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Mathematical model design of photovoltaic pumping water systems for irrigation

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ABSTRACT:

The agricultural sector has suffered from low penetration of the national energy grid in areas with irrigation capacity in developing countries, where the isolated needs access to the conventional power grid. Because of the low rate of population access to power, there is a need for the production of reliable and renewable energy for agricultural and domestic uses. PWPSFI (photovoltaic water pumping systems for irrigation) have been commonly used in many countries to improve access to irrigation resources.

In this article, we will present a new technical model that will be used as a guide for data collection and quantification of the electrical energy needed for irrigation based on the physiological requirements of each crop in terms of crop water needs, and then the irrigation water needs at all stages of crop development.

The crops are distinguished by their developmental stage, and the PVWSI is designed to satisfy the crop's water requirement.

The eggplant's sizing process is flowering, and the daily levels of excess electrical energy in the operation after irrigation in the four growth phases of the eggplant are 4.87 kWh, 2.65 kWh, 0.98 kWh, and 2.63 kWh, which can be retained and diverted to cover other electrical energy requirements.

Keywords
Crop coefficient , cycle growing , irrigation , Electricicital consumption Photovoltaic panels, Solar energy

1. Introduction

In certain parts of the planet, water supplies are becoming extremely limited. Irrigated agriculture is prevalent in these areas and is the primary beneficiary of water supplies. Indeed, more than 324 million hectares are fitted for irrigation globally, with nearly 85 percent, or 275 million hectares, being irrigated (FAO, AQUASTAT, 2014).

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Similarly, agriculture mobilizes more than 80% of water supplies in Morocco (Belghiti, 2012), which ensures that any initiative aimed at saving and maintaining the Kingdom's water resources, like the current national plan for saving and using water, is focused on modernizing and improving irrigation water quality and operation.

The FAO-56 PM equation is commonly used for estimating evapotranspiration in agriculture and is more reliable in ETO estimation since it uses several parameters (Allen and al.., 1998b; Allen, 2000).

Since 1977, PVWPS has proved to be a fruitful experience (Fedrizzi et al., 2009), and PWPSFI are proving to be a potential solution to mitigating the detrimental consequences of a lack of access to renewable electrical resources for irrigation (Zaki and Eskander, 1996; United Nations, 2016; Chilundo et al., 2018).

PV modules produce electrical energy from radiation (photons) (Wang et al., 2015). Since solar radiation cannot fulfill the electrical energy needs for irrigation, PWPSFI considers water storage tanks or a battery bank, depending on the precise conditions of each system/location.

The key performance influences on the PWPSFI architecture are technological, and external impacts (Chilundo et al., 2019). Several models are being established in this context to boost PWPSFI efficiency and implementation (Campana et al., 2013).

The contribution of this work is to create a dynamic model guidance that takes into account the dynamics of water demand of crops during their growth cycle, and to use PWPSFI as a clean production tool to provide electrical energy for irrigation and other electrical energy demands.

PWPSFI for crops may be used as a technological solution by governments of developed countries facing the issues posed in this study to improve access to electricity for irrigation and as an alternate energy supply to reduce the high rates of inaccessibility to resources.

The dynamics of water end-use as a vector are not taken into consideration by the PWPSFI models. The conceptual property examines how water demand for crops changes over time, based on the type of crop, and the stage of development, and other variables.

Photovoltaic cell manufacturing infrastructure, model of PV panel installation, country and area regulations, technology sophistication in the local sector, manufacturing costs, and incentive rate all affect device costs and payback time (NREL, 2004).

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2. Methodology

2.1 modeling and simulation

In order to meet the water needs with the lowest total cost in terms of technical, social, and environmental issues, the optimum solution to the PWPSFI design process is dictated by existing variables and the complexity of the system.

Taking the complex characteristics of crop water demand into account would cause the PWPSFI and water usage to be optimized, reducing excess or deficit irrigation. Through not pumping extra water, there is an automatic excess of electrical energy energy in the system that can be compensated and transferred to satisfy other electrical energy requirements, thus compensating for a portion of the electrical energy shortfall.

The mathematical model developed, as seen in flowchart methodology, is made up of four sub-model structures : The crop water need, irrigation water requirement, the electrical consumption , and the photovoltaic energy .

