Peer-reviewed version available at *Sustainability* **2018**, *10*, 4203; doi:10.3390/su10114203

Energy Consumption Optimization in Irrigation Networks Supplied by a Standalone Direct Pumping Photovoltaic System

Pardo, M.A.[a*], Manzano, J.[b] and García-Márquez, D [a].

[a] *Department of Civil Engineering, University of Alicante, Alicante, Spain.* mpardo@ua.es

[b] *Dept. Ingeniera Rural y Agroalimentaria, Universitat Politècnica de València, Valencia, Spain.*

ABSTRACT

Due to the fact that irrigation networks are water and energy-hungry and that both resources are scarce, many strategies have been developed to reduce this consumption. Otherwise, solar energy sources have become a green alternative with lower energy costs and, as a consequence, lower environmental impacts. In this work, it is proposed a new methodology to select the scheduled program for irrigation which minimizes the number of photovoltaic solar panels to be installed and which better fits energy consumption (calculated for discrete potential combinations; using a programming software to assist) to available energy obtained by panels without any power conditioning unit. So, the irrigation hours available to satisfy the water demands are limited by sunlight, the schedule type of irrigation has to be rigid (rotation predetermined) and the pressure at any node has to be above the minimum pressure required by standards. A real case study has been performed.

KEYWORDS

Energy efficiency, Photovoltaic system, energy audit, rigid scheduled irrigation

1. INTRODUCTION

It bears no surprise that irrigation agriculture accounts for 70% of the world's water use and also that water and energy consumption are inextricably linked [1]. Given the future demands of food production, efficient management strategies for both resources are of paramount importance. Some of the proposals to improve water efficiency in irrigation networks are the use of pressurized water distribution networks and also the use of emitters (sprinklers or drip irrigation) [2].

From the design and management of water irrigation networks standpoint, the fact that sustainable management of pressurized networks has become the key objective for water irrigation managers are justified by the high number of studies dealing with improvements in water efficiency [3, 4, 5], recent approaches are dealing with energy optimization: methods for the sectoring of irrigation networks [6], changes in the operating system, from scheduled to on-demand irrigation [7], selection of new pumping systems and / or changes in the diameter of water sprinklers [8], etc.

Thus, in water scarcity regions [9, 10], several technologies have been developed to reduce water and energy consumption. However, water and energy are so much interdependent in pressurized irrigation networks that in semi-arid regions energy needs have reached high values such as 0.95-1.55 kWh/m^3 [11].

The high costs of diesel fuels and the deficit in electricity affects the irrigation networks manager's decisions when considering the need of meeting water and energy requirements for crops irrigation. Solar water pumping based on photovoltaic (PV) technology has become one of the hottest topic in water irrigation networks because it has become an attractive alternative and with proven economic viability [12, 13]. Some other approaches are focused on calculating

Peer-reviewed version available at Sustainability 2018, 10, 4203; doi:10.3390/su10114203

energy production from a PV [14] or obtaining maximum power from PV with minimum motor losses [15].

Solar photovoltaic technology consists of a PV array that provides electricity for driving the pumps. This direct couple system is composed of a PV generator (which convert the irradiance (W m^{-2}) into direct current; DC), a frequency converter (which convert the DC into alternating current; AC) and an asynchronous motor (which converts AC into shaft work moving the pump) [16, 17].

The key advantages of incorporating PV technology in the optimization problem consists of the reduction of operation costs of pumping water into the system [18] and the environmental benefits associated [19]. On the contrary, the system should guarantee the supply for irrigating the crops and as the hourly irradiance is an input in the optimization process, the location and the period of the year convert into an important restriction as the parameter which controls the process is not only the water needs.

In this new scenario and considering the current state of the technology, a new optimization scheme minimizing the number of PV panels and the energy use is proposed. In this approach, the number of segments are constant and the pressurized irrigation network been modeled using a open source hydraulic modeling software. The irrigation network should be adjusted to meet all the water demands (supplying every consumption node with a pressure above the minimum required pressure). The methodology presented here calculates the most efficient combination of areas irrigated simultaneously which satisfies water demands in crops with pressures above the threshold service and with lower PV panels installed and with lower energy consumption. In order to meet these requirements, the hourly energy consumption (by the irrigation network) should be as close as possible to the available energy due to the hourly irradiance curve.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 October 2018 doi:10.20944/preprints201810.0387.v1

Peer-reviewed version available at *Sustainability* **2018**, *10*, 4203; doi:10.3390/su10114203

As the optimization problem is very time-consuming (the values of energy savings at every time step periods vary, daily sums of energy/water saved have been calculated), every hydraulic simulation for the possible combinations (rigid scheduled irrigation) have been calculated using the Matlab® code to assist with the epanet toolkit [20]. In every combination, the energy audit in irrigation networks [21] is calculated using a Matlab-based GUI (UAEnergy) developed for students and practitioners which can be downloaded at "*http://rua.ua.es/dspace/handle/10045/76947*".

The work is organized as follows. Section 2.1 shows the calculation of the net power transferred as hydraulic energy (Appendix A shows a way of calculating hourly irradiance), Section 2.2 shows the crops water demands. Section 2.3 presents the energy audits in irrigation networks, the schedule for irrigation is depicted in section 2.4 and the optimization problem is described in Section 3. A real case study is presented in Section 4, where the energy requirements are shown at Section 4.2, the quantification of the number of PV panels is calculated in Section 4.3, the results of the energy audit for the best DMPs combinations are showed in Section 4.4 and a comparison between cases is finally depicted in Section 4.5.

2. MATERIAL AND METHODS

In this section, some ideas to the PV panels and the irrigation network are showed as previous knowledge the reader should have to face the optimization problem.

2.1. Net power transferred to the water

The starting point should be to determine the hourly distribution of monthly solar radiation (and also considering the optimum angle of inclination (β) of the photovoltaic panels).

