Available online at www.sciencedirect.com

SCIENCE DIRECT®

ELSEVIER

Solar Energy 76 (2004) 465–473

SOLAR ENERGY

www.elsevier.com/locate/solener

A procedure to size solar-powered irrigation (photoirrigation) schemes

Francisco Cuadros [a,*], Fernando López-Rodríguez [b], Alfonso Marcos [b], Javier Coello [c]

[a] *Dpto de Física, Universidad de Extremadura, Avda de Elvas s/n, 06071 Badajoz, Spain*
[b] *Dpto de Expresión Gráfica, Universidad de Extremadura, Avda de Elvas s/n, 06071 Badajoz, Spain*
[c] *Universidad Agraria "La Molina", Lima, Peru*

Received 28 October 2002; received in revised form 6 August 2003; accepted 6 August 2003

Communicated by: Associate Editor Jean Rosenfeld

Abstract

The high cost of photovoltaic solar power makes it necessary, before undertaking any subsequent study, to dimension photovoltaic installations as accurately as possible. We here present a procedure to estimate the required dimension of a photovoltaic installation designed to power a pumping system for the drip irrigation of an olive tree orchard in SW Spain. The method consists of three main stages: (1) One determines the irrigation requirements of the specific estate according to the characteristics of its soil-type and climate. (2) A hydraulic analysis of the pumping system is made according to the depth of the aquifer and the height needed to stabilize the pressure in the water distribution network. (3) Finally, one determines the peak photovoltaic power required to irrigate a 10 ha sub-plot of the estate taking into account the overall yield of the photovoltaic-pump-irrigation system.

We call this arrangement "photoirrigation", and believe that it may be of great utility to improve the output of such socially significant crops as olives and wine grapes, optimizing the use of water and solar energy resources at the same time as preserving the environment.

Keywords: Solar energy; Irrigation; Photoirrigation; Olive tree orchard production

---

1. Introduction

Today's excessively high market prices of photon capture devices makes it necessary to correctly dimension photovoltaic (PV) solar power installations before initiating any subsequent study of their performance in a given application. i.e., one must determine the power requirements for a specific application accurately in order to make the cost of the installation profitable in as short a time scale as possible.

One of the most promising applications of PV solar power, especially in countries such as Spain which have very high levels of solar radiation, is for pumping the water needed to irrigate certain crops. There is a large bibliography on the subject—see, for instance, Handbook on Solar Water Pumping, 1984; Stand Alone Photovoltaic Systems. A Handbook of Recommended Design Practices, 1993; Alonso and Chenlo, 1994—that contain detailed studies of the application of solar PV for pumping water both in agricultural and domestic use. There is also extensive bibliography on irrigation technology—see, for instance, www.fao.org, 2003; Doorenbos and Pruitt, 1997; Allen et al., 1998—that discuss appropriate methods to estimate water requirements for a given crop in a given place. On the other hand it is rather difficult to find references on systematic

---

[*] Corresponding author. Tel.: +34-924-289541; fax: +34-924-289651.

E-mail address: cuadros1@unex.es (F. Cuadros).

0038-092X/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/j.solener.2003.08.040

studies connecting both technologies which, for the want of a better word, we call photoirrigation.

The main objective of this work is to present what we believe is a novel, simple, procedure to estimate the design requirements of a photovoltaic system to power the drip irrigation (photoirrigation) of an olive tree orchard in SW Spain. This is based on the separate existing knowledge on photovoltaic pumping and on the water requirements of the crop. We have specifically addressed the requirements of an olive tree orchard in the region of Tierra de Barros near de town of Badajoz, Spain.

For the connection between the irrigation system and PV solar-powered pumping equipment to be energetically and economically efficient, the following points have to be taken into account. (i) Efficient use must be made of the water resource, i.e., only the amount of water needed for the crop should be raised. This amount should, in turn take into account the soil's rainwater retention capacity during the wet season; (ii) this amount of water should be raised to the minimum height above ground level needed to stabilize the pressure at the irrigation heads; and (iii) the most efficient irrigation system for that particular crop should be adopted. In the case of olives, it has been shown (Pastor, 1999; Pastor et al., 2000) that drip irrigation is the most efficient technique, preferentially with buried emitters.

Our aim is to introduce a procedure for the design of a PV pumping installation that takes the above criteria into account, in order to make the system economically profitable in as short a time as possible. Subsequently, it may be necessary to evaluate olive production in a specific grove with one sector left without irrigation and another with irrigation—with buried and surface emitters—, so as to quantify and compare the yields in the different cases.