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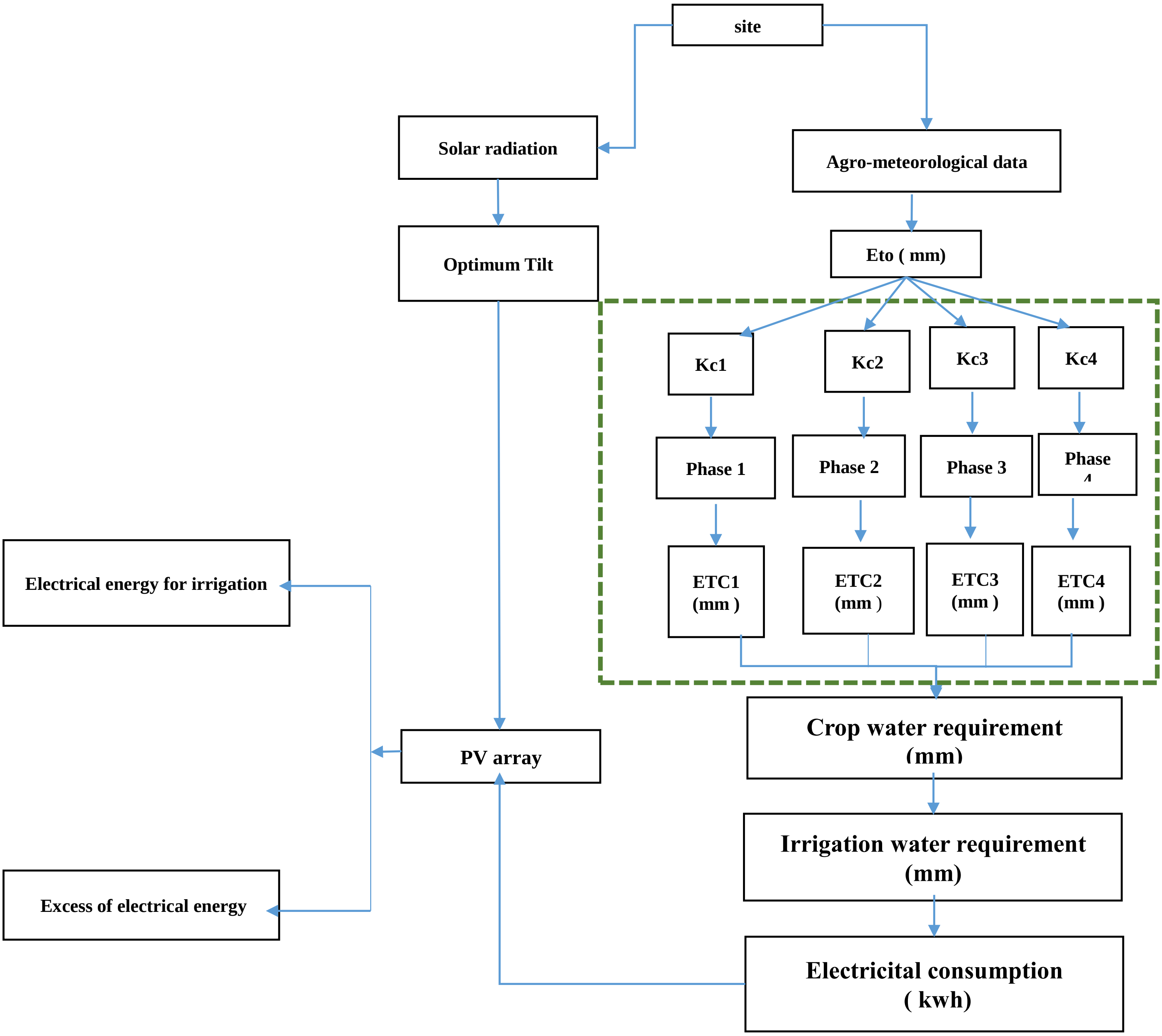

Figure 1 : The flowchart methodology of mathematical model for the PWPSFI design of crops irrigation

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2.1.1 Crop Evapotranspiration :

The water demand of crops varies depending on factors such as crop variety, climate, and soil type, but the most important element is typically the crop cycle growth .