Appendix A shows a way of calculation of the hourly distribution of irradiance for each month [22]

The net photovoltaic power provided by a PV generator is calculated as follows:

$$P_{PV} = \begin{cases} \frac{I(t)}{I_{STC}} PP\left(1-\gamma(T_{cell}-T_{STC})\right) & if\ I(t) > I_m \\ 0 & if\ I(t) < I_m \end{cases} \quad (1)$$

Where P_{PV} is the power obtained directly by the Photovoltaic system, $I(t)$ is the irradiance on the inclined collector plane expressed in W m^{-2}, I_{STC} is the irradiance under standard conditions (1000 W m^{-2}), PP is the peak power generated by the PV modules (in W), γ is the performance decay coefficient due to the rising temperature of the cell. T_{cell} is the cell temperature in the module and T_{STC} is the cell temperature under standard test conditions (25 ºC). It will be necessary to determine the minimum irradiation (I_m), the threshold value (depending on the frequency inverter and also the PV peak power) which may range between 250 W m^{-2} [23] or 500 W m^{-2} [24]. This value represents the daily irrigation period (the number of hours of irrigation).

The net power that it is finally transferred to water is calculated considering the efficiency of the devices involved in the process:

$$P_h = \eta_p \eta_{am} \eta_{fc} P_{PV} \quad (2)$$

Where P_h is the shaft power transferred to water, P_{PV} is the power obtained directly by the Photovoltaic system, and η_p, η_{am} and η_{fc} are the pump, asynchronous motor and converter efficiency (-).

2.2. Water demands requirements and network sectoring

When a decision maker deals with the reduction of energy consumption in irrigation networks, the first step is to properly calculate the amount of water required by crops.

Peer-reviewed version available at Sustainability 2018, 10, 4203; doi:10.3390/su10114203

Several approaches to calculate crop water needs have been proposed, among them, the most widely used is the Penman-Monteith FAO method [25] which considers the reference evapotranspiration (ET_o) and the type of crop, characterized by the crop coefficient (K_c). This method is robust and valid both for the irrigation network design stage and for selecting the schedule irrigation program (once the crops are growing). Some other methods, which calculates the water requirements more accurately, are based on direct measurements of the soil water content or based on plant water stress monitoring [25, 26]. Their use would require to have physically the irrigation network working as some sensors should be placed to get the data required (in other words, these methods can only be properly used in the schedule irrigation programming stage).

From the design and management of water irrigation networks standpoint and given the water needs to every irrigation area, the circulating flows and the irrigation time is calculated for every hydrant and/or subunit in the water irrigation network. This outlet hydrant demand depend on the type of emitters, irrigated area, application efficiency, etc. and their value is constant for every subunit while irrigation time depend on the crop needs and the scheduling program of irrigation. In this new approach, the minimum irradiation (I_m), from which the solar power can be obtained from the panels reveals the time of beginning an also the number of hours of irrigation. The pressure level at every hydrant is another parameter to check and it depends on the features of the irrigation subunits (lateral and submaine pipe sizes, emitter type, slope, etc) [27]. It seems obvious that pressurized irrigation requires an energy input (frequently a pump device is using to introduce shaft work into the system) to satisfy the water demands delivering water at pressure levels over the minimum pressure required by standards.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 October 2018 doi:10.20944/preprints201810.0387.v1

Peer-reviewed version available at *Sustainability* **2018**, *10*, 4203; doi:10.3390/su10114203

All this information, and also the pipes and hydrants characteristics has been added to a model in a hydraulic simulation software (EPAnet or any other) to solve the hydraulic problem. First, the model should be calibrated to represent reality. The objective of the calibration is to observe a good response between the simulated (model predicted) and the observed values (pressures and flows at several points of the network) over the entire simulation period. A model allows the user to know pressure levels in consumption nodes, flows, head losses and velocities in pipes, to simulate the energy requirements, etc. In short, it returns a valuable piece of information required in decision-making processes.

2.3. Energy Audit in irrigation networks

The calculation of the required shaft work in pumps (at every moment of the day) is calculated with the energy audit in irrigation networks [21]. The energy balance (where t_p is the simulation period) results in Eq. 1:

$$E_{input}(t_p) = E_n(t_p) + E_p(t_p) \pm \Delta E_c(t_p) = E_u(t_p) + E_l(t_p) + E_f(t_p) + E_v(t_p) \quad (3)$$

Where $E_N(t_p)$ is the energy supplied by reservoirs, $E_P(t_p)$ is the energy supplied by pumps, $E_U(t_p)$ is the energy delivered to the crops (throughout the water supplied), $E_L(t_p)$ is the energy lost through water losses, $E_F(t_p)$ is the energy dissipated in friction at pipes, $E_V(t_p)$ is the energy dissipated in valves and $\Delta E_C(t_p)$ is the energy that can be stored in a compensation tank which accumulates water during low consumption hours while releasing it in peak hours.

2.4. Network management

Once the model has been calibrated, the delivery scheduling method in an irrigation system demonstrates different levels of energy consumption [29, 10]. These schedule types

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 October 2018 doi:10.20944/preprints201810.0387.v1

Peer-reviewed version available at *Sustainability* **2018**, *10*, 4203; doi:10.3390/su10114203

may be should classified [30], in order of increasing flexibility, as rigid (rotation, predetermined), central control, intermediate control (arranged) or flexible (on-demand, modifiable). As the energy provided by the PV presents additional restrictions as a fixed time for irrigation and also hourly and monthly energy available variation (Figure 1), the consumption in segments with regard to time be the combination which involves energy consumption in pumps (shaft work) which better fits to the available energy. The combination of water demands have different values of energy consumption in pumps ($E_P(t_p)$) as some other parameters in the energy audit are also affected. To name a few, the relationship between energy dissipated in friction in pipes and flow is of quadratic type and the leakage depends (among some other factors) on the pressure levels (whose figures are directly linked to headlosses and circulating flows along the network).