This study was developed taking as a basis the climatic and soil-type parameters of an olive tree orchard in Extremadura (Spain). Extremadura is an Autonomous Region of SW Spain, consisting of the provinces of Cáceres and Badajoz, with an area of 41 636 km^2. It has borders with Andalusia on the south, with Portugal on the west, with Castille-Leon on the north, and with Castille-La Mancha on the east. The climate may be described as Mediterranean-continental, with mild winters, and two rainy seasons, one in spring and the other in autumn.

Olive production plays a major role in the wealth of Extremadura, not only in the farming sector, but also socially, environmentally, etc. The area of the region devoted to olives is around 238 000 ha, approximately 13% of the Spanish total (Anuarios Estadísticos de Extremadura, 1988–1994). In recent years the crop has become the second revenue earner of Extremadura.

Olive producing areas are in general socially and environmentally very sensitive. Olive plantations represent one of the few viable options for generating wealth, reducing rural depopulation, and preventing erosion. The olive tree has adapted itself perfectly to Mediterranean environments since it has a great resistance to prolonged droughts. Nonetheless, recent years have seen the introduction of irrigation in olive groves, especially in southern Spain, attaining considerable increases in olive production.

Most olive groves in Extremadura are still dry-land managed. In the few estates that have installed irrigation, the pumps are powered by contaminating electricity generators, and management follows the same routines as in the traditional dry-land production, so that productivity has not been ideal (Corraliza, 1998).

Several experiments (Solé, 1994; Pastor et al., 1997) have shown that olive grove irrigation, even at rates which are relatively small compared to those used for other crops, can raise olive production, in some cases by a factor of six compared to the dry-land output.

In places such as Extremadura, with abundance of sun and a water demand that is not excessively high—from 50 to 2000 m^3 day^{-1} for drip irrigation—pumping by solar power is a viable, competitive, and environmentally recommendable option (Handbook on Solar Water Pumping, 1984; Stand Alone Photovoltaic Systems. A Handbook of Recommended Design Practices, 1993; Alonso and Chenlo, 1994; Orellana and Zanga, 1996).

The aim of introducing photoirrigation into Extremadura's olive groves is to increase their productivity, and hence to allow the economic development of extensive rural zones of our Region, avoiding migration from these zones to the cities or to other Autonomous Regions of Spain. Under drip irrigation, the practice of "partial tilling", with its anti-erosion advantages, would be further justifiable since competition for the water from weeds would be minimized. Furthermore, the EU is vigorously encouraging the use of renewable, autonomous, non-contaminating energy resources (Comisión Europea, 1997).

The method presented here is likely be applicable to other crops and other regions of the world. As we discuss below, the crop water requirements (CWR) for a given zone of the Earth may be determined from the geographical coordinates and the soil-type characteristics of the estate in which irrigation is planned. Thus, the power needs may be calculated by taking into account the pumping height and the overall yield of the installation. It will be shown in the following sections that follow-up studies will be needed to fine-tune the procedure, and to determine more precisely the water and power demands of a given crop.

2. Olive grove irrigation technology

If the soil's 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 which is particularly important in semi-arid climates such as ours (Pastor et al., 1997). This evaporation basically depends on meteorological factors and soil-type characteristics. The sum of the water consumed by the plant in transpiration and evaporated from the soil is called the evapotranspiration (ET) of the crop, and must be wholly satisfied by rainfall and/or irrigation for the crop's potential production not to be affected. This is the most important variable to take into account in planning an irrigation strategy for a given crop in a given climatic regime (Pastor et al., 1997; Allen et al., 1998; www.fao.org, 2003; www.infoagro.com, 2003.

The calculation of ET is the first step towards establishing the CWR. The method most often used is that recommended by the FAO (Doorenbos and Pruitt, 1997) in which the crop's evapotranspiration (mm month^{-1}) is calculated as the product of three factors:

$$\mathrm{ET} = \mathrm{ET_o} K_c K_r, \tag{1}$$

where $\mathrm{ET_o}$ is the reference evapotranspiration (mm month^{-1}) which essentially depends on the site's climate, K_c is the crop coefficient characterizing the type of crop being dealt with, and K_r is the so-called growth coefficient of the crop, which takes into account the percentage of terrain covered by the shade of the tree.

