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Agricultural irrigation scheduling for a crop management system considering water and energy use optimization

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Abstract

Center pivot systems are widely used to overcome the irrigation needs of agricultural fields. In this paper, an autonomous approach is proposed in order to improve the low efficiency of irrigation by developing a system based on the water requirement of the plantations, through field data. The data are local temperature, local wind, soil moisture, precipitation forecast, and soil evapotranspiration calculation. This information enables the system to calculate the real evapotranspiration for not being necessary to restrict to lysimetric measures. By this way, the system schedules the irrigation for the lower cost periods, considering the produced energy by the local resources, and the price of energy purchased from the utility grid. Also, it is considered that the irrigation must be carried out within the time interval in which the plantations do not reach the wilding point, so it will be carried out at the periods with the lowest cost. This will optimize the overall operational costs of the irrigation.

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Keywords: Smart farming; Water resource scheduling; Agricultural irrigation; Energy optimization

1. Introduction

The need for irrigation management has become relevant in many regions, especially in Mediterranean areas. This leads to having a limitation on the water resources, changes in the climatic conditions and the negative effect of human behavior on the environment. The purpose of the irrigation is to give the proper amount of water to the plants in order to guarantee their necessity. The amount of water used in the irrigation system is also important, somehow the new irrigation methods implemented in such a manner that consume less water comparing to the previous and old technologies. Smart irrigation methods also can be implemented, which means not only they

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should consider consuming less water, but also, they should limit the water supply to optimize crop production. For optimum operation, soil water in the crop root-zone must be maintained between a desirable range with upper and lower limits of available water for the plant. Proper irrigation management will prevent economic losses (yield quantity and quality) caused by over or under irrigation. The objective of irrigation management is to establish a proper timing and amount of irrigation for greatest effectiveness [1].

In agricultural fields, the main intention is to reach the maximum yield of the crop with the minimum operational costs. One of the developed methods in this area, which improves the efficiency of the use of water and the use of energy as well, is the irrigation by sprinkler with a system of the center pivot. In this method, the device rotates around a pivot, in a circular path, and crops are watered with sprinklers as the machine moves. Also, this method can be integrated with multi-depth sensors for measuring and monitoring the conditions of the soil. Therefore, an optimal solution can be reached through these approaches for minimizing the use of energy and water. Soil moisture sensors and Photovoltaic (PV) arrays are also useful for the water pumping, while the minimum moisture level is reached. However, more deep studies and surveys are essential in this context in order to have an efficient use of those systems [2].

This paper proposes an autonomous approach for improving the low efficiency of irrigation by developing a system based on the water requirement of the plantations, through the field data. The data are local temperature, local wind, soil moisture, precipitation forecast, and soil evapotranspiration calculation. This information enables the system to calculate the real evapotranspiration for not being necessary to restrict to lysimetric measures. By this way, the system schedules the irrigation for the lower cost periods, considering the produced energy by a PV system, and the price of energy purchased from the utility grid. Also, it is considered that the irrigation must be carried out within the time interval in which the plantations do not reach the wilding point, so it will be carried out at periods with the lowest cost.

There are several similar works focused on this topic. Dong et al. [3] presented an autonomous precision irrigation model based on a center pivot irrigation system that uses wireless underground sensor networks. In the same work, the system provided autonomous irrigation management through monitoring the soil parameters in real-time. In Boobalan et al. [4], and Pernapati [5] the authors developed an automatic Internet of Things (IoT) based irrigation system in order to monitor the soil and weather conditions and afford with auto irrigation to the crops by employing microcontroller and cloud server. Debauche et al. [6] provided a center pivot irrigation method for optimizing the crop water necessity by using multi-depth sensors for monitoring the soil moisture. Also, Wang et al. [7] proposed a dynamic irrigation low limit method, which considers the crop growth and development time and water supply to settle the irrigation while the water source is limited. In Brajovic et al. [8], the authors explained four solutions to smart irrigation software, where the explored data obtained from various kinds of sensors. However, the main focus of this paper is given to optimizing the overall operational costs of a smart irrigation system equipped with a renewable energy resource, and it is aware of the real-time electricity market prices. Therefore, the irrigation can take place at the most economic moments considering the soil moisture, PV generation and electricity price.

The rest of this paper is organized as follows: Section 2 explains the proposed model including mathematical calculation and optimization algorithm. Section 3 demonstrates two scenario calculations for testing and validating the system performance, and the results are shown in the same section. Finally, Section 4 presents the main conclusions.

