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An analysis of photovoltaic irrigation system for olive orchards in Greece

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Abstract. Olive tree cultivation is of major importance in Greece. It has been proved that irrigation of olive orchards increases their production. The classic method followed is diesel pump irrigation. Since Greece favours high insolation the alternative of photovoltaic pumping is proposed. A case study for an olive orchard in Crete is studied with the two alternatives. The photovoltaic pumping system is a direct pumping system as olive trees tolerate even deficit irrigation and storage tank increases the cost. A comparison using the Life Cycle Costing method is proposed. Considerations about climate and economic conditions are taken into account and the study concludes with the profound advantage of the renewable system over the conventional one in strict economic terms.

1. Introduction

Olive trees were, traditionally, cultivated without artificial irrigation, exploiting rainfall conditions, even in the Mediterranean climate, characterized by low rainfall. However researchers [1] have shown that drip irrigation systems with a total discharge of 4000 to 9000 m^3 per ha, during the irrigation period, increased the yield by 30 to 52%. Irrigated olive trees apart from the higher production use less field area and demand increased fertilization. Consequently demand more energy than the traditional ones.

Greece is the third country in olive oil production and first in black olive production cultivating around 150 million of olive trees, comprising 87.21% of its tree cultivation. Their contribution to the local and national economy is of major importance.

The above mentioned characteristics of this cultivation underline the necessity of abundant energy for irrigation purposes with no grid topology limitation, thus call for solar energy which through photovoltaics is a well established practice since 1977 [2]. Greece is situated between 41^{o}45΄ and 34^{o}48΄north latitude with an average insolation of 4.56 kWh/m^2/day but ranging from 4.21 (lowest) to 6.61 (highest) during the irrigation period (April to September for olive trees), offering ideal conditions for solar energy utilisation.

The vast majority of off-grid irrigation systems in Greece use diesel pumps. However as the photovoltaic industry develops, photovoltaic module costs present a 22% annual cost reduction in the last few decades [3]. Meanwhile the unstable future of oil prices (significant rise between 1999-2008, ups and downs between 2009-2016) [4] and the possibility of bankruptcy in one third of gas and oil companies [5] does not support a stable future for diesel as a fuel. Already in 2013 ISES Solar World

Congress, R.Foster and Costa [6] presented case studies with great success in use of PV in water pumping applications with new technological innovations. Proving the economic viability of such a system tailored to the Greek climate, type of olive orchards and market environment will push the productivity and reduce the production cost in this sector. The aim of this paper is to prove that exists a viable solar solution for the irrigation of olive orchards as an alternative to a Diesel one.

2. System analysis

The system chosen is a direct pumping system that pumps directly the water to the distribution system avoiding the use of an elevated storage tank, which distributes the water exploiting the gravity.

The main components of a PV irrigation system are the power station (PV array, controller and possibly inverter) the pumping station (DC/AC motor, pump) and the distribution system (network, emitters) (figure 1). These three systems have to cooperate in the most efficient way to tackle the variable needs of olive trees in water. This is not as simple as it sounds, as the power source is variable and intermittent and the irrigation needs are also varying but not in the same mode. The storage tank could also act as a buffer, smoothing the time differences, however increasing the system cost and eliminating the flexibility (even the portability for small scale) of the system. For this reason a thorough analysis of the factors affecting the sizing of the system should follow.