The factor $\mathrm{ET_o}$ can be determined experimentally using balance evapotranspirometers or drainage lysimeters. These procedures are, however, difficult and costly, so that the indirect estimation of $\mathrm{ET_o}$ on the basis of empirical formulae is still widely used. In 1990, in Rome, FAO in collaboration with the World Meteorological Organization organized a meeting of experts to evaluate different methods for the calculation of $\mathrm{ET_o}$. The recommendation that came from this meeting was the FAO–Penman–Monteith equation for the reference evapotranspiration (Smith et al., 1996).

To calculate $\mathrm{ET_o}$ from the FAO–Penman–Monteith equation, one can use the program Cropwat version 7 for MS-DOS developed by the FAO's Water and Land Development division. Cropwat uses climate data from the Climwat database, which includes 3262 meteorological observatories in 144 countries.

Introducing the data for Badajoz's meteorological observatory (38.53 N, 6.58 W, 198 m a.s.l.), we obtain from Climwat the climatic data for Badajoz for each month of the year. The program Cropwat then calculates automatically the reference evapotranspiration values, $\mathrm{ET_o}$ (Table 1).

The next step is to calculate the coefficients K_c and K_r. There are not, as yet, any specific data for these coefficients for olive groves in the Extremadura Region. That will be the subject of a future study which will also include a determination of the olive yields under different irrigation regimes. We shall therefore use the values of K_c calculated by Orgaz et al. (1996) for the province of Córdoba—0.50 in winter, 0.55 in summer, and 0.65 in autumn and spring. The choice of the values used for K_c merits further discussion. We believe that the values of K_c used in a olive tree orchard in the province of Córdoba may be used to estimate the irrigation requirements of a olive tree orchard in the

Table 1
Climate data for the meteorological observatory of Badajoz, Spain (38.53 N, 6.58 W, 198 m a.s.l.), and calculation of the reference evapotranspiration ($\mathrm{ET_o}$) for that site using the FAO–Penman–Monteith method

Month	T_{MIN} (°C)	T_{MAX} (°C)	HR (%)	U_2 (km day^{-1})	n (h)	Rn (MJ m^{-2} day^{-1})	$\mathrm{ET_o}$ (mm day^{-1})
January	4.4	13.1	81	147	4.9	8.0	1.0
February	5.1	15.2	76	164	6.1	11.2	1.6
March	7.5	17.9	72	181	6.0	14.3	2.5
April	9.6	21.1	64	181	8.6	20.4	3.7
May	11.9	24.3	62	190	9.5	23.4	4.7
June	15.7	30.2	54	199	11.6	27.0	6.2
July	17.8	34.1	50	207	12.6	27.9	7.2
August	17.9	33.3	50	190	11.5	24.8	6.4
September	16.2	29.7	56	156	8.9	18.7	4.5
October	12.3	23.5	66	138	6.9	13.0	2.7
November	8.0	17.5	75	147	5.2	8.7	1.6
December	5.1	13.5	82	147	4.5	7.0	1.0
Average	11.0	22.8	66	171	8.0	17.0	3.6

Here: T_{MIN}, mean monthly minimum temperature; T_{MAX}, mean monthly maximum temperature; HR, Monthly relative humidity; U_2, wind speed at 2 m height; n: average hours of sun; Rn, net radiation at the surface of the crop; $\mathrm{ET_o}$, reference evapotranspiration. Source: Food and Agriculture Organization of the United Nations (FAO).

province of Badajoz, as both provinces are next to each other. However, the values of K_c given by Orgaz et al. (1996) were obtained using values of ET_o calculated by using the equation FAO–Penman. On the other hand we evaluated for this work the monthly values of ET_o using the FAO–Penman–Monteith equation. Comparing both sets of values shows an important difference. Gavilán and Berengena (2000) found an average difference between both values of 22% for the olive irrigation period in the mid valley of the Guadalquivir, namely where the province of Córdoba is sited, while Jensen et al. (1990) find this difference to be around 19% for arid regions. The importance of using an adequate method to compute ET_o for a particular set of K_c values is mentioned elsewhere, for instance, in Casa et al. (2000). Consequently, taking into account the proximity between the provinces of Badajoz and Córdoba, and the results of Gavilán and Berengena (2000), we assume that in our case the values of Et_o calculated by using the equation FAO–Penman are over estimated by 22% as compared with those obtained by using the FAO–Penman–Monteith equation. From Eq. (1) we find that, if ET_o has been over estimated, then the value of K_c is under estimated in the same proportion. Whence we are assuming that the values reported by Orgaz et al. (1996) are under estimated by 22% as compared with the values that would be obtained if the FAO–Penman–Monteith equation was used. Whence we use in this work the values given by Orgaz et al. (1996) but increased by 22%. The latter are referred as K′c in Table 2.

