

# Computer-assisted sizing of photovoltaic systems for drip irrigation of olive orchards in semi-arid climate

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## Abstract

One of the most promising applications of photovoltaic solar power, especially in areas which have high levels of solar radiation, is for pumping the water needed to irrigate the existing crops. However, it is absolutely necessary to accurately dimension the installations due to the high prices of photon capture devices. In this paper, a simple method, implemented in a spreadsheet, to calculate the design requirements of a photovoltaic system to power the drip irrigation of a field is proposed. The methodology is based on the link between the existing photovoltaic pumping techniques and the procedure to determine the crop water requirements. In the case study, 10 ha of olive grove, a photovoltaic field with 18 solar panels for 1.43 kWp is required. Besides the advantages for the environment, since it uses a renewable energy, a study on the economic viability of a photovoltaic system shows that it is similar to conventional systems which use a generator unit (twice the net present value for the photovoltaic system). Moreover, the high price of fossil fuels guarantees a progressive advantage of photovoltaic systems.

**Additional key words:** crop water requirements, irrigation scheduling, renewable energies, solar panels, spreadsheet.

## Resumen

### Dimensionamiento asistido por ordenador de sistemas fotovoltaicos para riego por goteo de olivares en climas semiáridos

Una de las aplicaciones más prometedoras de la energía solar fotovoltaica, especialmente en áreas con niveles elevados de radiación solar, es el bombeo del agua necesaria para regar los cultivos. Sin embargo, es absolutamente necesario dimensionar de forma precisa las instalaciones, debido al alto precio de los sistemas de captura fotónica. En este trabajo se propone un método simple, implementado en una hoja de cálculo, para calcular los parámetros de diseño de un sistema fotovoltaico capaz de suministrar la energía que precise un sistema de riego por goteo de una parcela agrícola. El método se basa en la unión de las técnicas conocidas para el bombeo fotovoltaico y para el cálculo de las necesidades hídricas de un cultivo. En el caso estudiado, con 10 ha de olivar, es necesario un campo fotovoltaico con 18 paneles solares para 1,43 kWp. Aparte de las ventajas medioambientales, ya que se emplea energía renovable, un estudio adicional demuestra la viabilidad económica de un sistema fotovoltaico, con unos costes similares a los sistemas convencionales consumidores de combustibles fósiles (más del doble de valor actualizado neto para el sistema fotovoltaico). Además, el precio cada vez más elevado de los combustibles hace que los sistemas fotovoltaicos sean una opción cada vez más ventajosa.

**Palabras clave adicionales:** energías renovables, hoja de cálculo, necesidades hídricas de un cultivo, paneles solares, programación del riego.

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## Introduction

Photovoltaic systems can be used for different purposes (e.g. World Bank, 1984; Sandia National Laboratories, 1993; Lillo Bravo *et al.*, 2004). From an agricultural point of view, one important application is for pumping water. There is an extensive bibliography on irrigation technology (e.g. Doorenbos and Pruitt, 1997; Allen *et al.*, 1998; García-Araque, 2000) that discusses appropriate methods to estimate water requirements for a given crop in a given place. However, to our knowledge, there are no references on studies connecting both technologies. The work of Cuadros *et al.* (2004) constitutes the first step to focus on the most innovative scopes to be used in agricultural systems.

Sometimes, it is difficult to obtain water for irrigation due to climatic conditions or a population increase. Therefore, it is frequently necessary to resort to the pumping of wells or rivers. Photovoltaic systems are especially appropriate for those places where there is no electricity supply. The main advantages, with respect to electric pumps or those powered by an internal combustion motor are their practically zero maintenance, long useful life, non-polluting characteristics and also very easy to install. They use the sun as energy source, and the periods of maximum water demand coincide with maximum solar radiation. The main disadvantages are the high initial cost and the yield variability of the solar panels depending on predominant meteorological conditions, although this may be solved, at least partially, by the storage of water in a tank at a given height.

The main objective of this paper is to explain a simple, user-friendly computer workbook, in order to size photovoltaic systems that can be used for irrigation in farms. The aim is to achieve maximum efficiency of this combination, *i.e.* to irrigate the maximum number of plants using the minimum number of solar panels. Thus, the power requirement for a specific application is accu-

ately determined to make the cost of the installation profitable in as short a time scale as possible.