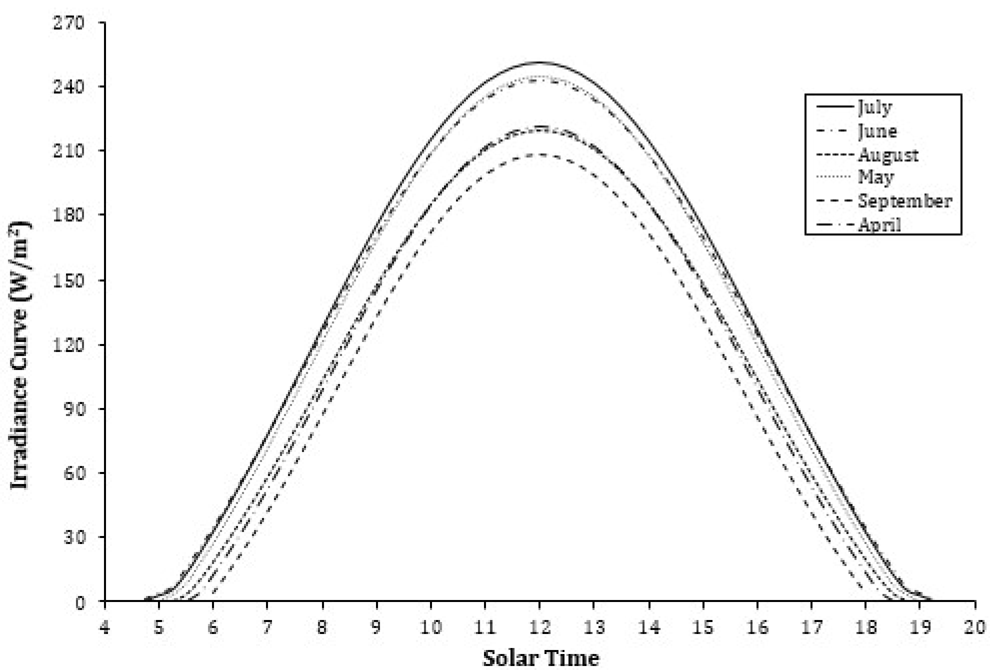


Figure 1. Monthly irradiation curves for Albamix Network.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 October 2018 doi:10.20944/preprints201810.0387.v1

Peer-reviewed version available at Sustainability 2018, 10, 4203; doi:10.3390/su10114203

With these limitations, rigid rotation scheduled irrigation is the only irrigation type which allows the network managers to fit the energy consumption to the energy available by the PV. Additionally, every subunit or hydrant (node where water leaves the irrigation network) is controlled by an electro valve (very common device in irrigation networks) which help the practitioner to control irrigation.

3. Optimization problem

3.1. Input data

The input data required to calculate the most energy efficient combination is depicted here.

- Irradiance Input data:
  - β is the angle of inclination (radians) of the photovoltaic panels
  - I_{sc} is the solar constant (1367 W m^{-2})
  - I_{STC} is the irradiance under standard conditions (1000 W m^{-2})
  - d is the performance decay coefficient due to the rising temperature of the cell (0.004 ºC^{-1})
  - H global irradiance on horizontal surface (kWh m^{-2})
  - T_{STC} is the cell temperature under standard test conditions (25 ºC).
  - T_{avg} Monthly average temperature (ºC)
  - φ is the latitude angle (positive to the North) (radians)
  - n is the day of the representative month
  - ρ the albedo (-)
  - PP is the peak power generated by the PV modules (W)
  - η_p the pump efficiency (-).

- η_{am} asynchronous motor efficiency (-).
- η_{fc} is the converter efficiency (-).

- Hydraulic Input data
  - A calibrated water pressurized network which represents the water delivery in crops. This file must represent the hydraulic features of the system and no errors should appear when running this model. Moreover, the water requirements of the networks should also be defined in the model and the segments (if any) should also be included in the model.
  - Report time step for the case study (minutes).
  - $\left(\frac{P}{\gamma}\right)_{treshold}$ (defined in section 2.2) Minimum pressure required by standards at any hydrant and any time (m.w.c.)
  - T_{irr} (defined in section 2.2)is the irrigation time (minutes)
  - $T_{\min\_irr}$ is the minimum irrigation time (minutes), a value which shows that if a node is delivering water to crops, it should be doing it for at least a time equal or higher than this value

3.2. Optimization parameters

The optimization parameters for a discrete optimization problem (like the problem analyzed here) where the combinations are finite (although high in number) are the demand multiplier patterns (DMPs). Every network studied is divided into n regions and every region is assumed to follow the same diurnal curve (i.e., same set of DPMs), being a DMP is a group of values (row vector, size (1,x)) which consider variation in time of the consumption nodes base demands.

Peer-reviewed version available at Sustainability 2018, 10, 4203; doi:10.3390/su10114203

The pattern time step represents the time interval after which a change in time patterns is produced (1 hour, 30 minutes, etc.) and the total simulation period is equal to the hours in which the irradiance curve is producing energy (7-9 hours). In short, if the pattern time step is equal to 20 minutes, and the hours of simulation are 8 hours, the DMP which analyses the evolution of irrigation in one segment has 480/20=24 values.

The network is divided into n segments (groups of subunits which totalizes the same base demand and creates a constant value for the injected flow) each of them following their particular set of DPMs. So, each combination should be composed of a matrix of size (i,j) (i rows, one per sector, and j columns, one per every time step considered).

With the following values:

$$a_{ij} = \begin{cases} 1 & if\ open \\ 0 & if\ closed \end{cases} \tag{4}$$

The values in this combinations are 1 (if subunit open) or 0 (if closed). The sum of the values per row should be equal to the irrigation time per sector (in short, if the crop requires 2 hours of water and the time step is 30 minutes, there has to be 4 values which should be equal to 1).

The sum of the values per column of every combination should be less than or equal to the maximum number of segments which can be opened simultaneously. As the irrigation system is divided into n segments, the potential combination of n segments irrigating simultaneously should be calculated as follows:

$$N_{Poscomb} = \sum_{i=1}^{n} \binom{n}{i} \tag{5}$$

Being an n= number of segments and i the number of segments irrigating simultaneously.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 October 2018 doi:10.20944/preprints201810.0387.v1

Peer-reviewed version available at *Sustainability* **2018**, *10*, 4203; doi:10.3390/su10114203

Among these number of combinations, pressured deficit conditions eliminate some possibilities as the network is not ready to satisfy the water requirements with the pressure above the minimum pressure threshold.