2. System description

In the agriculture fields, the main intention is to reach the maximum yield of the crop with the minimum operational costs as well as water consumption. The proposed model in this paper is based on the Center Pivot (CP) irrigation, which improves the efficiency of water usage and energy consumption. Fig. 1 illustrates the typical architecture of a CP irrigation system.

As Fig. 1 shows, the CP system rotates around a pivot, in a circular path somehow the crops are watered with sprinklers as the machine moves.

The irrigation method presented in this paper considers multiple zones of the agricultural field that allows having different plantations or planting the same type but in different stages of growth. Fig. 2 demonstrates the proposed irrigation method. The system considers the irrigation requirements for each zone and regulates the speed of the electrical motor, related to the rotation of the infrastructure, and the valve motor related to the water pumping, based on the plant's requirements in each zone.

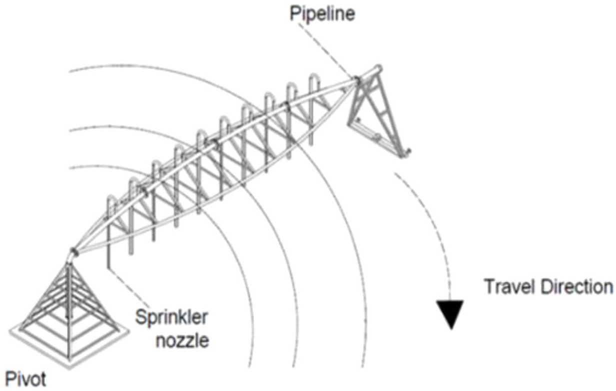

Fig. 1. The CP irrigation system.

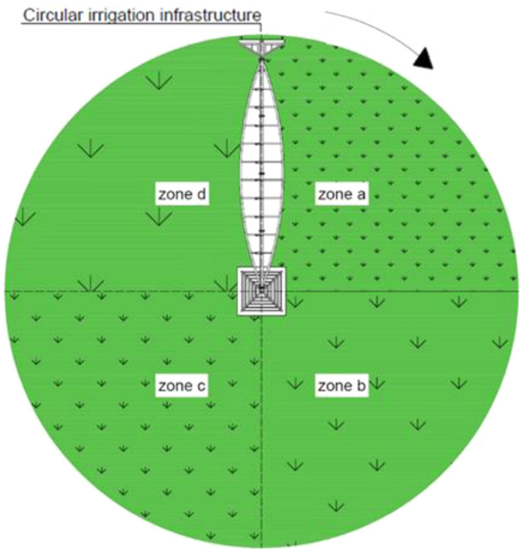

Fig. 2. Multiple zones CP irrigation system.

The system calculates the time remaining until the level of soil moisture goes below a desired limit for the plantations of the different zones considering the evapotranspiration of each zone and the precipitation forecast. Furthermore, the system obtains the local PV production and the electricity market price, in order to propose the most optimized scheduling for the irrigation of each zone. The priority of the system is set to use the local energy generation for the electricity demand of the devices. The presented optimization algorithm for the system is shown in Fig. 3, where the output would be the optimal irrigation scheduling. There are several sensors in the system, which enables the scheduling process to have real-time data, such as soil moisture, solar radiation, temperature, humidity etc.

The system is also able to perform precipitation and sun forecasting, which are used by the irrigation scheduling process. The algorithm checks the PV generation, electricity price, precipitation and sun forecast for the next three periods, and selects the best and optimal period that the irrigation can be performed with the minimum operational cost.

In order to estimate the period and the adequate amount to irrigate the field, it is necessary to calculate the evapotranspiration of the plantations. For this purpose, the FAO Penman-Monteith method [9] is utilized to estimate the potential evapotranspiration (ET_0) and the evapotranspiration of the crop (ET_c). Eq. (1) shows the calculation of the potential evapotranspiration considering the stage of vegetative growth of the crop by weighting the potential