The method consists of three principal stages and, in consequence, three modules were developed in separated worksheets: i) Determination of the crop water requirements (Doorenbos and Pruitt, 1997; Allen *et al.*, 1998), located at a field anywhere, for which variables supplied from any climatic database, such as Climwat of the FAO ([www.fao.org](http://www.fao.org)), are used. ii) Design of the drip irrigation system (Arviza, 1996; Orgaz *et al.*, 1996). The irrigation system can be outlined considering various possibilities, in terms of the number and flow of drippers, number of irrigation sectors and irrigation times per sector, always taking into account the gross irrigation requirement. The main advantage of localised irrigation is the saving of water. It obtains up to 90% efficiency compared with 70% for sprinkler systems and 40% with furrow irrigation (Nakayama and Bucks, 1986; Arviza, 1996). Nowadays, efficient water use is a basic factor in proposing a particular irrigation system due to water shortage in many places around the world. iii) Design of the pump system (Lorenzo, 1994; Hamidat and Benyoucef, 2008; Kaldellis *et al.*, 2009) depending on the depth of the aquifer and the height necessary to stabilize the pressure in the heads of the water distribution network, and determination of the maximum power required to irrigate a field, taking into account the average yield of the photovoltaic irrigation-pumping-generation system.

## Material and methods

The spreadsheet, where all stages of the methodology were implemented, consists of several worksheets used to enter data, choose solutions and carry out operations, at the same time as obtaining results. Interactive screens change automatically the values obtained we modified. New results are produced again and so on,

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Abbreviations used: ACWR (annual crop water requirement), AW (available water),  $E_H$  (hydraulic energy),  $E_{PG}$  (maximum energy required by the photovoltaic generator),  $E_{rad}$  (radiant energy),  $ET_c$  (evapotranspiration of the crop),  $ET_0$  (reference evapotranspiration), FC (field carrying capacity),  $G$  (number of drippers per tree),  $G_d(>G_{threshold})$  (fraction of the day when solar radiation is below a threshold), GR (gross irrigation requirement),  $h_s$  (effective hours of sun per day), IRR (internal rate of return),  $K_c$  (crop coefficient),  $K_r$  (crop growth coefficient),  $N_{pe}$  (number of solar panels), NPV (net present value), NR (net irrigation requirement),  $P$  (peak photovoltaic power),  $P_e$  (effective precipitation),  $P_{pg}$  (power of the photovoltaic generator), PBT (payback time), PEL (permissible exploitation level), PWP (permanent wilting point),  $Q_g$  (flow rate of a dripper),  $R$  (energy losses in the pipes of the irrigation system),  $R_d$  (available water to the plants),  $R_m$  (monthly reserve of soil water),  $S_c$  (percentage of ground covered by the shade of the trees), TCI (total capital investment), TRd (total irrigation time), TRs (irrigation time per sector),  $g_s$  (efficiency of a drip irrigation system),  $m$  (overall efficiency of the generator-pump connection),  $m_G$  (efficiency of the photovoltaic generator),  $m_l$  (efficiency of the current converter),  $m_{MB}$  (efficiency of the pump).

until the results are adapted to the needs of the project designer.

### Water requirements calculation

If the soil water content is insufficient to replace the transpiration losses from the trees, the crop will be subjected to a water deficit that will alter a series of processes with negative repercussions on production. Similarly, there is a major water loss by evaporation from the surface of the soil, depending on meteorological factors and soil-type characteristics, which is particularly important in semi-arid climates. The sum of the water consumed by the plant in transpiration and evaporated from the soil is called the evapotranspiration of the crop,  $ET_c$ , and it must be wholly satisfied by rainfall and/or irrigation for the crop production potential not to be affected.  $ET_c$  constitutes the most important variable to be considered when designing an irrigation strategy for a particular crop in a specific soil and under a climatic regime (Allen *et al.*, 1998).

The calculation of  $ET_c$  is the first step in order to estimate the annual crop water requirement,  $ACWR$ . The most usual method to determine it is that recommended by the FAO (Doorenbos and Pruitt, 1997), whereby  $ET_c$  ( $\text{mm month}^{-1}$ ) is calculated through the product of three factors:

$$ET_c = ET_o \cdot K_c \cdot K_r$$

where  $ET_o$  is the reference evapotranspiration ( $\text{mm month}^{-1}$ ), which basically depends on the local climate, reflecting the atmospheric evaporative demand;  $K_c$  is the crop coefficient, characterising the type of crop, and  $K_r$  is a reduction coefficient, the so-called crop growth coefficient, which estimates the percentage of soil covered by the shade of the trees.

The determination of  $ET_o$  is usually made with empirical formulae. The FAO recommends the Penman-Monteith equation (Smith *et al.*, 1996) which is implemented in the Cropwat programme, developed by the FAO Water and Land Development division. This programme uses climatic data from the Climwat database, which includes 3,262 meteorological observatories in 144 countries.

#### Crop and crop growth coefficients

$K_c$  and  $K_r$  are experimental coefficients whose values do not exist for all regions.