Finally, as the electro-valves have to be opened for a time larger than the minimum irrigation time, there are one additional restriction as if there is a subunit opened (an 1 in the matrix), there has to be consecutive values up to reaching a value of time with the subunit opened (i,e: if time step is 30 minutes, and minimum irrigation time is equal to one hour, there has to be at least 2 consecutive values equal to 1). This restriction has been adopted to reduce the number valves opening and closing.

3.3. Calculation process

Step 1: The first stage in the calculation is focused on calculating the monthly energy available per PV system. The unitary energy available is computed (Section 2.1, Appendix A).

Step 2: The second stage involves to calculate the shaft work required by the pumps in the network (Section 2.3) for every segment combination (Eq. 5). Moreover, the *m* potential cases (DMPs) are calculated with the aforementioned restrictions:

- Volume delivery should be constant
- The minimum pressure at every node and at every time should always be equal or higher than the minimum pressure required by standards.
- Every time a segment is delivering water, the electro-valves have to be opened for a time larger than the minimum irrigation time.

For each of the *m* combinations, the DPMs are added to the initial irrigation network model (hydraulic input data) modifying their hydraulic response which should be calculated with the use of the hydraulic simulation software (as many combinations should be performed,

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 October 2018 doi:10.20944/preprints201810.0387.v1

Peer-reviewed version available at Sustainability 2018, 10, 4203; doi:10.3390/su10114203

a programming software to assist with the hydraulic software is also recommended). The minimum pressure at every consumption node should be above the minimum threshold (if not, the DMPs combination is rejected) and the hourly energy audit is also calculated.

Step 3: For the *m* combination, and at every *i* time step, the number of solar panels are calculated as:

$$N_{mod}^{*} = \min\left(\max\left\{ceil\left[\left(\frac{E_{req-i}}{E_{av-i}}\right)_{m}\right]\right\}\right) \quad (6)$$

Being E_{av-i} the *i*-th value for the unitary energy available (calculated in Step 1) and E_{req-i} *i*-th value for the energy available (calculated in Step 2). The quotient $ceil\left[\left(\frac{E_{req-i}}{E_{av-i}}\right)_{m}\right]$ represent the number of solar panels to satisfy the *i*-th water demand (being "ceil" the ceiling function that takes as input a real number *X* and gives as output the least integer than or equal to *X*). The maximum of these *i* values result in the number of solar panels required for the *m* combination. Finally, a row vector of size (1,*m*) is obtained (one for each *m* combination) and the minimum of these figures should be the number of modulus (N_{mod}^{*}) obtained at the m^* combination.

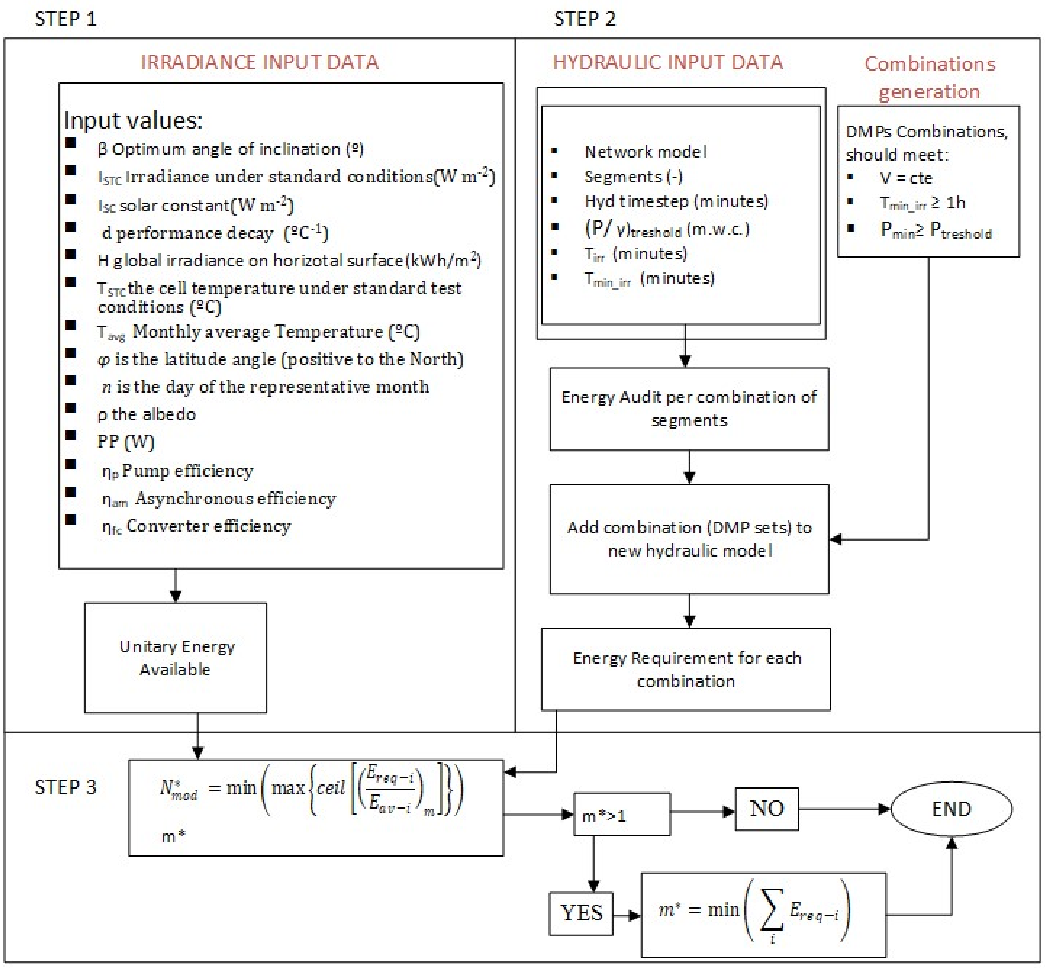
If m^* =1, this should be the final DPM (minimizing the number of solar panels), but if there are more than 1 possible combination, the selected combination should be the one with lower energy required, as flows:

$$m^{*} = \min\left(\sum_{i} E_{req-i}\right) \quad (7)$$

When $\sum_i E_{req-i}$ is the sum of the total energy required for the combinations with the lowest number of modulus (N_{mod}^{*}).