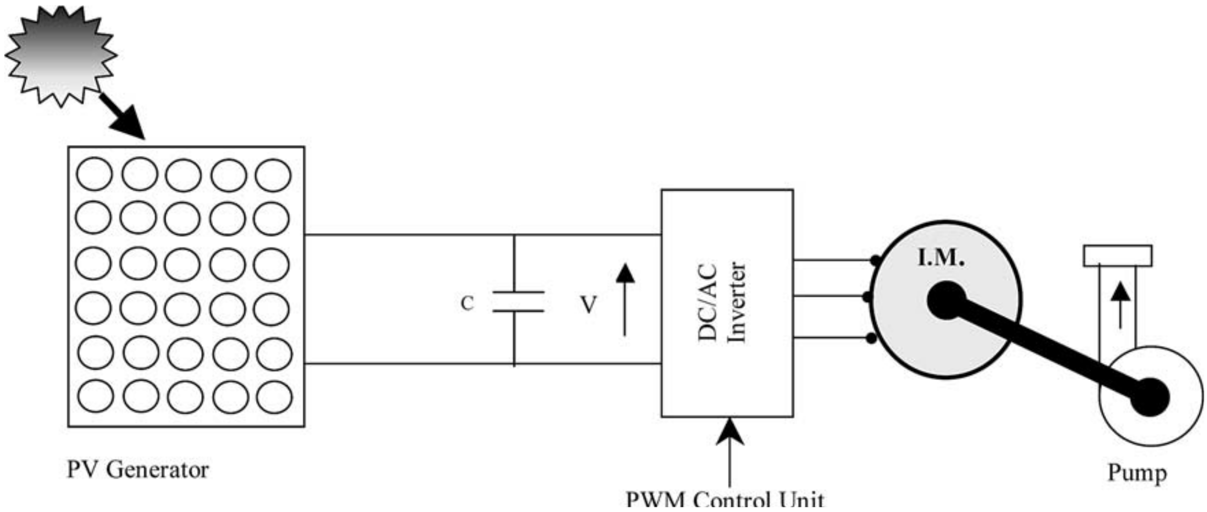

Figure 1 PV direct pumping system [7]

2.1 The distribution network

The most appropriate irrigation systems are the drip irrigation and the small water sprinklers system [1]. Drip irrigation is the most widely applied system and our research focuses on this system. In such a system two are the crucial parameters for network's proper operation: the total pumping head H and the volume of water pumped V. The total pumping head equals to the sum of static head which is the suction head (height from suction point till pump) and the discharge head (height from pump to storage inlet) and of dynamic head which is the frictional losses and the discharge pressure at the irrigating outputs (equation (1)). On the other hand the necessary volume of the water is calculated through a complicated process based on the crop evapotranspiration as proposed by FAO [8].

$$H = h_{stat} + h_{dyn} \qquad (1)$$

where

h_{stat} : the static head

h_{dyn}: the dynamic head which can be expressed as a function of the water volume V [9]

2.2 The pumping station

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Assuming that the amount of water for a certain day is known [8] the pump and consequently the motor, calls for the optimum operation (speed) which obviously is variable and thus an electronically variable speed pump is necessary. This kind of operation can best be met by variable speed AC motor as 3-phase asynchronous motor with a generic frequency inverter [7]. The produced electrical energy E should cover the hydraulic energy E_h taking into account the pumping station efficiency η_{ps} (equation (2)),

$$E = E_h \ \eta_{ps} \qquad (2)$$

the hydraulic energy for a certain day is given by the following equation

$$E_h = H \, V \rho \, g \qquad (3)$$

where
ρ: water density
g: standard gravity

2.3 The power station
Obviously the sizing of the power station has to satisfy the amount of energy E, thus the energy produced by the photovoltaic system has to match that amount. However the PV array energy production depends on parameters related to the array and on climate conditions, mainly insolation. The variability of the weather conditions and size optimization demands the use of a maximum power point tracker (MPPT). In order to minimize the cost of PV system, we have chosen a non sun-tracking system with a tilt equal to the local latitude

3. Economic analysis
The methodology chosen to evaluate the feasibility of the direct pumping PV system over a Diesel one takes into account all parameters affecting on these systems such as; capital cost of the components, installation, structures, fuels, operating and maintenance (O&M) costs.

The method of the Life Cycle Costing (LCC) is widely used to evaluate the financial viability of a system [11, 12, 13]. To evaluate the LCC of a photovoltaic system of water pumping the period of analysis is supposed to be 25 years.

The life-cycle cost of a solar PV system consists of the initial capital investment C_0 and the present value of operation and maintenance costs OM_{pv}.

$$LCC_{PV} = C_{0PV} + OM_{pv} \qquad (4)$$

The three major elements of the initial capital investment C_{0PV} are the PV array, motor-pump-control unit, and costs of installation. These investments depend on the peak power rating of the PV array.