The following are the major crop growth phases: emergence, branch forming, flowering, releasing the first fruits, and leaf dropping. The following formula expresses crop evapotranspiration: [2]

$$\boldsymbol{ETC = ETo \times Kc} \qquad \text{[Eq.1]}$$

ETC denotes the crop's potential evapotranspiration, while Kc denotes the crop coefficient, which varies with the crop's growth cycle. The crop coefficient takes into account a number of environmental factors as well as the crop's effect on evapotranspiration. [3]

$$Q_{ph1/4} = \frac{\mathbf{E_{tf1} \times D_{ph} \times A}}{\mathbf{E_i}} \qquad \text{[Eq.2]}$$

As shown in Eq. 3, the crop water demand for each growth period, denoted as Qph, is equivalent to the product of evapotranspiration during the considered process (E_{tf}), the number of days per phase (D_{ph}), and the irrigated area (A), divided by the irrigation method's efficiency (E_i) .

In fact the following Equation ensures that the overall water demand during the efficient period (Qtot) equals the number of the values of the average water intake (Q_{ph}) of the four crop phases: [4]

$$Q_{tot} = \sum_{k=1} 4\ Qph(K) \qquad \text{[Eq.3]}$$

Where k denotes the various stages of crop production.

The irrigation regime, availability of local solar radiation, and financial capital, among other factors, characterize the water storage scheme.

2.1.2 Electrical criteria evaluation:

Equation (5) specifies the method for designing electric power based on potential evapotranspiration requirement for crops . [5]

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$$P_{EL} = \frac{Q_{Ph} * TDH * P * g}{\eta_{MP}} \qquad [Eq.4]$$

P_{EL} is the needed electric power [W], η_{MP} is the motor pump performance, Q_{Ph} is the amount of crop water necessary per hour/development process [m3/h], TDH is the total dynamic head [m], *P* is the water density [kg/m3], and g is the gravity [m/s2].

2.1.3 Power of system

The required power supply is determined by the relationship between solar radiation and the amount of electric energy required for irrigation during the crop's peak water demand season (Kassel, 2003) as indicated in the following equation : [6]

$$P_{PV} = \frac{Q_{ELmax} * t * QG_{ref}}{G_{Tmin} * F_Q} \qquad [Eq.5]$$

Where :

Q_{ELmax} the requisite maximum electricity [W]; t the pump in reference process time in hours [h]; $G_{Tmin}$the worldwide minimum solar power for the area considered; [Wh/m2];G_{ref} the reference solar radiation [1000w/m2] and FQ the PV network efficiency factor.

The PV array structure according to Bexiga (2014) is: [7]

$$M_S = \frac{P_{pv}}{P_{mod} * M_p} \qquad [Eq.6]$$

Where P_{mod} is the PV module's electrical control.

At the performance of PV power system at each cultivation phase, the electrical energy available can be determined by: [8]

$$P_{ElA(ph)} = E_{ElA(d)} * N_{(d)} \qquad [Eq.7]$$

Where $E_{ElA(d)}$ is available at the power output of each crop, $P_{ElA(ph)}$is the normal power available [W] at PV control sub-systems, and t(h) is available at hours of sunshine daily for any crop development process; $E_{ElA(d)}$ Daily Power subsystems output capacity [Wh] for every crop development phase, N(d) Daily Power output .

The following equation determines electricity required for irrigation : [9]

$$E_{Ell\,(ph)} = \sum_{d=1} P_{Ell\,(d)} * t_{(h)} \qquad [Eq.8]$$

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Where E_{EII} (f) is the energy generated [WH] necessary for irrigation at each step of cropping, P_{EII}(d) the daily electrical power (W] necessary for irrigation at each stage of crop production, t(h) the daily running time of the motor pump [h], E_{EII}(d) the daily electrical electric energy [Wh] needed for irrigation at each phase of cultivation development.