The dimensionless evaporation reduction coefficient (Allen *et al.*, 1998),  $K_r$ , the so-called crop growth coefficient, which depends on the cumulative depth of water evaporated from the topsoil, can be determined with the following equation:

$$K_r = \frac{2 \cdot S_c}{100}$$

where  $S_c$  is the percentage of ground covered by the shade of the trees. It may be estimated as:

$$S_c = \frac{\pi D^2 N}{4 \cdot 10,000} \cdot 100$$

where  $D$  is the diameter of the tree crowns (in m), and  $N$  the plantation density ( $\text{plants ha}^{-1}$ ).

$D$  may be obtained through simple geometric calculations, based on direct measurements, or using aerial photographs and geographical information systems (Rovira-Más *et al.*, 2005).

For olive (*Olea europaea* L.) groves with  $S_c > 50\%$ ,  $K_r$  close to 1 is usually used. Values of  $K_r$  obtained from experiments conducted in the province of Jaén, southern Spain, are 0.4-0.5 in dry-land conditions and 0.65-0.7 after several years of irrigation, when tree size and yield have adapted to the new productive setting (Orgaz and Fereres, 1998).

$K_c$  is characteristic of each crop and fairly exact values are known for some locations. For instance, Orgaz *et al.* (1996) calculated  $K_c$  for olive groves in the province of Córdoba, southern Spain. In this case, the value of  $K_c$  fluctuates between 0.50 (winter) and 0.65 (autumn and spring). Usually, these values are applied to olive groves in the surrounding areas. Thus, the irrigation requirements of a olive tree orchard in the province of Badajoz, southwestern Spain, are estimated using the same  $K_c$  data, as both provinces are next to each other and there is not any other specific information for this area.

Other values of  $K_c$  for some olive producing regions of the world are, for example, between 0.6-0.75 for Creta, Greece, and 0.55-0.75 for California, USA (Orgaz *et al.*, 1996).

$K_c$  is highly sensitive to the water requirements of the crops and currently its determination through a universal expression for all crops and soils constitutes a real challenge.

#### Permissible exploitation level and irrigation scheduling

During the rainy season, the effective precipitation is higher than the evapotranspiration and, consequently,

water reserves are important. The effective precipitation,  $P_e$ , is the water quantity that could be used by the plants. It is usually calculated as a fraction of the total precipitation. For example, and for the majority of Spanish olive groves, 70% of mean monthly total precipitation is recommended (Orgaz and Fereres, 1998). The monthly reserve of soil water,  $R_m$  (mm month<sup>-1</sup>), is determined by means of the water balance:

$$R_m = P_e - ET_c$$

The sum of the monthly water reserves accumulated during the rainy season determines the quantity of water at the beginning of the dry season. Only part of this water content is available to the plants,  $R_d$ , and it cannot exceed a threshold level, the so-called permissible exploitation level,  $PEL$ . This threshold,  $PEL$ , is a fraction of the available water,  $AW$ , which constitutes the difference between the field carrying capacity,  $FC$ , and the permanent wilting point,  $PWP$ . For instance, for olive trees,  $PEL$  is estimated by the following expression:

$$PEL = 0.75 AW = 0.75 Zr (FC - PWP)$$

where  $Zr$  is the mean root depth.

One strategy followed in many irrigation schedules is to apply a quantity of water equivalent to the difference  $ET_c - P_e$  during dry periods, when  $ET_c > P_e$ . This procedure does not consider the water stored in the soil during the wet months of water surplus. It has the advantage of exceeding any underestimate of  $ET_c - P_e$  but disadvantages are greater, such as wasting water and the need for higher water flows (Orgaz and Fereres, 1998).

A more reasonable strategy consists of using water reserves accumulated during the wet season to complement the water provided by irrigation, which will minimise the irrigation water flow per hectare, with the corresponding decrease in power requirements. This will allow the irrigation of a larger surface area for the available water supply. Thus, the annual crop water requirement,  $ACWR$  would be:

$$ACWR = \sum_{\text{months}} (ET - P_e) - \sum_{\text{months}} R_m$$

where  $\sum (ET - P_e)$  is the total annual difference between  $ET_c$  and  $P_e$ , and  $\sum_{\text{months}} R_m$  is the total annual reserve accumulated in the soil.

The  $ACWR$  is obtained as mm year<sup>-1</sup>, but may also be expressed in m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup>. If these requirements are

divided between the number of months in which irrigation is necessary (for example, April to October in dry regions of southern Spain), the net irrigation requirement is obtained ( $NR$ ). When the number of trees per hectare is known,  $NR$  may ultimately be expressed in L tree<sup>-1</sup> day<sup>-1</sup>.