The general flow-chart of this methodology is shown in Figure 2.

Peer-reviewed version available at *Sustainability* **2018**, *10*, 4203; doi:10.3390/su10114203



$$N^*_{mod} = \min\left(\max\left\{ceil\left[\left(\frac{E_{req-i}}{E_{av-i}}\right)_m\right]\right\}\right)$$

$$m^* = \min\left(\sum_i E_{req-i}\right)$$

Figure 2. Workflow for the process to calculate the most energy efficient combination of temporal consumption

Peer-reviewed version available at Sustainability 2018, 10, 4203; doi:10.3390/su10114203

4. Numerical example

To illustrate the proposed methodology, a real case study is presented here. Two scenarios are analyzed, the 0-case (current state) and the case 1, which entails a direct pumping supplied by photovoltaic energy. The comparison has been proposed for the month with higher water demands, July. Figure 3 shows a branched irrigation network (Albamix network) in a western Mediterranean area of Spain**.** The data required to calculate irradiance curves are shown in Table 1. Albamix network supplies water to 167.7 Has which are irrigating different varieties of citrus orchards, with a usual planting pattern of 5 x 4 m2 per tree, and consists of 132 nodes and 131 pipes. The total length of the network is 4,05 km. The pipe material is PVC and the pipe roughness for the aged pipes are 0.02 mm (a usual value in water irrigation networks; [31]) and the minimum service pressure required is $\left(\frac{P}{\gamma}\right)_{treshold}$ =25 meters of water column. The irrigation networks have been grouped into five segments which have been designed under the criteria of uniformity of pressure (and consequently flow) at each subunit. The water demands required for the consumption of each segment is 79.7, 84.4, 85.4, 85.3 and 84 l/s for sectors 1, 2, 3, 4 and 5 respectively. All the subunits are equipped with drippers (4l/h per emitter) and 6 emitters are required to irrigate every tree. The irrigation management system (current state; Case 0) is based on central system scheduled delivery and the total irrigation time (T_{irr}) varies with regard to every month considered. The monthly water demands are calculated with the meteorological information recovered in the irrigation area and the reference crop evapotranspiration has been calculated from using the Penman-Monteith method from the last 13 years (from 2005-2017). Regional recommendations [32] has been followed to calibrate crop coefficients (K_c) and finally, the monthly average water needs varies from 0.31 l/m^2 in January to 3.4 l/m^2 in July. The irrigation times values are depicted at Table 2.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 October 2018 doi:10.20944/preprints201810.0387.v1

Peer-reviewed version available at *Sustainability* **2018**, *10*, 4203; doi:10.3390/su10114203

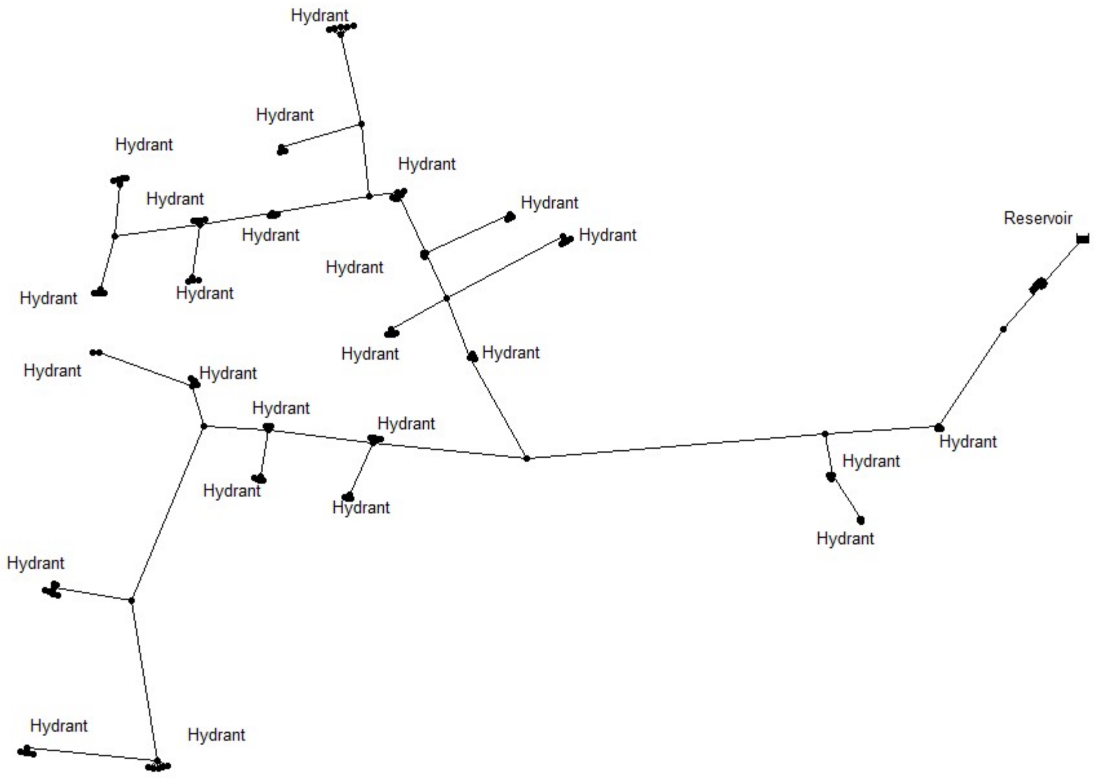


Figure 3. General layout of the network.

Table 1. Data required for Irradiance curves calculation

β= 15º	H_{avg}=8 kWh m^{-2}	n =198 (-)	η_{am}=0.8 (-)
I_{sc} =1367 W m^{-2}	T_{STC}= 25ºC	ρ = 0.2 (-)	η_{fc} = 0.95 (-)
I_{STC} =1000 Wm^{-2}	T_{avg}=24.9 ºC	PP = 250 W	
d = 0.004 $ºC^{-1}$	φ = 39.47 º	η_p=0.75 (-)	

Table 2. Monthly irrigation time (water demands) in Albamix network.

