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Optimal design of a standalone direct pumping photovoltaic system for deficit irrigation of olive orchards

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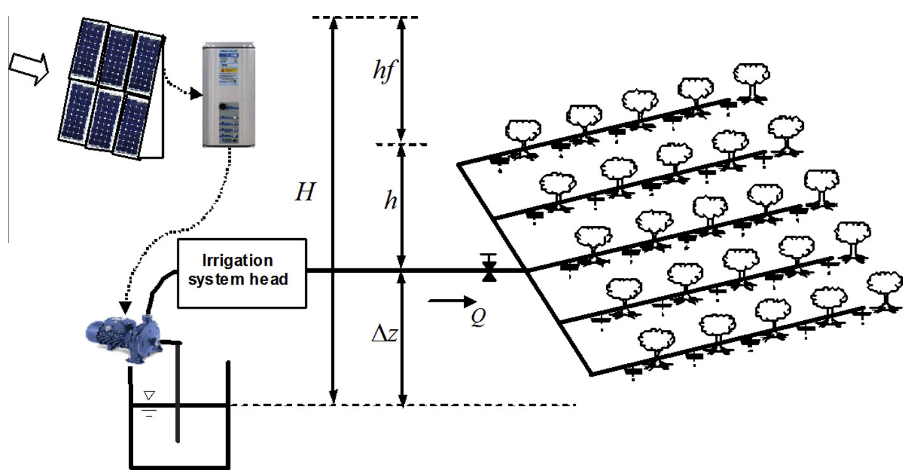
HIGHLIGHTS

- The new concept called Photovoltaics Opportunity Irrigation (PVOI) is introduced.
- A standalone PVOI system is proposed for the irrigation of olive trees.
- A simulation model of a PVOI system is developed to optimize its design.
- The optimal design of the PVOI system was achieved under deficit irrigation.
- The PVOI approach provided reductions in the investment costs and water savings.

GRAPHICAL ABSTRACT

Scheme of the proposed PV direct irrigation system.



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ABSTRACT

In this work, an optimal standalone direct pumping photovoltaic irrigation system is proposed for the deficit irrigation of olive orchards. A simulation model of the system was developed in order to obtain the economically optimal design of this system. This model is composed of different sub-models: the photovoltaic power generation capacity sub-model, the direct pumping management sub-model and the sub-model that evaluates the economic and productive response of the crop to the application of water. The model simulates for increasing values of peak power of the photovoltaic system, the water and energy balance in the photovoltaic irrigation system and the crop yield. It also calculates the investments and operational costs of the system and, finally, the net economic returns to the farmer. The model enables us to select the optimal design of the system that achieves its maximum economic profitability.

The economically optimal designs provided by the model are not achieved for a completely full irrigation of the crop but rather for deficit irrigation. In this way, we propose a new approach to PV irrigation systems design and management that we call PV opportunity irrigation (PVOI). PVOI makes use of the ability of many crops to undergo some water stress without experiencing a significant yield loss in order to reduce the size of the PV irrigation system. The operational strategy in the PVOI approach is to irrigate as long as enough power is supplied by the PV array. Unlike any other conventional design method available in literature, the total amount of water applied to the crop depends on the energy provided by the PV