Taking into account the efficiency of a drip irrigation system,  $g_s$ , around 80% (Arviza, 1996), the gross irrigation requirement,  $GR$ , will be:

$$GR = \frac{NR}{g_s}$$

### Design of the photovoltaic pumping and the drip irrigation systems

Photovoltaic pumping systems have three principal components (e.g. Lorenzo, 1994): the photovoltaic panels, one motor and one pump. Depending on the design, the system may use storage batteries and a charge regulator. The batteries allow the pump to operate when the intensity of solar radiation is low (on cloudy days, at sunrise or sunset). However, the systems without batteries are cheaper and simpler, requiring very low maintenance. In these cases, raised tanks to store water are used which also regulate the flow and pressure at the irrigation heads (batteries are not considered in this work). The motor must be chosen according to the power requirements and the type of current to operate. If the motor uses alternating current, which is the most common, a current converter will need to be installed (Figure 1).

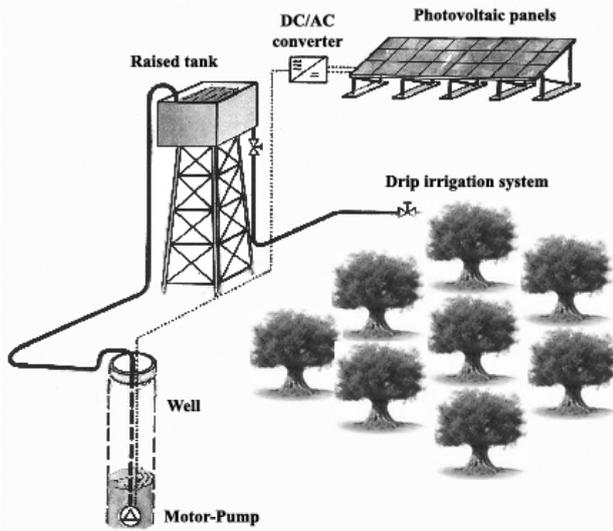
Taking into account: 1) energy losses caused by the water friction in the pipes of the irrigation system,  $R$ ; 2) the fraction of the day when the solar radiation is below the threshold at which the pump starts to work,  $G_d (> G_{\text{threshold}})$ ; 3) the efficiency of the photovoltaic generator,  $m_G$ ; 4) the efficiency of the current converter,  $m_j$ ; 5) the efficiency of the pump,  $m_{MB}$ ; the maximum energy required by the photovoltaic generator,  $E_{PG}$ , will be:

$$E_{PG} = \frac{(E_H + R)}{(G_d (> G_{\text{Threshold}})) \mu_G \mu_j \mu_{MB}}$$

where the hydraulic energy,  $E_H$  (kW h day<sup>-1</sup>), necessary to pump a volume  $Q$  (daily water flow) to a height  $H$ , is:

$$E_H = 2,725 \cdot 10^{-3} Q H$$

$H$  is the total height to which the water is pumped, being the sum of the depth of the well and the neces-



**Figure 1.** Diagram of a photovoltaic pumping system for an olive grove. Source: adapted from <http://www.suelosolar.es/guiasolares/riego.asp>.

sary height to establish the pressure at the irrigation heads.

The optimum acceptable values of friction losses  $R$  are around 10% of  $E_H$ . With respect to the efficiencies, Lorenzo (1994) suggested  $G_d (>G_{threshold}) = 0.95$ ;  $m_G = 0.85$ ;  $m_I = 0.90$ ;  $m_{MB} = 0.43$ . The product of all these efficiencies gives rise to an overall efficiency of the generator-pump connection, which, expressed as a percentage, is:  $m = 31.26\%$ .

The power of the photovoltaic generator,  $P_{pg}$ , is calculated according to the method of the peak sun hours (Censolar, 2004; Lillo Bravo *et al.*, 2004). It is the most used methodology and all field and laboratory experiments on photovoltaic panels are usually carried out considering one peak sun intensity ( $1 \text{ kW m}^{-2}$ ). Therefore, the nominal power of a panel is expressed as kW or peak W. Thus:

$$P_{pg} = \frac{E_{pg}}{hs}$$

where  $hs$  is the number of effective hours of sun per day (the number of hours per day above the standard level of radiation of  $1,000 \text{ W m}^{-2}$ ). The value of  $hs$  coincides numerically with the data for solar radiation expressed in kWh, which may be obtained from any meteorological observatory or from the Climwat database.

Finally, the power loss produced when the solar cells are operating in temperatures above  $25^\circ\text{C}$  must be considered. These losses are approximately 10% of  $P_{pg}$

(Censolar, 2004; Lillo Bravo *et al.*, 2004). Therefore, the peak photovoltaic power,  $P$  (kWp), will need to be:

$$P = (1+0.1) P_{pg}$$

The solar installation sizing is based on the expressions previously indicated. The final number of panels chosen for the installation,  $N_{pe}$ , is determined from:

$$\sum_{i=1}^{12} (Erad_i \cdot Np_i) = N_{pe} \sum_{i=1}^{12} Erad_i$$

where  $Erad$  (kW month) is the radiant energy, being the product of multiplying the total power of the solar panel field ( $Np \cdot Wp$ ) by the days of the month, and  $Np_i$  is the number of panels necessary for each month.