Month	January	February	March	April	May	June
Irr. time(h)	0.52	0.69	1.12	1.29	1.93	2.92
Month	July	August	September	October	November	December
Irr. time(h)	3.25	2.70	1.62	0.75	0.43	0.30

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 October 2018 doi:10.20944/preprints201810.0387.v1

Peer-reviewed version available at *Sustainability* **2018**, *10*, 4203; doi:10.3390/su10114203

The minimum irrigation time ($T_{\min\_irr}$) is equal to 1 hour (once the segment is opened, it has to be delivering water for at least 60 minutes), the time profitable to convert solar energy into shaft work in pumps is 9 hours (540 minutes) and the report time step is 10 minutes, which means that there are 540/10=54 periods of time for every subunit to be opened or closed (6 values hourly for 9 hours). In July (the month with highest water requirements), every segment should be irrigated for 3.25 hours/day (Table 2) and it means that our five (one per sector) DPMs should consider an irrigation period of 200 minutes (20 periods out of these aforementioned 54 periods should consider the segment opened while 34 periods consider the segment closed).

4.1. Irradiation Curves

The Monthly irradiation curves for Albamix Network are shown in Figure 1. These values have been obtained with the formulas described in Appendix A. As it is considered 9 hours as the time profitable to convert solar energy into shaft work in pumps, the net energy transferred to the water considers the nine hours of higher irradiance for one single PV panel (from 7.5 to 16.5h; Figure 4).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 October 2018 doi:10.20944/preprints201810.0387.v1
Peer-reviewed version available at Sustainability 2018, 10, 4203; doi:10.3390/su10114203

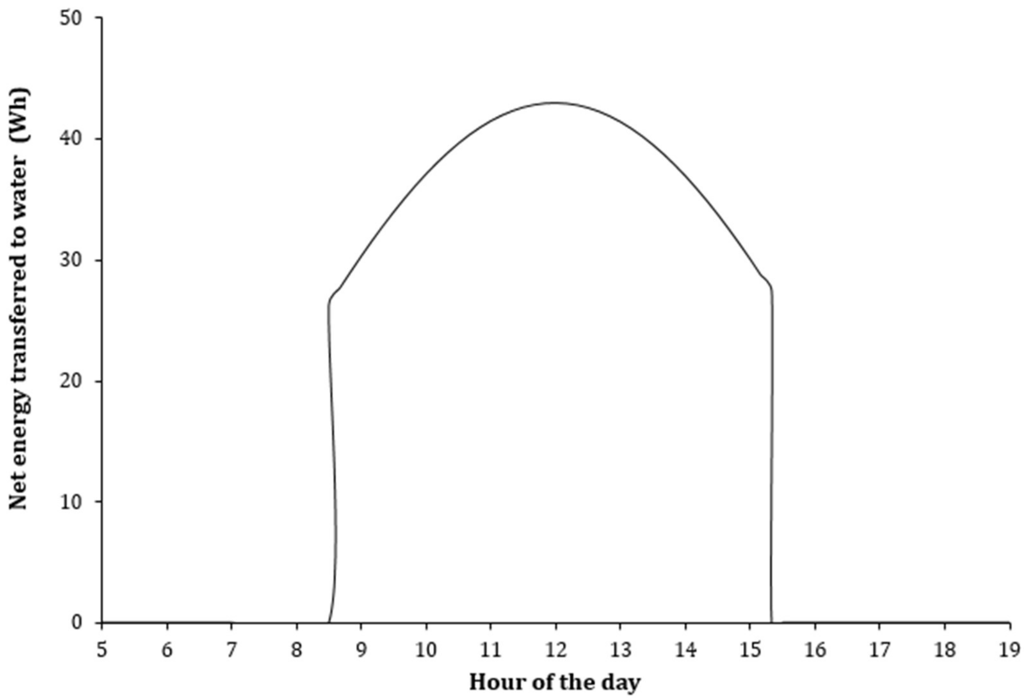


Figure 4. Net power transferred to the water for one single PV panel in the Albamix network.

4.2. Energy requirements for every segment combination Case 0

Water and energy audits have been calculated using UAEnergy for every possible combination for the case study is shown in Table 3. Being 5 the number of sectors, the possible combinations of simultaneous water demands are $\sum_{i=1}^{n=5}\binom{n}{i}$=31. Combinations for 3, 4 and 5 segments opened simultaneously are not considered as minimum pressure at some periods of the day are below the threshold pressure (combinations rejected for the current study). In short, there are only 15 possible combinations (5 individual and 10 combinations of 2 regions) for segments delivering water to crops.

4.3. Combinations performed

The combinations should include a 5x54 matrix (5 rows, one per sector and 54 columns one per every time step of 10 minutes which produces an irrigation time of 9 hours). The

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 October 2018 doi:10.20944/preprints201810.0387.v1

Peer-reviewed version available at *Sustainability* **2018**, *10*, 4203; doi:10.3390/su10114203

number of potential combinations are 5x 2^53 (a very high value even for automatic calculation). Some restrictions reduce this number of combinations, which are:

$$a_{ij} = \begin{cases} 1 & if\ open \\ 0 & if\ closed \end{cases}$$

$$\sum_{j=1}^{j=54} a_{ij}=20$$

$$\sum_{i=1}^{i=5} a_{ij} \leq 2 \qquad (8)$$

The irrigation time should be higher than 194.9 minutes for July (Table 2) and due to every time step is 10 minutes, the irrigation time should be 200 minutes (20 periods with the subunit opened). As the minimum irrigation time is 1 hour (6 time steps period), irrigation of every sector should contain at least 6 consecutive values equal to 1. The following condition $\sum_{i=1}^{i=5} a_{ij} \leq 2$ comes as a result of being impossible to irrigate more than two segments simultaneously (Table 3).

Table 3. Shaft work required and minimum pressure at every node for every water requirement combination.