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Nomenclature

D	soil water depletion
ET_a	actual evapotranspiration of the crop (mm)
ET_c	crop evapotranspiration (mm)
ET_o	reference evapotranspiration (mm)
F_w	fraction of soil wetted by the emitter
H	total energy head (m)
h	working pressure head at the emitter (m)
hf	overall head loss in the distribution network (m)
$I(t)$	irradiance on the inclined collector plane (W m^{-2})
$I_b(t)$	solar direct irradiance as a function of time t (W m^{-2})
$I_d(t)$	solar diffuse irradiance as a function of time t (W m^{-2})
I_m	irradiance minimum threshold value (W m^{-2})
I_{STC}	irradiance under standard conditions (W m^{-2})
k	discharge coefficient of the emitter
K	overall inverse discharge coefficient of the emitters in the irrigation network
K_c	crop coefficient
K_{Es}	crop coefficient due to the surface evaporation from the soil outside the wetted bulb
K_{Ew}	crop coefficient due to the Surface evaporation from the soil wetted by the emitters
k_s	water stress coefficient
K_{Tc}	crop coefficient due to the tree transpiration
K_{Tw}	crop coefficient due to the cover crop (or actively growing weeds) transpiration
K_y	yield response factor
N	pump speed (rpm)
n_e	total number of emitters in the irrigation system
P	net power transferred to the water (W)
P_e	effective precipitation (mm)
PP	peak power generated by the PV modules under standard conditions (W)
P_{PV}	photovoltaic power provided by the PV system (W)
$P_{PV,min}$	minimum value of utilizable photovoltaic power (W)
q	emitter discharge
Q	total discharge of the pumping system (m^3/s)
r_h	ratio of the minimum working pressure of the emitter (h_m) to the maximum (h_M)
R_n	net irrigation depth (mm)
R_s	equivalent resistance coefficient of the irrigation network
S	slope coefficient for silicon cells °C/(W m^{-2})
T_a	air temperature (°C)
T_{cell}	temperature of the cells in the module (°C)
T_{STC}	cell temperature under standard test conditions (°C)
x	pressure-discharge exponent of the emitter
Y_a	actual crop yield
Y_M	potential crop yield
β	performance decay coefficient due to the rising temperature of the cell
Δz	elevation change (m)
φ	tilt angle of the PV modules
ρ	albedo
θ	direct solar radiation incidence angle with respect to the inclined collector plane
θ_z	direct solar radiation incidence angle with respect to the horizontal plane

Subscripts

d	refers to a specific day d
i	refers to the working conditions for the pump operating at any intermediate speed
M	refers to the working conditions for the pump operating at its maximum speed
m	refers to the working conditions for the pump operating at its lowest speed

array rather than on a strict fulfillment of the pre-established crop water irrigation requirements. The application of the PVOI approach implies not only a reduction in the investment costs of the system but also some water savings, which is very important in areas with water scarcity.

1. Introduction

Solar energy has a very high potential in Mediterranean areas as this region's climate is characterized by a high number of sunlight hours. For this reason, the irrigation of many crops in these areas with photovoltaic (PV) energy systems is increasingly gaining interest.

Olives are one of the most widespread crops in the Mediterranean basin. Their contribution to the local economy of many areas is of paramount importance. Traditionally, olives are cultivated under rainfed conditions; however, many studies have shown that the application of irrigation water results in a significant increase in yield and a considerable reduction of the problem of alternate bearing [1,2]. For this reason, in recent years, there has been an enormous increase in irrigated olive land area using drip irrigation systems.

Controlled deficit irrigation has been proposed as a profitable technique in water stress tolerant crops like olive orchards. The objective of deficit irrigation is to apply less water than that required to achieve a maximum potential yield. This technique is economically feasible for crops that are relatively tolerant to water stress and when the cost of the water applied is relatively high. The effect of different controlled deficit irrigation strategies on olive yield have been studied in different research works [3,1,4–7].

In spite of the abovementioned benefits of irrigation on the production of olive oil, many traditional olive orchards continue to be only rainfed as farms are located in outlying lands where other alternative crops are not feasible and, in many cases, far from electricity distribution facilities. The investment costs needed to electrify these farms can be excessively high. In addition, in many countries in the Mediterranean basin like Spain, the price of electricity has become increasingly higher in recent years. The increase in energy costs can jeopardize the economic feasibility of most of these olive orchards. The use of off-grid powering systems seems to be appropriate in cases like this one. At present, off-grid electrification is becoming an active field of research [8].

Standalone photovoltaic irrigation systems are being used for many types of irrigation systems throughout the world [9,10].