In each crop production stage, the excess electrical energy is : [10]

$$E_{EIIx(ph)} = E_{EIA(ph)} - E_{EII(ph)} \quad [Eq.9]$$

2.2 The area study

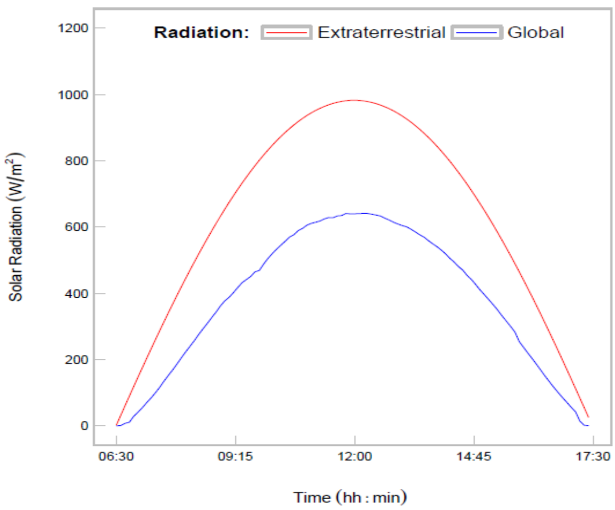

Figure 2: Solar radiation for a typical clear sky day.

The research case position is SA TAZI in the Gharb area (34°35'; 6°15'; 7 m). The PWPSFI scaling of the eggplant crop in 0.6 hectares was conducted on a daily drip irrigation system of irrigation. It takes 135 days for the eggplant production period. The irrigation cycle is established between April and August. The production process is expected to take place in April, during the third phase of cycle growing in May, June and July, and at the end of July and beginning of August.

2.3 Meteorological information

The TCSC weather station in SA TAZI was used to collect all meteorological data. Temperature (T_{max}, T_{min}, $T_{average}$), wind speed, net radiation, relative humidity, and reference evapotranspiration were assessed during the 2019-2020 season.

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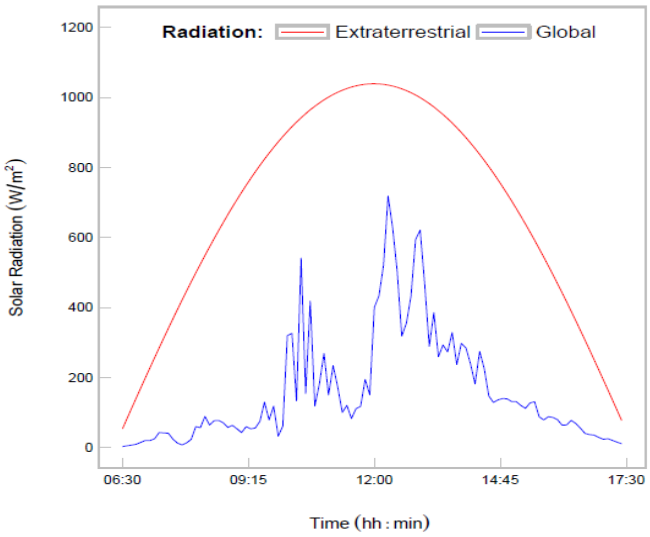

Figure 3: Solar radiation for a typical cloudy sky day.

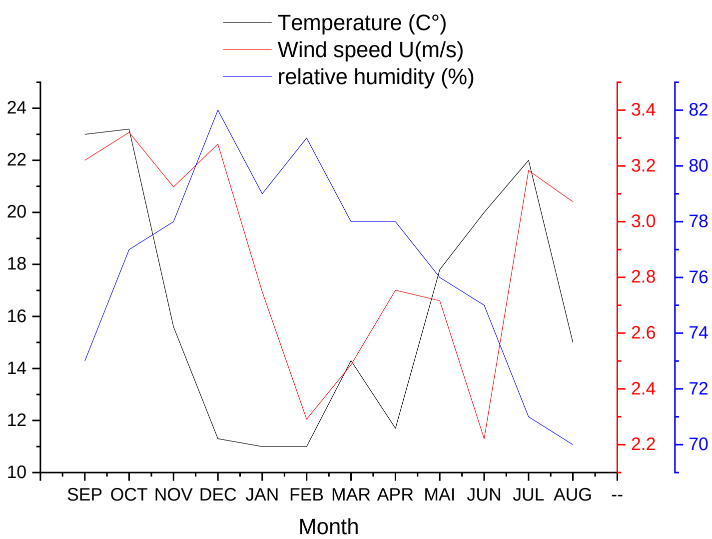

Figure 4: climatic data during the compaign Season 2019-2020

ETC is the mechanism by which evapotranspiration loses water. (Doorenbos 1984) [11]. Both transpiration and evaporation processes are concurrent and closely linked (Ding et al., 2013). [1]