The number of drippers per tree,  $G$ , is related to the flow rate of each dripper,  $Qg$  ( $1 \text{ h}^{-1}$ ), from which the irrigation time per sector can be derived,  $TRs$  ( $\text{h sector}^{-1}$ ). Moreover, the total irrigation time,  $TRd$  ( $\text{h day}^{-1}$ ), is calculated in accordance with the number of sectors into which the operation is divided. If the irrigation time per sector,  $TRs$ , is higher than the number of effective sun hours per day,  $hs$ , more drippers per tree will need to be installed, or the flow of each dripper will need to be increased in order to cover the water requirement.

Alternatively, there is the possibility of using more than one irrigation sector to avoid the excessive diameter of the pipes, or considering a water accumulation since the installation is calculated without storage.

## Case study

The study is carried out for data corresponding to the area of Tierra de Barros, which is an olive producing area of Badajoz, southwestern Spain. Gentle hills dominate the topography; in the substrate limestones predominate over intrusive acidic rocks. According to the USDA-NRCS Soil Taxonomy System (1998), the soil is classified as Rhodoxeralf type. It has a medium level of organic matter content and a good cation exchange capacity. An intense biological activity is denoted by the carbon/nitrogen ratio, around 10. The soil has a loamy texture, with a great water retention capacity due to its depth and also a sufficient internal drainage, which is suitable for olive growing. The olive varieties in the experimental field are 'Verdial' (50%) and 'Carrasqueños' (50%), in a  $10 \times 10 \text{ m}^2$  grid.

According to Orgaz and Fereres (1998), the *FC* and *PWP* values are 0.36 and 0.17 respectively, which gives 142.5 for the *PEL* value.

The climate of this area is characterised by a variation in both temperature and precipitation typical of a Mediterranean climate. However, this feature is modified by the interior location and by oceanic influences that penetrate the Iberian peninsula due to its proximity to the Atlantic.

Mean annual precipitation reaches less than 500 mm. One of the most important characteristic of the precipitation is its interannual variability. There are a dry season, from June to September, and a wet season, from October to May (80% of the precipitation falls between these months).

Data related to the field location (geographic coordinates, 38.53°N and 6.58°W; mean altitude, 198 m.a.s.l.), characteristics of the crop (mean crown diameter of the trees, 6.43 m, and number of trees, 100 trees ha<sup>-1</sup>), irrigation (efficiency, 0.81, and well depth, 20 m) and photovoltaic installation (panel power, 110 Wp, and installation efficiency, 31.26%) must be provided (Figure 2). Furthermore, monthly climate and *K<sub>c</sub>* are included in the

same worksheet. Climatological information may be obtained from the Climwat database.

For crop water requirement (Figure 3) all values are generated automatically. They depend on the data that were introduced in the climate data worksheet (Figure 2). Through calculations indicated in previous sections, the monthly and annual crop water requirements are determined.

Later, all variables of the drip irrigation system are provided. Thus, irrigation time, water flow rate and gross irrigation requirement are calculated (Figure 4). In the case study, it is necessary around 1,724 m<sup>3</sup> ha<sup>-1</sup> to satisfy the water requirement of the olive orchard. Assuming 100 trees ha<sup>-1</sup> and if an effective pump height (sum of the depth of the aquifer, the elevation height to regulate the pressure of the irrigation heads, and the losses due to friction) of 50 m is established, a 0.6 kW pump would give a coverage of 102%, requiring power to be installed of around 1.5 kWp (Figure 5). This power can be provided by a diesel generator or a photovoltaic installation.

According to Barranco and Fernández-Escobar (2008), the production of a dry olive grove is 2,000 kg

#### FIELD LOCATION AND CLIMATE DATA

Location	Badajoz
Altitude (m)	198
Latitude (°)	38.53 N
Longitude (°)	6.58 W
Area (ha)	10
Crown diameter (m)	6.43
Tree number ha <sup>-1</sup>	100
Well depth (m)	20
Irrigation efficiency	0.81
Panel power (Wp)	110
Installation efficiency (%)	31.26

Month	ET <sub>0</sub> (mm month <sup>-1</sup> )	P (mm month <sup>-1</sup> )	K <sub>c</sub>	T min	T max	hs	Rn (MJm <sup>-2</sup> day <sup>-1</sup> )	RH (%)
January	31.0	61.0	0.50	4.40	13.10	4.90	8.00	81
February	44.8	50.0	0.50	5.10	15.20	6.10	11.20	76
March	77.5	64.0	0.65	7.50	17.90	6.00	14.30	72
April	111.0	46.0	0.65	9.60	21.10	8.60	20.40	64
May	145.7	43.0	0.65	11.90	24.30	9.50	23.40	62
June	186.0	18.0	0.50	15.70	30.20	11.70	27.00	54
July	223.2	3.0	0.50	17.80	34.10	12.60	27.90	50
August	198.4	5.0	0.50	17.90	33.30	11.50	24.80	50
September	135.0	25.0	0.65	16.20	29.70	8.90	18.70	56
October	83.7	52.0	0.65	12.30	23.50	6.90	13.00	66
November	48.0	62.0	0.65	8.00	17.50	5.20	8.70	75
December	31.0	62.0	0.50	5.10	13.50	4.50	7.00	82
<b>Total Annual</b>	1315.3	491.0	Mean	10.96	22.78	8.03	17.03	65.67