For the values of K_r, we use those obtained from experiments carried out in the province of Jaén—0.40–0.50 in dry-land conditions, increasing to typical values of 0.65–0.70 after several years of irrigation when tree size and output have adapted to the new productive setting (Orgaz and Fereres, 1998).

In irrigation, it is fundamental to take both the climate and the soil-type characteristics of each zone into account in deciding on the strategies and scale to use. Water stored in the soil during the rainy season can be used by the crop in the dry season. How much water can be stored depends on the depth and water retention capacity of the soil and on the rainfall (Orgaz et al., 1996).

During the rainy season, the effective precipitation, Pe, is greater than the evapotranspiration so that the soil's water reserves are replenished. The effective precipitation is defined as the amount of rainfall usable by the plant. It us usually calculated as a fraction of the total precipitation, Pr. For most olive-growing areas of Spain, the recommendation is to take the value of 70% of the mean monthly total rainfall (Orgaz and Fereres, 1998). The monthly reserve of water in the soil, Rm ($\text{mm}\,\text{month}^{-1}$), may be determined by means of the water balance of the wet months:

$$R_m = \text{Pe} - \text{ET}. \tag{2}$$

The sum of the monthly water reserves accumulated during the rainy season indicates the soil's water content at the beginning of the dry season. Only a part, Rd, of this content is available to the plants, and this cannot exceed the permissible exploitation level, PEL, of the soil, $R_d \leqslant \text{PEL}$. In the case of olive trees, Orgaz and Fereres (1998) propose the following expression for PEL:

$$\text{PEL} = 0.75 \cdot Z_r \cdot (\text{CC} - \text{PWP}), \tag{3}$$

where Z_r is the mean depth reached by the roots (estimated at 1000 mm), CC is the field carrying capacity, and PWP is the permanent wilting point.

We applied the photoirrigation method to the "Vega Toro" estate in the area of Tierra de Barros, some 50 km from the city of Badajoz. The topography is one of gentle hills, and in the substrate limestones predominate over intrusive acidic rocks. The soil is of the Rhodoxeralf type, somewhat mineralized, with a medium level of organic matter content and a good cation exchange capacity. The carbon/nitrogen ratio is around 10, indicative of intense biological activity. The soil has a loamy texture, and a great water retention capacity due to its depth, although it also has sufficient internal drainage. Such soils are well suited for olive growing, since they are deep, clayey, with no coarse elements on the surface, and well drained. The olive varieties grown on the estate are Carraqueños (50%) and Verdial (50%), in a $10 \times 10\ \text{m}^2$ grid. These varieties are perfectly adapted to the climate and the quality of the soils.

The recommended values (Orgaz and Fereres, 1998) for the Vega Toro loamy soil are $\text{CC} = 0.36$ and $\text{PWP} = 0.17$. Eq. (3) then gives the value $\text{PEL} = 142.5$.

The evapotranspiration for the crop, ET, as noted above, may be split up into two factors—the evaporation from the soil, E, and transpiration from the crop, T. The technique of drip (or localized) irrigation in comparison with furrow irrigation only wets a fraction of the soil, so that the value of E will be smaller and there will be a saving in water use. However, there will also be a greater level of transpiration since, as only a fraction of the soil is wet, there will be a greater heating of the surface (and hence of the air above it), so that the soil will emit more long-wave infrared radiation. Part of this radiation is captured by the leaves of the tree, leading to an increase in transpiration. Nevertheless, the net balance ($\text{ET} = E + T$) is clearly favourable to drip irrigation, especially if the trees are young and broadly spaced—the present case with the olive trees. Indeed, the main characteristic of drip irrigation is its savings in water. Its efficiency reaches 90%, as against 70% for sprinkler systems, and 40% for furrow irrigation. In today's world, with water scarcity an ever greater