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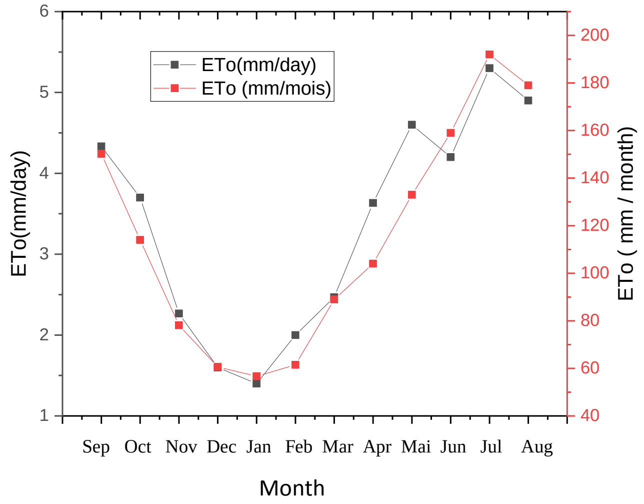

Figure 5: The reference evapotranspiration during the growing season (2019-2020)

3. Results and discussion :

3.1 eggplant water demand

This chapter discusses the findings of the measurement of water need for eggplant water, the PWPSFI eggplant and PWPSFI energy efficiency. A 0.6 ha irrigated area was taken into account in this study.

Table 1 shows the water need of crop requirement for each phase of eggplant and subsequently the crop coefficient values. Where Dph is the number of days per phase of eggplant production, kc is the crop coefficient by phase of eggplant development, and Qph represents the water required for eggplant irrigation in each phase of development.

Table 1 : Water demand and the respective crop coefficient per eggplant development phase.

crop cycle growth	D_{ph}*days	kc	Q_{ph} (mm/phase)	Q_{ph} [mm/day]	Q_{ph} [m3/mm/day]
[1] **Initial phase**	30,00	0.65	37.5	1,27	12,70
[2] **Development Phase**	35,00	0,73	72.9	2,13	21,30
[3] **Flowering phase**	40,00	1,2	127.7	3,05	30,50
[4] **maturation phase**	30,00	0.8	66.7	2,35	23,50

Table 2 : Total water requirement throughout the eggplant crop productive cycle for 0.6 ha.

crop	sowing	cyce growth period	Total water needed (mm/cycle)	Total water needed (m3/cycle)
Eggplant	First April	136,00	307,00	3070,00

The maximum demand for water exceeds the minimum by 2.5 times.

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The results show that the PWPSFI has excess electrical power in eggplant-development phases when demand for water is lower than maximum, given the dimensions of the system dependent on crop phases growing, with maximum water demand. In the eggplant flowering season, the average maximum daily use of water in the region is 30m^3 to 50m^3, according to the FAO (Steduto et al., 2012). max water demand during the manufacturing cycle of eggplantes.Table 2 reveals that (Qtot) is 307 mm.

According to the FAO's findings, the total water demand for a 1ha eggplant crop varies from 420mm to 600mm, depending on the eggplant variety and agroclimatic area.

As a result, the water need for irrigation in the study region could range from 300 to 480 millimeters. Table 3 indicates a total water need for irrigation in the study region of 348.9mm, as shown below :

Table 3 : Total water need for eggplant irrigation in the study area.

Phases	Month	decade	Kc	ETC (mm/dec)	Effective rain (mm /dec)	Irrigation water requirement (mm/dec)
A	Apr	Init	0,62	21,80	19,57	3,20
	Apr	Init	0,63	20,80	19,27	2,50
	Apr	Init	0,65	20,00	14,57	5,70
B	May	Deve	0,76	20,60	8,27	12,90
	May	Deve	0,80	23,60	3,47	20,70
	May	Deve	1,04	26,60	4,17	25,70
C	Juin	Mid	1,16	28,20	5,47	24,00
	Juin	Mid	1,19	26,20	5,57	21,00
	Juin	Mid	1,19	26,80	5,57	21,30
	Jul	Mid	1,19	27,30	5,67	22,10
D	Jul	Late	1,14	27,30	5,77	22,20
	Jul	Late	1,03	27,20	5,27	25,10
	Aug	Late	0,81	26,30	4,07	22,70
	Aug	Late	0,74	26,20	0,87	6,30
				348,90	107,58	235,40

Table 4: The proportional ratio between the daily average monthly solar radiation and