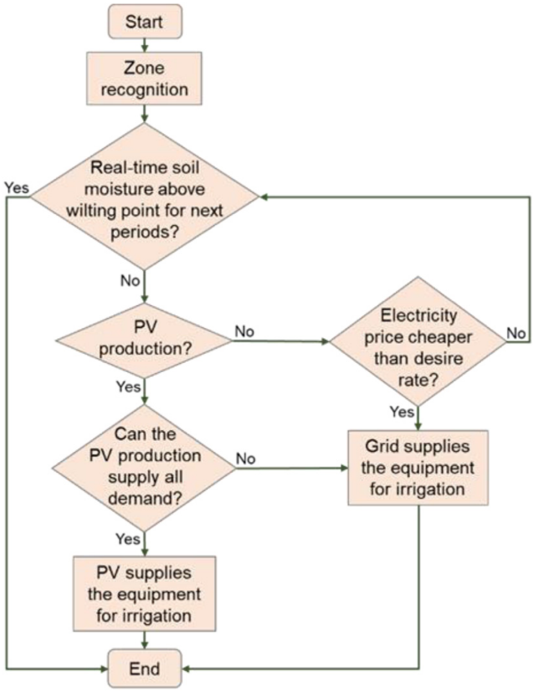

Fig. 3. Flowchart of the irrigation scheduling process.

evapotranspiration (K_c).

$$ET_0 = \frac{0.408\Delta\,(R_n - G) + \gamma\,\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{1}$$

where:

ET_0	Reference evapotranspiration [mm day^{-1}];
R_n	Net radiation at the crop surface [MJ m^{-2} day^{-1}];
G	Soil heat flux density [MJ m^{-2} day^{-1}];
T	Air temperature at 2 m height [°C];
U_2	Wind speed at 2 m height [m s^{-1}];
e_s	Actual vapour pressure [kPa];
e_a	Actual vapour pressure [kPa];
e_s-e_a	Saturation vapour pressure deficit [kPa];
Δ	Slope vapour pressure curve [kPa °C^{-1}];
γ	Psychrometric constant [kPa °C^{-1}].

The calculation of ET_c (as Eq. (2) shows) is the product of ET_0 and K_C, which K_C is determined from the type, growth length of the crop and chooses the corresponding coefficients K_C.

$$ET_c = ET_0 * K_c \tag{2}$$

where:

ET_c	Crop evapotranspiration [mm day^{-1}];
ET_0	Reference evapotranspiration [mm day^{-1}];
K_c	Single crop coefficient.

As a summary, this section demonstrated the proposed model for optimal irrigation by considering several real-time data and forecast information. The performance of the system would be validated through two scenario calculations presented in the next section.

3. Scenario calculations

In this part, two scenarios are presented for testing and validating the performance of the irrigation system. For this purpose, it is considered that the system is equipped with a 5 kW PV arrays, which can supply a part of irrigation system consumption. Therefore, a real production profile adapted from GECAD research center database, is provided to the algorithm, as Fig. 4-(A) shows. For the electricity market prices, a random day has been selected from the Iberian Electricity Market (www.omie.es), and the prices are provided to algorithm by considering a coefficient (Fig. 4 -(B)).

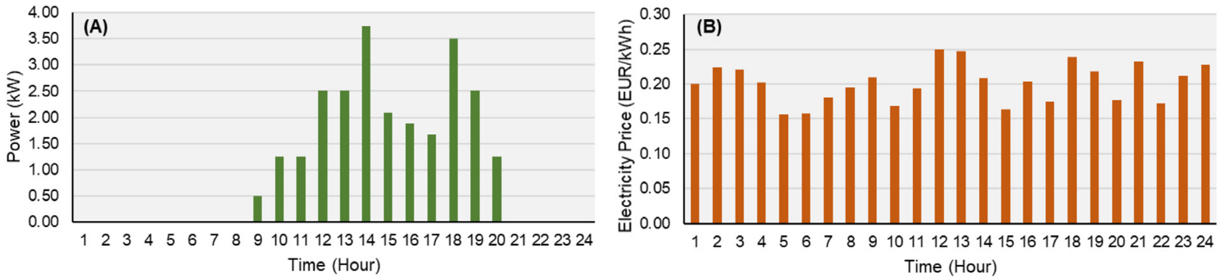

Fig. 4. Input data for the irrigation algorithm: (A) PV production profile; (B) Electricity market prices.

In addition to the production profile and the electricity prices, the precipitation and sun forecasts are calculated and provided to the irrigation algorithm as inputs.