Combination	*1*	2	*3*	*4*	5	1,2	1,3	1,4
Injected flow (l/s)	85.1	84.4	85.4	85.3	84	169.5	170.5	170.4
Shaft work (Kwh)	5.24	5.20	5.26	5.25	5.18	8.41	8.42	8.42
Min Pressure (m.w.c.)	42.75	40.77	39.02	38.61	38.48	30.33	29.29	28.91
Combination	1,5	2,3	*2,4*	2,5	3,4	3,5	4,5	
Injected flow (l/s)	169.1	169.8	169.7	168.4	170.7	169.4	169.3	
Shaft work (Kwh)	8.40	8.41	8.41	8.39	8.43	8.41	8.40	
Min Pressure (m.w.c.)	28.75	29.02	28.65	28.46	28.44	28.24	28.27	

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 October 2018 doi:10.20944/preprints201810.0387.v1

Peer-reviewed version available at *Sustainability* **2018**, *10*, 4203; doi:10.3390/su10114203

4.4. Results for the DPMs combinations

Finally, 10^5 potential combination meeting the restrictions before has been originated. For each combination, it has been calculated the $ceil\left[\left(\frac{E_{req-i}}{E_{av-i}}\right)_m\right]$ for the 54 time steps in order to know the number of solar panels required at every instant of the day to satisfy the i water demand. Of course, the maximum of these values result in the number of PV necessary to satisfy water demand in this combinations. So, it is calculated the number of solar panels for each of the 10^5 potential combinations (a row vector of size (1, 1x10^5) containing the panels required). Among these, 60 combinations reached the minimum value of 651 solar panels (which returns the number of modulus (N^*_{mod}) obtained at the m^* combination.

For selecting the most appropriate value, it has been calculated the total energy required for these 60 combinations, and the selected combination should be the one with lower energy required, $m^* = \min(\sum_i E_{req-i})$=428.74 kWh. The Selected DMP values are depicted in Table 4 and the relationship between the energy consumed for this result and the energy available (as a result of the panels installed) is shown at Figure 5.

Table 4. Demand Pattern multipliers and energy consumption per time step.

Time	1	2	3	4	5
0	1	0	0	0	0
0.17	1	0	0	0	0
0.33	1	0	0	0	0
0.50	1	0	0	0	0
0.67	1	0	0	0	1
0.83	1	0	0	0	1
1.00	0	0	0	0	1
1.17	1	0	0	0	1
1.33	1	0	0	0	1
1.50	1	0	0	0	1
1.67	1	0	0	0	1
1.83	1	0	0	0	1
2.00	1	0	0	0	1
2.17	1	0	0	0	1
2.33	0	1	0	0	1
2.50	0	1	0	0	1
2.67	0	1	0	0	1
2.83	0	1	0	0	1
3.00	0	1	1	0	0
3.17	0	1	1	0	0
3.33	0	1	1	0	0

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 17 October 2018 doi:10.20944/preprints201810.0387.v1

Peer-reviewed version available at *Sustainability* **2018**, *10*, 4203; doi:10.3390/su10114203

3.50	0	1	1	0	0
3.67	0	0	1	1	0
3.83	0	0	1	1	0
4.00	0	0	1	1	0
4.17	0	0	1	1	0
4.33	1	0	0	1	0
4.50	1	0	0	1	0
4.67	1	0	1	0	0
4.83	1	0	1	0	0
5.00	1	0	1	0	0
5.17	1	0	1	0	0
5.33	1	0	1	0	0
5.50	0	1	1	0	0
5.67	0	1	1	0	0
5.83	0	1	1	0	0
6.00	0	1	1	0	0
6.17	0	1	1	0	0
6.33	0	1	1	0	0
6.50	0	1	1	0	0
6.67	0	1	0	1	0
6.83	0	1	0	1	0
7.00	0	1	0	1	0
7.17	0	1	0	1	0
7.33	0	1	0	1	0
7.50	0	0	0	1	1
7.67	0	0	0	1	1
7.83	0	0	0	1	1
8.00	0	0	0	1	1
8.17	0	0	0	1	1
8.33	0	0	0	1	1
8.50	0	0	0	1	0
8.67	0	0	0	1	0
8.83	0	0	0	1	0

Table 5. Results of the energy audit for Case 0 (irrigation time 16.8 hours) and Case 1 (irrigation time 9 hours).

	Case 0	Case 1
E_N (kWh)	3134.95	3134.98
E_B (kWh)	522.66	428.74
E_U (kWh)	3634.87	3492.72
E_F (kWh)	22.70	70.94

Peer-reviewed version available at Sustainability 2018, 10, 4203; doi:10.3390/su10114203

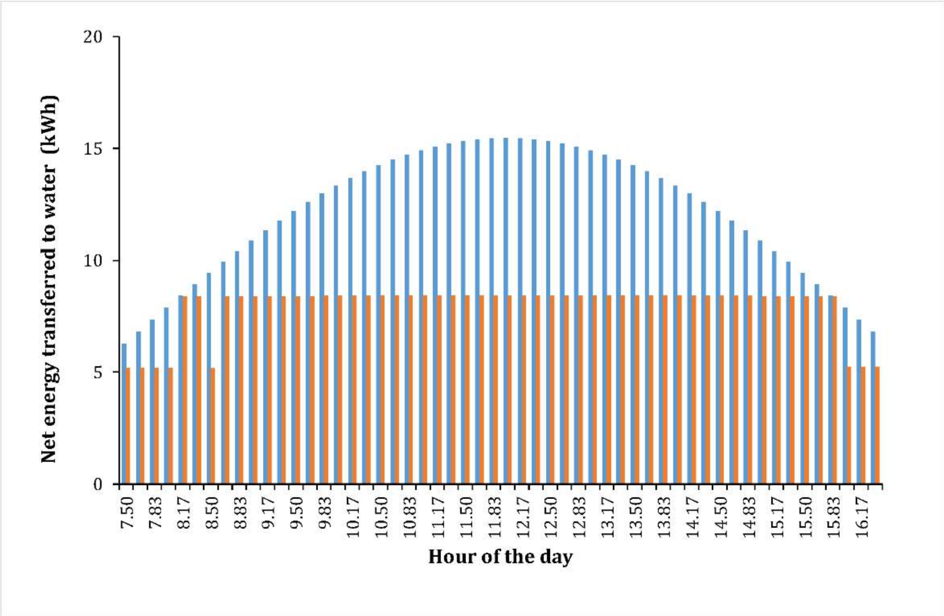


Figure 5. Hourly comparison between energy available and required in Albamix irrigation network.