	April	May	June	July	August
G_T ([kW/m2/day]	5,87	6,11	6,05	6,11	6,32
Q_{ph} (m3/ha, day)	12,30	20,50	13,50	12,30	21,70
Proportion	47,10	30,30	19,10	18,20	28,70

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Table 5 : PV selection and power capacity sizing.

scenario	Q_{ph} (m3/h)	Daily number of hours water pumping: Hours number	Start (hours)	End (hours)
A	3,50	9,00	07:00	16:00
B	3,40	8,00	07:00	15:00
C	5,30	6,00	08:00	14:00
D	8,00	4,00	09:00	13:00

Table 6 : Scenarios for PV power calculation and PV array sizing scenarios depending on crop irrigation times.

pumping hours	Solar radiation (w/m2)	PV power (w)	PV modules in series	PV modules in parallel	Pv array (m2)
9,00	613,00	2671,00	8,90	2,00	15,60
8,00	719,00	2245,00	7,50	2,00	13,10
6,00	819,00	1959,00	6,50	2,00	11,40
4,00	890,00	1814,00	6,00	2,00	10,60

Table 7 : The final configuration of the eggplant PWPSFI design.

Units	parameters
Irrigated field [ha]	0,6
Water demand [m3/day]	31,9
Qmax [m3/h]	6,7
Total dynamic head [m]	16
Hours of daily service [h]	7
Electricity supplied by the motor pump [W]	680
Average daily solar radiation [kWh/m2 day]	6,3
Performance of motor pumps [%]	93
Array PV power [W]	2084
PV array [m2]	12
Angle of tilt (south-east)	32

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3.2. The PWPSFI for eggplant irrigation design

The worst proportional relationship between daily average monthly solar radiation and average monthly water demand was considered when choosing the reference month for eggplant PWPSFI design, as seen in Table 4.

June has the lowest proportion (19.3%), and was chosen as the reference month for PWPSFI design due to the higher water requirement during the eggplant active period. The comparison month corresponds to the crop's flowering stage. As a function of the number of daily hours of water pumping, four potential scenarios for PV power and PV array sizing were developed, as shown in Table 5.

The lower the solar radiation for which the device would be sized, and the greater the power and PV array available, the greater the amount of hours of water pumping a day for irrigation. As seen in Table 6, the smaller the solar radiation value for which the device is sized, the greater the power value and the appropriate PV array for the same motor pump and water demand.