**Figure 2.** Field location and climate data worksheet. Data refer to the characteristics of the crop to be irrigated and the photovoltaic installation. Monthly climate data: reference evapotranspiration, ET<sub>0</sub>; mean precipitation, P; crop coefficient, K<sub>c</sub>; maximum and minimum temperatures, T min and T max; effective sun hours per day, hs; net solar radiation on the crop surface, Rn; and relative humidity, RH.

Water requirements														
MONTH	ET <sub>0</sub> (mm month <sup>-1</sup> )	P (mm month <sup>-1</sup> )	Pe (mm month <sup>-1</sup> )	Kc	Kr	ETc (mm month <sup>-1</sup> )	ETc-Pe (mm month <sup>-1</sup> )	Rm (mm month <sup>-1</sup> )	Rd (mm)	RN (m <sup>3</sup> ha <sup>-1</sup> month <sup>-1</sup> )	RN (L plant <sup>-1</sup> day <sup>-1</sup> )	RB (L plant <sup>-1</sup> day <sup>-1</sup> )	RB (m <sup>3</sup> ha <sup>-1</sup> day <sup>-1</sup> )	
JANUARY	31.00	61.00	42.70	0.50	0.65	10.07	-32.63	32.63	90.17	0.00	0.00	0.00	0.00	
FEBRUARY	44.80	50.00	35.00	0.50	0.65	14.55	-20.45	20.45	110.62	0.00	0.00	0.00	0.00	
MARCH	77.50	64.00	44.80	0.65	0.65	32.72	-12.08	12.08	122.71	0.00	0.00	0.00	0.00	
APRIL	111.00	46.00	32.20	0.65	0.65	46.86	14.66	0.00	131.71	236.57	76.31	94.22	9.42	
MAY	145.70	43.00	30.10	0.65	0.65	61.51	31.41	0.00	123.96	236.57	76.31	94.22	9.42	
JUNE	186.00	18.00	12.60	0.50	0.65	60.40	47.80	0.00	99.82	236.57	76.31	94.22	9.42	
JULY	223.20	3.00	2.10	0.50	0.65	72.48	70.38	0.00	53.10	236.57	76.31	94.22	9.42	
AUGUST	198.40	5.00	3.50	0.50	0.65	64.42	60.92	0.00	15.83	236.57	76.31	94.22	9.42	
SEPTEMBER	135.00	25.00	17.50	0.65	0.65	56.99	39.49	0.00	0.00	236.57	76.31	94.22	9.42	
OCTOBER	83.70	52.00	36.40	0.65	0.65	35.33	-1.07	1.07	0.00	0.00	0.00	0.00	0.00	
NOVEMBER	48.00	62.00	43.40	0.65	0.65	20.26	-23.14	23.14	24.20	0.00	0.00	0.00	0.00	
DECEMBER	31.00	62.00	43.40	0.50	0.65	10.07	-33.33	33.33	57.54	0.00	0.00	0.00	0.00	
Total annual	1315.30	491.00	343.70			485.64	264.65		122.71	1419.45	1419.46		1724.14	
				Verowen (m3) =	10439.82					PEL =	142.50			
				Scrowen (m2) =	32.47									

**Figure 3.** Crop water requirement worksheet. Reference evapotranspiration, ET<sub>0</sub>; mean precipitation, P; effective precipitation, Pe; crop coefficient, Kc; crop growth coefficient, Kr; evapotranspiration of the crop, ETc; soil water reserve, Rm; available water to the plants, Rd; permissible exploitation level, PEL; net irrigation requirement, RN; gross irrigation requirement, RB. Data corresponding to 2006.

ha<sup>-1</sup> year<sup>-1</sup>, while, with a conservative approach, assuming that there is a support irrigation system, an olive grove of 1-ha gives an average annual production of 5,000 kg (2.5 times more than a dry hectare). The price of olives for pressing is 0.60 € kg<sup>-1</sup> in Spain, including subsidies, so the guaranteed profit, when switching from dry to irrigated land is 1,800 € ha<sup>-1</sup> year<sup>-1</sup>.

## Results and discussion

### Calculation program

The overall summary data (Figure 5) contains information regarding the installation location, area to be irrigated, and irrigation values that were chosen or calculated. At this point, some information can be modified and new values recalculated. The number of photo-

voltaic panels to be installed and the corresponding coverage is shown, and a pump is chosen according to the required power. The number of panels can be changed and, if so, new values recalculated.