Table 2
The irrigation schedule for the olive grove of the Vega Toro estate

Month	ET$_o$ (mm month^{-1})	Pr (mm month^{-1})	Pe (mm month^{-1})	K_c	K'_c	K_r	ET (mm month^{-1})	ET − Pe (mm month^{-1})	Rm (mm month^{-1})	Rd (mm)	NIR (m^3 ha^{-1} month^{-1})	NIR (l tree^{-1} day^{-1})	GIR (l tree^{-1} day^{-1})
January	31.0	61.0	42.7	0.50	0.61	0.65	12.3	−30.4	30.4	80.3	0.0	0.0	0.0
February	44.8	50.0	35.0	0.50	0.61	0.65	17.8	−17.2	17.2	97.5	0.0	0.0	0.0
March	77.5	64.0	44.8	0.65	0.79	0.65	39.8	−5.0	5.0	102.5	0.0	0.0	0.0
April	111.0	46.0	32.2	0.65	0.79	0.65	57.0	24.8	0.0	116.5	388	129	161
May	145.7	43.0	30.1	0.65	0.79	0.65	74.8	44.7	0.0	110.6	388	129	161
June	186.0	18.0	12.6	0.55	0.67	0.65	81.0	68.4	0.0	81.0	388	129	161
July	223.2	3.0	2.1	0.55	0.67	0.65	97.2	95.1	0.0	24.7	388	129	161
August	198.4	5.0	3.5	0.55	0.67	0.65	86.4	82.9	0.0	0.0	388	129	161
September	135.0	25.0	17.5	0.65	0.79	0.65	69.3	51.8	0.0	0.0	388	129	161
October	83.7	52.0	36.4	0.65	0.79	0.65	43.0	6.6	0.0	0.0	388	129	161
November	48.0	62.0	43.4	0.65	0.79	0.65	24.6	−18.8	18.8	18.8	0.0	0.0	0.0
December	31.0	62.0	43.4	0.50	0.61	0.65	12.3	−31.1	31.1	49.9	0.0	0.0	0.0
Annual total	1315.3	491.0	343.7				615.5	374.3	102.5				

Here ET$_o$ is the reference evapotranspiration, Pr the mean annual rainfall, Pe the effective rainfall, K_c the crop coefficient reported by Orgaz et al. (1996), K'_c is the corrected value used in this work, K_r the crop's growth coefficient, ET the crop's evapotranspiration, Rm the monthly reserve of water in the soil, Rd the monthly available reserve of water $\leqslant$ the permissible exploitation level (PER), NIR the net monthly or daily irrigation, and GIR the gross daily irrigation.

problem, efficient water use is a factor of prime importance in proposing irrigation systems.

Irrigation schedules have to be adapted every year to the particular conditions of each soil type (Pastor et al., 1997). In no case should one dictate general norms for all of the olive-growing areas of a river basin, since small changes in the design variables can give rise to a large variation in the estimates of water requirements (Rojas et al., 1996).

A first strategy that is customarily applied in scheduling irrigation for other crops is to apply an amount equivalent to the difference (ET − Pe) during dry periods in which ET is greater than Pe (Pastor et al., 1997). This procedure, however, neglects the water stored in the soil during the months of water surplus, so that the soil would theoretically always be at capacity. It has the advantage that this "safety net" in water input may absorb any underestimate of the difference (ET − Pe) in dry years. But it has the drawback of wasting water, and of requiring high water flows (Orgaz and Fereres, 1998).

Another, more attractive, alternative is to use the available reserve accumulated during the rainy season—whose total annual value, ARm, is the sum of the Rm's—as a complement to irrigation during the dry season, so that the irrigation flow rates per ha will be minimized, as will be the power requirements. This will allow us to irrigate the largest area with a given available flow rate (Orgaz et al., 1996). In this case, the annual crop water requirement (ACWR) would be

$$\mathrm{ACWR} = A(\mathrm{ET} - \mathrm{Pe}) - \mathrm{ARm}, \tag{4}$$

where $A(\mathrm{ET} - \mathrm{Pe})$ is the annual total of the difference between the evapotranspiration, ET, and the effective precipitation, Pe.

Table 2 list the values of $A(\mathrm{ET} - \mathrm{Pe}) = 374.3$ mm, and of ARm = 102.5 mm. Thus ACWR = 271.8 mm. The irrigation requirements for the Vega Toro estate are therefore 2718 $\mathrm{m^3\,ha^{-1}\,year^1}$. If we divide these annual requirements by the number of months in which irrigation is necessary (April to October, as seen from Table 2), we find that the net irrigation requirements, NIR, are 38.8 $\mathrm{mm\,month^{-1}} = 388$ $\mathrm{m^3\,ha^{-1}\,month^{-1}}$. Given that there are 100 $\mathrm{trees\,ha^{-1}}$ and the number of days in each month, we can calculate the net irrigation requirements as 129 $\mathrm{l\,tree^{-1}\,day^{-1}}$ (Table 2). The gross irrigation requirement, GIR, for a drip irrigation scheme, taking into account the overall efficiency of the application, η_s, is

$$\mathrm{GIR} = \mathrm{NIR}/\eta_s. \tag{5}$$

The values of η_s recommended by Arviza (1996) are around 80–85%. Taking the least favourable value (80%), the gross irrigation requirement, GIR, given in the last column of Table 2, has a mean value of 161 $\mathrm{l\,tree^{-1}\,day^{-1}}$.