As it was mentioned in the previous section, the system is equipped with several types of sensors in order to monitor the environmental and soil conditions in real-time. Therefore, two scenarios with 24 h duration (24 periods) are presented in this section by considering different input parameters, and the algorithm will calculate the most economic period to perform the irrigation. Table 1 demonstrates the parameters considered for the two proposed scenarios. In fact, the input data shown on Fig. 4 are equal for both scenarios, and only some critical parameters and irrigation devices characteristics are changed in order to survey the performance of the model.

Table 1. Input parameters for the two proposed scenarios.

Scenario 1		Scenario 2	
Soil moisture level [mm]	800	Soil moisture level [mm]	1500
Evapotranspiration crop [mm]	100	Evapotranspiration crop [mm]	100
Wilting point plantation [mm]	450	Wilting point plantation [mm]	800
Motor power [kW]	75	Motor power [kW]	100
Irrigation capacity [mm/min]	20	Irrigation capacity [mm/min]	30
Desired soil moisture level [mm]	1500	Desired soil moisture level [mm]	3000
PV panel capacity [kW]	5	PV panel capacity [kW]	5
Precipitation Forecast [mm]	50	Precipitation Forecast [mm]	0

Furthermore, the precipitation forecast is considered in scenario 1, which happens in the first four periods (between 12:00 AM to 04:00 AM) with 50 mm in each period. In fact, the precipitation increases the soil moisture, and therefore, the irrigation would be occurred shorter in order to reach the desired level. The gained outputs of algorithm are shown in Table 2. The results shown in Table 2 are the irrigation scheduling with the cost in each period, somehow the green is the most economic period for the irrigation and the red is the most expensive period. The costs are calculated by respect to the market prices considering the consumption of the devices and duration of the irrigation in each period.

The duration of irrigation in each period is based on the real-time and desired soil moisture level and the irrigation capacity. As it is clear in Table 2, the irrigation scheduling is shown until one period before the soil moisture is reduced to the wilting point. If the soil moisture becomes equal to the wilting point, the irrigation should be performed in any condition, and therefore, no algorithm is required for scheduling of the irrigation. Moreover, since there are precipitations in the first four periods of scenario 1 (50 mm in each period), and also the evapotranspiration rate is considered as 100 mm in each period, the soil moisture level would be compensated in the rainy periods

Table 2. The results of the irrigation scheduling algorithm.

Time	Scenario 1			Scenario 2		
	Soil moisture level [mm]	Irrigation duration [min]	Irrigation price [EUR]	Soil moisture level [mm]	Irrigation duration [min]	Irrigation price [EUR]
12:00:00 AM	800.00	35.00	2.34	1500.00	16.67	1.67
1:00:00 AM	750.00	37.50	2.81	1400.00	20.00	2.25
2:00:00 AM	700.00	40.00	2.94	1300.00	23.33	2.57
3:00:00 AM	650.00	42.50	2.86	1200.00	26.67	2.70
4:00:00 AM	550.00	47.50	2.47	1100.00	30.00	3.15
5:00:00 AM	-	-	-	1000.00	33.33	3.33
6:00:00 AM	-	-	-	900.00	36.67	3.31

(first four periods). Therefore, the most economic periods for irrigating in scenario 1 are firstly on 12:00 AM, and then on 4:00 PM. However, in scenario 2, the only economic period for irrigation is 12:00 AM.

The results and performances of the proposed irrigation scheduling algorithm have been shown and discussed in this section. Using this algorithm would enable the farmers to have smart management on the operational costs in the irrigation process. However, the proposed optimization approach should be implemented in a real pilot case in order to survey all functionalities of the model and identify the practical gaps for overcoming them in the future works

4. Conclusion

An autonomous approach was proposed in this paper to provide an optimal and efficient irrigation system. The model utilized the field data, in order to meet the requirements of the plantations. These data enable the system to calculate the real evapotranspiration for not being necessary to restrict to lysimetric measures and schedule the irrigation for the affordable periods. The electricity market prices, and a local renewable energy source are also considered in the scheduling algorithm. The important functionality of the presented scheduling algorithm is considered that the irrigation must be carried out within the time interval in which the plantation does not reach the wilting point, so it will be carried out at the periods with the lowest cost.

Two scenario calculation were demonstrated to validate the performance of the irrigation scheduling process. Precipitation and sun forecasts were also considered, which affected the soil moisture and therefore, it reduced the irrigation duration. From the results shown on the scenarios, it can be concluded that using the proposed irrigation scheduling approach enables the farmers to have affordable irrigation and smart management with a significant reduction in the operational costs.

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