### Installation data

Location	Badajoz
Longitude	6.58 W
Latitude	38.53 N
Altitude	198 m
Area (ha)	10
Tree number ha <sup>-1</sup>	100
Mean Eto (mm day <sup>-1</sup> )	109.61
Mean Precipitation (mm day <sup>-1</sup> )	40.92
Mean Kc	0.58
Mean Kr	0.65
Wp panel <sup>-1</sup>	110

### Design characteristics

#### Drip Irrigation

Drip irrigation system							
G (drip/tree)	Qg (L h <sup>-1</sup> )	No (Sectors)	TRs (h sector <sup>-1</sup> )	TRd (h day <sup>-1</sup> )	SR (ha)	Qt (L s <sup>-1</sup> ha <sup>-1</sup> )	
4	2	1	11.8	11.8	4.5	0.22	
	2	2	11.8	23.6	9.0	0.11	
	4	2	5.9	11.8	4.5	0.22	
	4	3	5.9	17.7	6.8	0.15	
	4	4	5.9	23.6	9.0	0.11	
	6	3	3.9	11.8	4.5	0.22	
	6	4	3.9	15.7	6.0	0.17	
	6	5	3.9	19.7	7.5	0.13	
	6	2	7.9	15.7	6.0	0.17	
	6	2	7.9	23.6	9.0	0.11	
6	4	3	3.9	11.8	4.5	0.22	
	4	4	3.9	15.7	6.0	0.17	
	4	5	3.9	19.7	7.5	0.13	
	4	6	3.9	23.6	9.0	0.11	
	6	5	2.6	13.1	5.0	0.20	
	6	6	2.6	15.7	6.0	0.17	
	6	8	2.6	21.0	8.0	0.13	
					RB day max =	94.2	L plant <sup>-1</sup> day <sup>-1</sup>
					RB day max =	9.42	m <sup>3</sup> ha <sup>-1</sup> day <sup>-1</sup>
					RB annual =	1724.14	m <sup>3</sup> ha <sup>-1</sup>

**Figure 4.** Design of the drip irrigation system: number of drippers per tree, G; drip flow rate, Qg; irrigation time per sector, TRs; total irrigation time, TRd; irrigated surface, SR; flow rate per hectare, Qt; gross irrigation requirement, RB.

#### Photovoltaic system

Power (kWp)	1.43
Number of panels	18
Coverage degree	102%
Pump power (kW)	0.6

**Figure 5.** Design characteristics of the drip irrigation and photovoltaic systems.

In the example, for an area (10 ha) with 100 olive trees per ha in Badajoz, four drippers, with a water flow of 2 L h<sup>-1</sup> each, can be installed per olive tree and two irrigation sectors can be established. The annual crop water requirement of 1,724.14 m<sup>3</sup> ha<sup>-1</sup> was calculated and the peak power of the photovoltaic generator estimated to be 1.43 kW. In these conditions, a photovoltaic installation should be built with 18 solar panels of 110 Wp each, with a coverage degree of 102% and a submersible pump of 0.6 kW capacity.

The procedure described in this paper is versatile, user-friendly and sizes both the irrigation installation and the photovoltaic pumping, so it is not necessary to be an irrigation specialist to use it, making it valid for installers, project designers and farmers. The method involves the link between the separate existing knowledge on photovoltaic pumping and the water requirements to irrigate a crop. In this sense, the worksheet incorporates a new methodology because there is not references on studies connecting both technologies.

The photovoltaic installations have some important advantages over conventional generator units that use fossil fuel. They require very low maintenance, have long average lifespan (up to 40-50 years, although the manufacturer, *e.g.* www.technosum.com, gives a guarantee of 20 years), low amortization period (around 5-6 years), and similar cost to that of a generator unit (without requiring fuel). However, their power should be adjusted through the worksheet due to the high cost of the photovoltaic installation.

The aims of generating wealth in agricultural regions and reducing the use of highly pollutant fossil fuels, which are becoming more and more expensive, are implicitly included. Producing more work and sustainable development opportunities in rural areas is one outcome.

Some further considerations are:

a) The workbook may be applied to any crop located anywhere. For example, in Southern Spain, where there is an abundance of sun, olive groves and vineyards, which are very important from economic, environmental and social perspectives, can be irrigated using solar-powered installations. Obviously, in these cases, it would be necessary to find the appropriate  $K_c$  and  $K_r$  coefficients, besides the climatic and soil characteristics of the studied area.

b) The accurate determination of  $K_c$  and  $K_r$  for different crops is an important task, for which in-depth research is required, given the importance of these parameters in the irrigation schedule and the size of the

photovoltaic installations, and therefore, the cost (Figure 6).