From the summary of the results for the scheduling of the Vega Toro estate's olive grove in Table 2, the available water reserve, Rd, is less than the soil's PEL.

With respect to the type of irrigation installation that we shall set up, all irrigated olive tree plantations currently opt for two emitters per tree. It has been shown experimentally, however, that production is raised noticeably by increasing this number, especially in dry years. The recommendation is to use from 4 to 6 emitters per tree.

For the field trials that we shall begin in the near future, we have chosen a 10 ha sub-plot of the estate. Since the irrigation requirement is 161 $\mathrm{l\,tree^{-1}\,day^{-1}}$, and the plantation density is 100 $\mathrm{trees\,ha^{-1}}$, the total water flow required for the sub-plot will be 161 $\mathrm{m^3\,day^{-1}}$. We shall use 4 emitters per tree, with a flow rate of 10 $\mathrm{l\,h^{-1}}$ each. The sub-plot will be divided into three sectors, with an irrigation time of 4 h for each sector. The total irrigation time will be 12 h each day. With this schedule, the necessary irrigation flow rate is 0.37 $\mathrm{l\,s^{-1}\,ha^{-1}}$.

3. Photovoltaic pumping technology

Due to the increase in population and to climatic factors, water resources are tending to become depleted in many parts of the world. It is in this context that one understands the need to pump water from wells and rivers.

A pumping system demand is defined as the product of the mean depth from which the water must be raised and the daily flow that is needed. The unit of measurement is $\mathrm{m^4\,day^{-1}}$.

Photovoltaic systems are especially designed to supply water and irrigation in areas where there is no mains electricity supply. Their main advantages over hand pumps or internal combustion engine pumps are their practically zero maintenance, their long useful life, that they do not require fuel, that they do not contaminate, and finally that they are straightforward to install. Another important characteristic is that, as they use the sun as their energy source, the periods of maximum demand for water coincide with the periods of maximum solar radiation. Their disadvantages are their high initial capital costs (as was mentioned in Section 1), and the variability of the yield of the solar panels according to the prevailing weather conditions, although this latter problem can be at least partially solved by storing the water in a cistern at a certain height.

Photovoltaic pumping systems consist of three principal components: the photovoltaic panels, a motor, and a pump. Depending on the design, a system may use storage batteries and a charge regulator. Batteries confer the advantage of working when the intensity of solar radiation is low (on cloudy days, or at dawn or dusk). Battery-less systems are, however, cheaper and simpler, needing practically no maintenance. In these cases, one usually employs raised cisterns to store the water's potential energy, and if drip irrigation techniques are used these cisterns serve also to regulate flow and pressure at the irrigation heads (Lorenzo, 1994). It is this last design that we shall be using in our field trials.

The motor has to be chosen according to the power requirement and the type of current one will be working with. If the motor uses AC, it will be necessary to install a DC/AC converter.

The daily hydraulic energy, E_H, required to pump a volume Q to an elevation H, is

$$E_H = \rho g Q H/3600, \tag{6}$$

in which E_H is expressed in W h day^{-1}, ρ is the density of water (1000 kg m^{-3}), g the acceleration due to gravity (9.81 ms^{-2}), Q the total daily flow of water which, as we calculated above, is 161 m^3 day^{-1}, and H the total pumping height. For the Vega Toro estate, the aquifer is at a depth of 10 m, to which we add another 10 m for the elevation of the cistern. Hence $H = 20$ m. Simplifying Eq. (6) then becomes

$$E_H = 2.725 \times 10^{-3} QH \ (\text{kW h day}^{-1}). \tag{7}$$

We now take into account: (i) energy losses due to friction of the water in the irrigation system, R; (ii) the fraction of the day during which solar radiation is above the threshold at which the pump starts to work $G_d(> G_{\text{threshold}})$; (iii) the yield, μ_G, of the photovoltaic generator; (iv) the yield, μ_I, of the AC/DC converter; and (v) the yield, μ_{MB}, of the pump. Then the maximum energy required from the photovoltaic generator, E_{el}, will be:

$$E_{el} = (E_H + R)/(G_d(> G_{\text{threshold}})\mu_G \mu_I \mu_{MB}). \tag{8}$$