Operation and maintenance costs include taxes, insurance, maintenance, recurring costs, etc. It is generally specified as a percentage t% of the initial capital cost. All operating costs are escalated at a rate e_0 and discounted at rate d. The life-cycle maintenance for a lifetime of N (25) years is:

$$OM_{PV} = OM_{0PV} \, [(1+e_0)/(d-e_0)] \, (1 - [(1+e_0)/(1+d)^N]) \qquad (5)$$

where

$$OM_{0PV} = t \, C_{0PV}/100 \qquad (6)$$

For the relevant diesel system the total life-cycle cost LCC_d is the sum of capital cost C_{0d}, LCC_f of fuel cost, LCC_m of maintenance cost and LCC_r of replacement cost.

$$LCC_d = C_{0d} + LCC_f + LCC_m + LCC_r \qquad (7)$$

where

$$LCC_f = \text{annual fuel cost} \, [(1+FE)/(d- FE)] \, (1 - [(1+ FE)/(1+d)^N]) \qquad (8)$$

with FE the mean annual fuel escalation

$$LCC_m = \text{annual maintenance cost} \, [(1+e_0)/(d-e_0)] \, (1 - [(1+e_0)/(1+d)^N]) \qquad (9)$$

$$LCC_r = \Sigma_i \, (\text{item cost} \, [(1+e_i)/(1+d)^{N*i/v+1}]) \qquad (10)$$

where
e_i the escalation rate of item prices
N lifetime of the project

i, the number of replacement (1 to v)
v the number of replacements over lifetime of items

We have to underline here that the lifetime of diesel-generator set is around 6 years. Thus equations (8) and (9) present recurring costs over project's lifetime, whereas equation (10) are the non-recurring life-cycle costs which are presented in the 6^{th}, 12th and 18^{th} year of the project (3 replacements).

As we can see there are some initial values depending on the size of the system as C_{0PV}, C_{0d}, annual fuel cost, annual maintenance cost and item cost. Thus is necessary to size the system for the case chosen and later calculate the LCC and compare the systems.

4. Case study

The olive orchard chosen is located in the island of Crete which favours high insolation values (figure 3). The island has a Mediterranean semiarid climate, with an average monthly rainfall from 1 to 11 mm during the irrigation period. Average monthly temperatures range from 11ºC in January to 26ºC in July, which means that winters are mild and the risk of frost is very low as the absolute minimum temperature is above 0ºC. The analysis has been performed per hectare

The PV system is located at 35º12' North latitude and 24º54' Western longitude. The tilt angle of the PV cells is 30º, its azimuth is 0º and. It is assumed that the olive orchard (Olea Europea, var. Koroneiki) is already established and aged approximately 25 years. The trees are spaced 5X5 m and the density is 300 trees per hectare. The water for each tree is estimated to 7 l/hr or 2.1 m^3/hr. The pumping head is taken 40m.