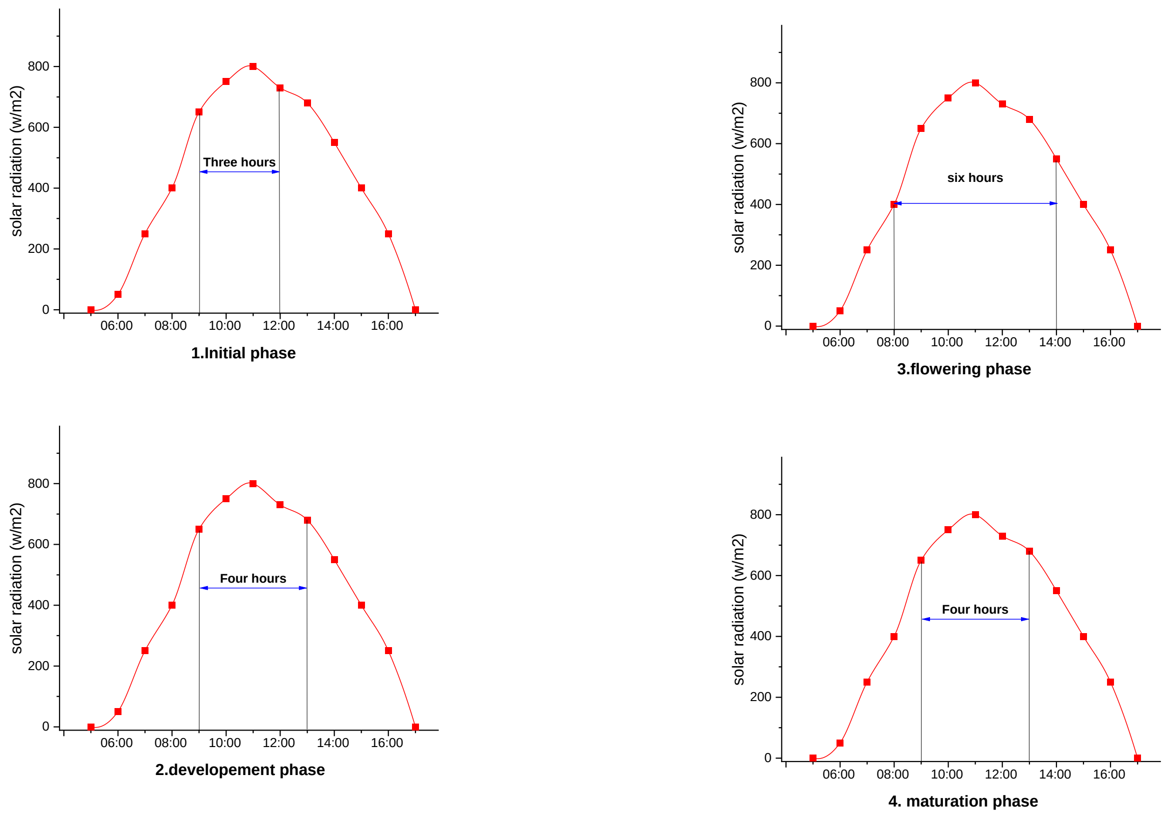

Figure 6 : Solar radiation and the period of normal hours at which water is pumped for eggplant irrigation.

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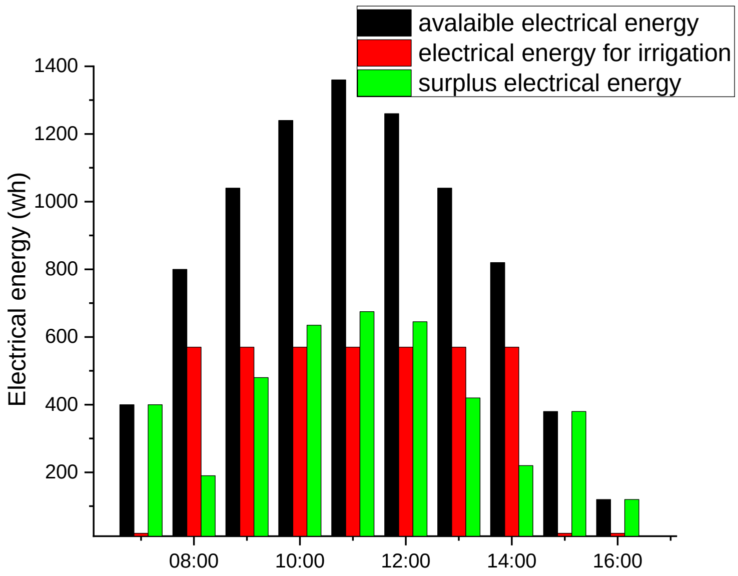

Figure 7 : PWPSFI average daily efficiency during the cycle growing of the eggplant

Solar radiation is above 500W/m2 at all stages of eggplant growth, even when water pumping for irrigation starts. The motor pump output must be at least $6m^3/h$, so this is the absolute minimum. Figure 7 depicts the PWPSFI's regular energy efficiency during the eggplant flowering process. If the motor pump begins at 8:00 p.m. and finishes at 2:00 p.m. during the month of June, the average electrical energy available in the system is 8770 Wh, the average electrical energy needed for irrigation is 4200 Wh, and the average electric excess power is 4570 Wh.

However, to ensure that the water supply operation is not disrupted during periods of low solar radiation, the excess electrical power provided by the system during times when water pumping for irrigation is taking place will not be compensated for the supply of other electrical energy needs in all stages of the crop's production. In this scenario, the total daily excess electrical energy in the flowering period is 1020 Wh after pumping water for irrigation. The excess average electrical energy is 40650Wh during the flowering eggplant season, which lasts forty (40) days.

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Figure 8 depicts PWPSFI's average daily energy efficiency at all stages of eggplant growth. There is an accumulated average amount of excess electrical energy everyday during the four (4) eggplant growth stages.

The average cumulative electrical energy value for each eggplant growth process as shown in Table 8. There is an estimated excess electricity of 370 kWh at the conclusion of a sustainable period of the 135-day eggplant crop for the supply of other electrical energy uses.

