G. Falbel, J. Puig-Suari, and A. Peczalski, "Sun oriented and powered, 3 axis and spin stabilized CubeSats," *Proceedings, IEEE Aerospace Conference*, 2002, pp. 1-1, doi: 10.1109/AERO.2002.1036864.

[14] I. Reda and A. Andreas, "Solar position algorithm for solar radiation applications," *Solar Energy*, vol. 76, no. 5, pp. 577–589, 2004, doi: 10.1016/j.solener.2003.12.003.

[15] M. Alata, M.A. Al-Nimr and Y. Qaroush, "Developing a multipurpose sun tracking system using fuzzy control," *Energy Conversion and Management*, vol. 46, no. 7-8, pp. 1229-1245, 2005, doi: 10.1016/j.enconman.2004.06.013.

[16] S. C, Ribeiro, P. P. L. do Prado, J. B. Gonçalves, and Á. M. de Souza Soares, "Design and development of a low-cost solar tracker," *Australian Journal of Mechanical Engineering*, vol. 11, no. 2, pp. 139-150, 2013, doi: 10.7158/M12-082.2013.11.2.

[17] C. Olcan, "Multi-objective analytical model for optimal sizing of stand-alone photovoltaic water pumping systems," *Energy Conversion and Management*, vol. 100, pp. 358–369, 2015, doi: 10.1016/j.enconman.2015.05.018.

[18] H. Suehrcke, J. Appelbaum, B. Reshef, "Modelling a permanent magnet DC motor/centrifugal pump assembly in a photovoltaic energy system," *Solar Energy*, vol. 59, no. 1-3, pp. 37–42, 1997, doi: 10.1016/S0038-092X(96)00117-X.

[19] A. Hafian, M. N. Kabbaj, A. Abouabdillah, M. Benbrahim, and A. Bouazi, "A new approach for optimal sizing of photovoltaic pumping systems for irrigation," *2020 5th International Conference on Renewable Energies for Developing Countries (REDEC)*, 2020, pp. 1-6, doi: 10.1109/REDEC49234.2020.9163869.

[20] A. A. Ghoneim, "Design optimization of photovoltaic powered water pumping systems," *Energy Conversion and Management*, vol. 47, no. 11-12, pp. 1449-1463, 2006, doi: 10.1016/j.enconman.2005.08.015.
[21] R. G. Allen, L. S. Pereira, D. Raes, and M. Smith, "Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56," *FAO - Food and Agriculture Organization of the United Nations*, vol. 300, no. 9, 1998.
[22] J. Doorenbos, "Crop Water Requirements," *FAO Irrigation and Drainage Paper 24*, 1977.
[23] T. Jenkins, "Designing solar water pumping systems for livestock," *Circular (New Mexico State University. Cooperative Extension Service)*, no. 670, 2014.
[24] J. Kenna and B. Gillett, *Solar water pumping*. London, UK: Intermediate Technology, 1985.
[25] T. D. Morales and J. Busch, "Design of small photovoltaic (PV) solar-powered water pump systems," *United States Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS)*, 2010. [Online]. Available: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_046471.pdf.

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