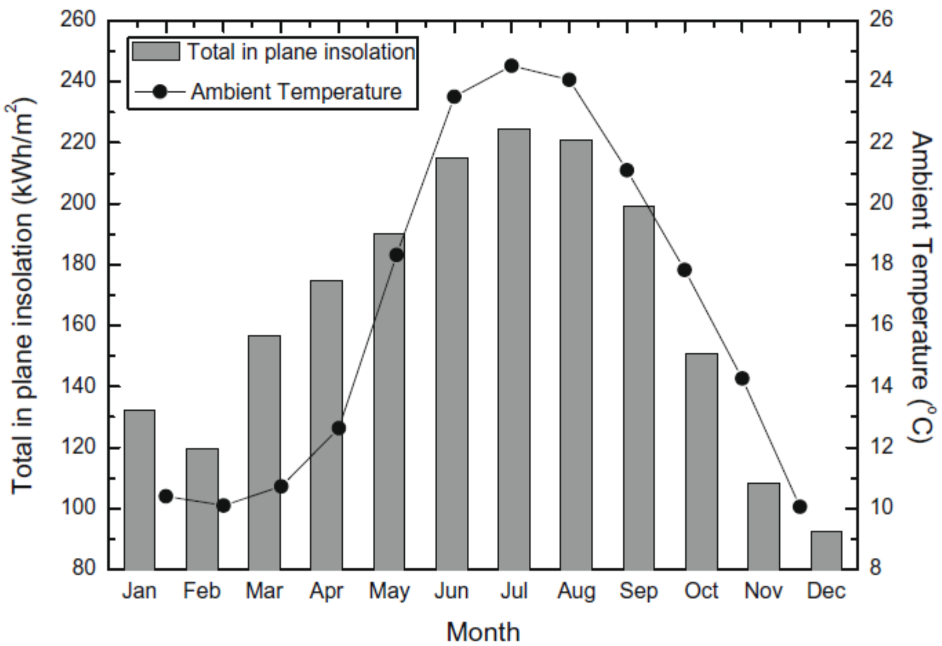

Figure 2 Monthly averaged total in-plane insolation and ambient temperature averaged during the daytime hours [10]

As far as the economic data are concerned according to Oil Institute (http://www.oliva.net/), the price of olive oil varies throughout the year and from one year to another. In this work, an average price of 3.1 €/kg (for extra virgin oil), has been considered. Cultivation costs for an intensive irrigated olive orchard (300 trees per ha) were taken from the report issued by the International Olive Council [14] resulted equal to 2.13 €/kg or for a production of 1000kg/ha, 2130 €/ha. Indirect cost (managerial, insurances, olive mill, etc.) were assumed equal to 10% of total cost. The drip irrigation system investment cost was considered equal to 2500 € /ha. The above data are useful to understand the necessity of irrigation, no matter the system chosen.

According equations (2) and (3), with a pumping station efficiency η_{ps}=0.85 and a daily irrigation time of 8hr the necessary daily energy is 215kWh/ha.

PV arrays can operate in standard conditions (insolation 1000W/m^2, temperature 25^{o}C) with an efficiency of 15%. However due to different losses (temperature, soiling, degradation, internal network, inverter etc) the whole system's efficiency amounts to 10%. With a mean daily insolation on the 30^o tilted surface around 6 kWh/m^2, we need a 300m^2 of a 4.5kW PV system, we can satisfy the hydraulic needs of the irrigation system and losses of the pumping station. The initial capital investment of the PV stand alone system was assumed (based on market prices) equal to 1.5 € per peak Watt, or C_{0PV} = 6750€ and with t=1% OM_{0PV} = 675€. Thus for PV maintenance escalation rate e_0=2% (due to gradual ageing) and a discount rate value d equal to 3%, as it seems reasonable in the current economic situation in the European context, equation (6) gives OM_{PV} = 14900€ and the LCC for PV reaches 22325€ throughout the 25 years system's lifetime.

The diesel generator system similarly has to have a rated power of 4,5 kVA. However the initial capital investment of such a system is only C_{0d}=1550€ but the annual maintenance cost arises to 10% of this or 155€. The fuel consumption is around 1.1 l/h or about 1600 l for the irrigation period. With a current price for agricultural diesel around 0.65€, the annual fuel cost, equals to 1040€. Even for the most advantageous case with a zero escalation in fuel price (FE=0), from equation (8) LCC_f =18110€. With the annual maintenance cost of 155€ equation (9) results in LCC_m= 3422€. Finally considering 4 replacements for all the system equation (10) produces a result of LCC_r = 3922€. All these values result to LCC_d of 27000€ throughout the 25 years project's lifetime

5. Results and Discussion

The economic viability of a stand alone direct pumping system against a diesel one for an olive orchard in Crete has been proven. Although the parameters chosen are in favour of diesel (zero annual escalation in price, subsidised agricultural diesel) the PV system is the lower cost option. We have to underline also that environmental parameters, which probably are in favour of PV systems haven't been considered. Also the adoption of a subsidy system for agricultural purposes (similar to that of agricultural diesel) is proposed to be taken seriously into consideration. Finally, the future of PV is much more promising than the "grey" one of diesel and the earliest extended adoption of an innovative and promising technology will lower its cost even more and lead to more efficient systems.

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