Table 8: average daily and phases electric excess capacity during the growing cycle of eggplant

scenario	development period (days)	Average excess electrical energy	
		Daily (kwh)	Total (kwh)
A	30,00	4.78	153,00
B	32,00	2.65	102,00
C	40,00	0.98	45,00
D	32,00	2,63	79,00

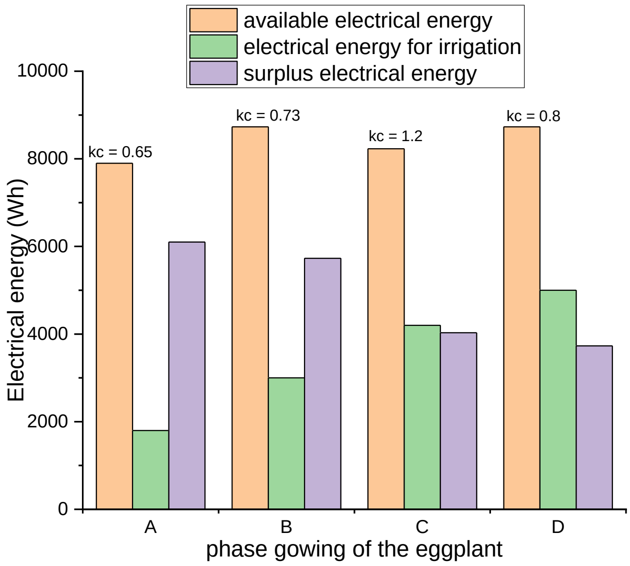

Figure 8 : Average daily energy performance of PWPSFI during the four eggplant development with kc =0.65 , kc=0.73 , kc=1.2 and kc = 0.8 .

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We checked our design with a high crop coefficient of about 1.2 to see if it is well suited to other type of crops and if the planting of another crop would not result in an adjustment of the photovoltaic pumping system. The result is shown in figure 9.

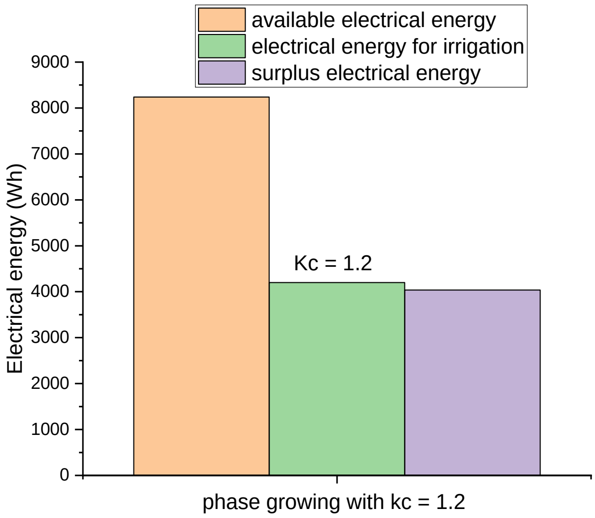

Figure9 : Average daily energy performance of PWPSFI during the phase with kc = 1.2

The dimensioning of the solar pumping system for irrigation with a crop coefficient equal to 1.2 shows that our system is well adapted to all types of crops, and that the system can largely meet the need for irrigation water, and subsequently the need of the crop.

4.Conclusions :

The photovoltaic water pumping systems will be introduced and explored as a cleaner electrical source for irrigation generation and other energy requirements, based on the complex model architecture developed for PWPSFI by means of eggplant case study. the fundamental conclusions are as follows:

crops usually have four phases of growth, with PWPSFI to be scaled according to the growing phase, with a maximum water requirement. Therefore daily electrical power is generated from the PWPSFI for irrigation and the device contains excess electrical energy.

The energy is recovered and can be taken into account and aimed at supplying other energy requirements.

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The size process is the flowering cycle of eggplantes. The system has a daily averages of excess power after irrigation in four phases of eggplantes development: 4.87 kWh (f1), 2.65 kWh (f2) and 0.89 kWh (ph3) and 2.63 kWh.

Solar photovoltaic systems for irrigation can help lead to cleaner electrical energy generation for irrigation, minimizing the usage of diesel engines, which are still widespread in the irrigation industry. The use of diesel engines for electrical energy generation for agriculture or the provision of other electrical energy demands is being phased out, resulting in less negative environmental impacts.

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