Acceptable optimized values of R are around 10% of E_H. With respect to the yields in the denominator of Eq. (8), Lorenzo (1994) gives the values: $G_d(> G_{\text{threshold}}) = 0.95$, $\mu_G = 0.85$, $\mu_I = 0.90$ and $\mu_{MB} = 0.43$. The product of these yields gives the overall yield of the generator-pump connection, which as a percentage is $\mu = 31.26\%$. The power, P_{el}, of the photovoltaic generator is

$$P_{el} = (E_{el}/h), \tag{9}$$

where E_{el} is the required electrical energy (kW h), and h the effective number of hours of sun per day (i.e., the number of hours in the day above a standard radiation level of 1000 Wm^{-2}). This is numerically equal to the mean daily value of the energy density at a given site (in kW h m^{-2}). For the present case, we took the solar radiation data corresponding to Badajoz city (the Vega Toro estate is at 50 km from the city) supplied by Spain's National Meteorological Service. Finally, we have to take into account the power losses when the panels are working at temperatures above the standard 25 °C. These may be taken to be approximately 10% of the P_{el}.The required peak photovoltaic power, P (kW p) will then be:

$$P = P_{el}(1 + 0.1). \tag{10}$$

Table 3 lists the values of all the variables that are involved in the connection between the pumping and photovoltaic systems. The results show that October is the month that requires the highest power. This was to be expected, since October is the month that has the fewest effective hours of sun, only about 3.8 h. If we want to secure water supply for the month of October as well, the scale of the photovoltaic installation should be around 8.93 kW p (see Table 3). This would make the photovoltaic installation almost prohibitively expensive. Hence we will design the installation taking into account the September results, which will need about 6 kW p of photovoltaic power. This way we secure the required power for the month of September and a shortfall of 33% for October. Such a reduction implies a reduction in irrigation during October. However such a reduction is not excessively dramatic if we take into account that the first rains normally fall in October.

Table 3
Daily effective hours of sun, h, during the irrigation months

Month	h (h day^{-1})	H (m)	Q (m^3 day^{-1})	E_H (kW h day^{-1})	R (kW h day^{-1})	E_{el} (kW h day^{-1})	P_{el} (kw)	P (kW p)
April	6.0	20	161	8.77	0.88	30.87	5.14	5.65
May	7.0	20	161	8.77	0.88	30.87	4.41	4.85
June	7.6	20	161	8.77	0.88	30.87	4.06	4.47
July	7.8	20	161	8.77	0.88	30.87	3.96	4.36
August	7.0	20	161	8.77	0.88	30.87	4.41	4.85
September	5.6	20	161	8.77	0.88	30.87	5.51	6.06
October	3.8	20	161	8.77	0.88	30.87	8.12	8.93

Total pumping elevation, H; gross daily irrigation rate, Q; hydraulic energy, E_H; friction losses in the conduit system, R; electrical energy required in pumping, E_{el}; electrical power required in pumping, P_{el}; peak required photovoltaic power, P.

4. Conclusions

This study is the first of a research line whose ultimate objective is to elaborate a computer program, that we shall call photoirrigation, to correctly and straightforwardly design a photovoltaic installation to power an irrigation pumping system for a given crop at a given site. Due to the high cost of PV systems, this study must be performed prior to the real installation at a given site, which will then be followed by a study to quantify the crop yields under different conditions with and without irrigation. This will only have to take into account the soil-type characteristics of the zone, the characteristics of the crop, and the pumping elevation. In this first work, we have described the procedure that we shall be following in these studies and that we have applied to a specific case for which we know the soil characteristics, and a specific crop, for which the characteristic parameters are well known for the neighbouring Region of Andalusia, although not for Extremadura. We therefore believe it is necessary to carry out further studies to determine with greater precision the value of the crop coefficients, K_c, and growth coefficients, K_r, in the case of olive groves, and of other types of socially significant crops in our region, such as, wine grapes.

We believe that the procedure described here could be of greatest use in scheduling irrigation strategies and in improving the production of these crops. The ultimate goal will be the creation of wealth in economically depressed regions, the avoidance of erosion and use of fossil fuels, etc. Summing up, the aim is to provide opportunities for work and sustainable development for the rural population.

The following conclusions may be drawn:

1. From the soil-type characteristic of the estate and the local climate conditions we have evaluated the optimal irrigation requirements for the months April–October. The result, averaged over these seven months in which irrigation is needed, was a total flow rate of 161 $m^3\ day^{-1}$ for a 10 ha sub-plot.