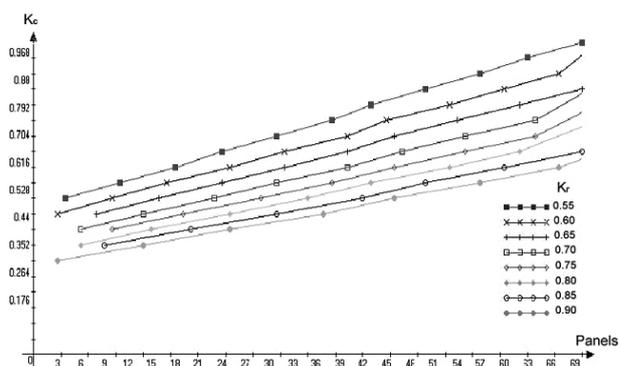
c) When a traditional olive grove begins to be irrigated, the tree crown volume increases considerably and consequently, the value of  $K_r$  will not stabilize until several years after installing the irrigation equipment. This must be taken into account to properly design the installation, in view of the sensitivity that  $K_r$  has on the dimensions and power. This consideration is also important for other crops.

### Study of economic viability

To ascertain what would be the most profitable installation, two options are proposed to be compared: 1) electric energy supplied by a generator unit; 2) electric energy supplied by a photovoltaic installation.

Thus, if a generator unit is used, its power should be 1.5 kW at least, taking into account the requirements to start the pump. Petrol units are the only ones with such a low power level, rotating at 3,000 rpm, unusable for a continuous work (they have to be cooled every 2 or 3 hours). Therefore, petrol units at 1,500 rpm or diesel units at 3,000 rpm should be used, being the lowest power in both cases 3.2 kW (www.imbasa.com). The diesel unit is preferred, which price is €3,476 (similar to the 1.5 kW petrol unit at 3,000 rpm; thus, the economic study will not be affected due to this reason).

However, it should be taken into account that, as well as the purchase of the unit and the fuel costs, there are other costs of lubricating oil and equipment maintenance. Furthermore, these motors suffer breakdowns, which contribute to increase the price of water unit that is pumped.



**Figure 6.** Variation in the number of solar panels used in the study (110 Wp each), depending on the crop and the crop growth coefficients ( $K_c$  and  $K_r$  respectively).

**Table 1.** Economic and power variables assumed in the study for the electric and photovoltaic generators

Variables	Electric generator	Photovoltaic generator
Total capital investment, €	3,476	10,500
Average diesel consumption, L h <sup>-1</sup>	0.8	-
Diesel oil price, € L <sup>-1</sup>	1	-
Maintenance cost, €	347	-
Pump power, kW	0.57	0.57
System power, kW	3.2	1.5

Usually, the maintenance costs are considered to be 10% of the total capital investment, *TCI*, that is, €347 in this study.

The diesel motor has an average life of 10,000 hours (García-Araque, 2000). If the motor is operating for an average of 7 hour day<sup>-1</sup> and 7 month year<sup>-1</sup>, as it was indicated before, the average life of this motor would be less than 7 years. At the end of this time another one would have to be purchased, or the existing one would have to undergo extensive.

With regard to the photovoltaic generator option, the cost of installing 1 kWp of photovoltaic power is around 7,000 € kWp<sup>-1</sup>, including the price of the inverters, regulators, batteries, etc. (ASIF, 2007). Therefore, the irrigation of a hectare of olive trees in Tierra de Barros, with 50 m pumping height, will cost 10,500 € ha<sup>-1</sup> (1.5 kW ha<sup>-1</sup> x 7,000 € kWp<sup>-1</sup>), which would be paid entirely at the beginning of the irrigation installation. There are also subsidies for these types of installations in all European countries (IDAE, 2005).

Table 1 shows the economic variables for an average project life of 25 years, which is established by the manufacturers of solar panels and electronic elements as the time period without efficiency losses (ASIF, 2007), and 6% annual interest rate. Table 2 shows the economic indices, for the electric generator or the alternative photovoltaic generator, calculated from the variables of Table 1. According to Table 2, the net present value, *NPV*, is higher, and the internal rate of return, *IRR*, is lower for the the photovoltaic generator, being similar the payback time, *PBT*, for both alternatives, which determines that the photovoltaic installation is more profitable than the electric generator.

The profitability achieved through the integration of irrigation technology and photovoltaic pumping, optimising the efficiency of both systems, is finally demonstrated.

**Table 2.** Economic indices for the electric and photovoltaic generators. *TCI*, total capital investment (€); *NPV*, net present value (€); *IRR*, internal rate of return (%); *PBT*, payback time (yr)

Technology	TCI	NPV	IRR	PBT
Electric generator	3,476	11,019	38	3.00
Photovoltaic generator	10,500	28,094	28	3.38

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