2. Taking into account the depth of the aquifer, the friction losses in the irrigation conduits, as well as the yields of all the components in the photovoltaic generator/pump system, the dimensions of the photovoltaic installation needed to supply the irrigation requirements until September of the 10 ha sub-plot on the estate, has been estimated as 6 kW p.

References

Allen, R., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration—guidelines for computingcrop water requirements. FAO Irrigation and Drainage, Paper 56, Rome.

Alonso, M., Chenlo, F., 1994. Testing results of PV pumping for stand alone installation. Paper presented to 12th European Photovoltaic Solar Energy Conference, Amsterdam.

Anuarios Estadísticos de Extremadura, 1988–1994, Mérida, Spain.

Arviza, J., 1996. Riego localizado, Universidad Politécnica de Valencia, Valencia, Spain.

Casa, R., Russell, G., Lo Cascio, B., 2000. Estimation of evapotranspiration from a field of linseed in central Italy. Agriculture and Forest Meteorology 104, 289–301.

Comisión Europea, 1997. Libro Blanco para una estrategia y un plan de acción comunitarios. Europa para el futuro: Fuentes de energía renovables, Brussels.

Corraliza, J.F., 1998. Informe sobre el sector olivarero del aceite de oliva y de la aceituna de mesa en Extremadura. Consejería de Agricultura y Comercio, Junta de Extremadura, Mérida, Spain.

Doorenbos, J., Pruitt, W.O., 1997. Guideline for predicting crop water requirements. FAO Irrigation and Drainage, Paper 24, Rome.

Gavilán, P., Berengena, J., 2000. Comportamiento de los métodos Penman–FAO y Penman–Monteith–FAO en el valle medio del Guadalquivir. Paper presented to XVIII Congreso Nacional de Riegos, Huelva, Spain.

Handbook on solar water pumping, 1984. IT Power Ltd. and Partners.

Jensen, M.E., Burman, R.D., Allen, R.G., 1990. Comparative performance of 20 ET estimation methods. In: Evaporation and Irrigation Water Requirements. ASCE, Manual No. 70.

Lorenzo, E., 1994. Electricidad solar. Ingeniería de los sistemas fotovoltáicos. Universidad Politécnica de Madrid, Madrid.

Orellana, R., Zanga, O., 1996. Bombeo fotovoltáico. Energía para el desarrollo, Bolivia.

Orgaz, F., Fereres, E., 1998. Riego. In: Barranco, D., Fernández-Escobar, R., Rallo, L. (Eds.), El Cultivo del Olivo. Consejería de Agricultura y Pesca de la Junta de Andalucía, Sevilla, Spain.

Orgaz, F., Pastor, M., Vega, M., Castro, J., 1996. Necesidades de agua del olivar. In: Pastor M. et al. (Eds.), Manejo del Olivar con Riego por Goteo. Consejería de Agricultura y Pesca de la Junta de Andalucía, Informaciones Técnicas 41/96, Sevilla, Spain.

Pastor, M., 1999. Riego en olivar de aceituna de almazara en Andalucía. Vida Rural, No. 90, July 1999.

Pastor, M., Castro, J., Vega, V., 1997. Programación de riego en olivar en Andalucía. Paper presented to VIII Simposium Científico-Técnico, Jaén, Spain.

Pastor, J.M., Hidalgo, J., Camacho, L., Martínez, A., Nieto, J., Arroyo, P., 2000. Mejora en la eficiencia del uso del agua: asesoramiento a regantes. Vida Rural, No. 115, October 2000.

Rojas, R., Roldán, J., Alcalde, M., Camacho, E., 1996. El riego del olivar en la provincia de Jaén: Programación de riegos. Ingeniería del agua. Universidad Politécnica de Valencia, Valencia, Spain.

Smith, M., Allen, R., Pereira, L., 1996. Revised FAO methodology for crop water requirements. Paper presented to ASAE International Conference on Evapotranspiration and Irrigation, San Antonio, USA.

Solé, M.A., 1994. Influencia del riego de auxilio por goteo con pequeñas dosis de agua en el olivar de las Garrigas (cv. Arbequina). Fruticultura Profesional 62, 24–36.

Stand Alone Photovoltaic Systems. A Handbook of Recommended Design Practices, 1993. Sandia National Laboratories.

www.fao.org, 2003.

www.infoagro.com, 2003.