4.5. Comparison between scenarios

Both case 0 and case 1 have the same injected volume 5090.44 m^3 (which also involves that natural energy remains constant as the water level in the reservoir). On the one hand, the pumping system is more energy-hungry in case 0 than in the case of operation with solar panels case 1. This is due to the fact that the irrigation time is much higher 16.8 (case 0) vs 9 hours (case 1). On the other hand, this lower irrigation time involves greater flow rates and according to this, higher friction losses. Finally, useful energy is lower in case 1 than in case 0 (maintaining the pressure above standards at every node and every hour of the day), this decrease shows a better network operating efficiency as overpressure is avoided (with the benefits inherent to reduce pressure) while reducing the energy consumption in pumps (522.66-428.74= 93.92 kWh/day).

5. CONCLUSIONS

This paper calculates the most efficient combination of hydrants and subunits opened simultaneously in an irrigation network which minimizes the number of solar photovoltaic panels and the energy consumption required to drive pumping devices directly connected to solar panels. This multi-objective optimization problem should be focused considering that water delivery should be performed delivering water with pressures above the minimum threshold service pressure in irrigation networks.

This approach should be performed after calculating crop water needs (when designing or when operating the network) and after the network segmentation (creating a constant value for the injected flow). In order to reduce the environmental impact of the network operation, solar energy source has been selected as a green alternative. This results in energy availability for a limited period of time (a consequence of the hourly irradiance curve) and an energy optimization problem arises to solve this new restriction making the energy consumption as similar as possible to energy production. The energy consumption (shaft work in pumps) is a result of the irrigation network hydraulic behavior (with some other factors involved as friction, etc.) and this is calculated with the use of a hydraulic simulation software. As this process is very time-consuming a programming software such as Matlab® code to assist has also been written to assist practitioners when dimensioning the PV array sets and another GUI (UAenergy) has also been used for calculating the energy audits in networks.

6. ACKNOWLEDGMENTS

This work was supported by the research project ‘‘GESAEN’’ through the 2016 call of the Vicerrectorado de Investigación, Desarrollo e Innovación de la Universidad de Alicante GRE-16-08.

Peer-reviewed version available at Sustainability 2018, 10, 4203; doi:10.3390/su10114203

7. REFERENCES

1. WWAP (United Nations World Water Assessment Programme). 2014. "The United Nations World Water Development Report 2014: Water and Energy". Paris, UNESCO.

2. David Molden, Theib Oweis, Pasquale Steduto, Prem Bindraban, Munir A. Hanjra, Jacob Kijne (2010). Improving agricultural water productivity: Between optimism and caution. Agricultural Water Management 97 528–535

3. Lorite, I.J., Mateos, L. and Fereres, E. (2004). "Evaluating irrigation performance in a Mediterranean environment". Irrigation Science 23 (2), 85-92.

4. Ferreres, E., and Soriano, M.A. (2006). "Deficit irrigation for reducing agricultural water use" Journal of experimental botany. 58 (2007), 147-159.

5. Greaves, E., G., and Wang, Y. (2017) "Identifying Irrigation Strategies for improved Agricultural water productivity in Irrigation Maize Production through Crop simulation Modelling". Sustainability 2017, 9, 630.

6. Jimenez-Bello, M.A., Martínez, F., Bou V. and Ayala, H., (2010). "Methodology for grouping intakes of pressurized irrigation networks into sectors to minimize energy consumption". Journal of Agricultural Engineering Biosystems engineering. Elsevier,105 (2010) 429 – 438

7. Rodriguez, J.A., López, R,. Carrillo, M.T., Montesinos, P., Camacho, E. (2009). "Exploring energy saving scenarios for on-demand pressurised irrigation networks". Journal of Agricultural Engineering Biosystems.104. Pp 552-561

8. Moreno, M.A., Córcoles, J., Tarjuelo, J.M. and J.F. Ortega, (2010). "Energy efficiency of pressurised irrigation networks managed on-demand and under a rotation schedule". Journal of Agricultural Engineering Biosystems engineering. 107 (2010) 349 – 363

9. Jackson TM, Khan S, Hafeez M. (2010)A comparative analysis of water application and energy consumption at the irrigated field level. Agric Water Management;97:14771485

Peer-reviewed version available at *Sustainability* **2018**, *10*, 4203; doi:10.3390/su10114203

10. José M.Tarjuelo, Juan A.Rodriguez-Diaz, Ricardo Abadía, Emilio Camacho, Carmen Rocamora, Miguel A. Moreno, 2015 Efficient water and energy use in irrigation modernization: Lessons from Spanish case studies. Agricultural Water Management. Volume 162, Pages 67-77

11. M. Soto-García, B. Martin-Gorriz, P.A. García-Bastida, F. Alcon, V. Martínez-Alvarez (2013) Energy consumption for crop irrigation in a semiarid climate (south-eastern Spain). Energy 55, 1084-1093

12. Chandel, S.S., Nagaraju Naik, M. and Chandel, R. (2015). "Review of solar photovoltaic water pumping system technologies for irrigation and community drinking water supplies". Renewable and Sustainable Energy Reviews, 29 (2015) 1084-1099

13. Senol, R. (2012). "An analysis of solar energy and irrigation systems in Turkey". Energy policy 47 (2012) 478-486.

14. De Soto, W., Klein, S.A. and Beckman, W.A. (2006)" "Improvement and validation of a model for photovoltaic array performance". Solar Energy, Vol 80, 78-88, 2006.

15. Elkholy, M. M. and Fathy, A. (2016). "Optimization of a PV fed water pumping system without storage based on teaching-learned-based optimization algorithm and artificial neural network". Solar Energy 139 (2016) 199-212.

16. Carrillo-Cobo, M.T., Camacho-Poyatp, E., Montesinos, P., and Rodriguez-Diaz (2014). "Assessing the potential of solar Energy in pressurized irrigation networks, The case of Bembézar MI irrigation district (Spain). Spanish Journal of Agricultural Research 2014 12 (3): 838-849.

17. Reca, J., Torrente, C., López-Luque, R. and Martínez, J. (2016). "Feasibility analysis of standalone direct pumping photovoltaic system for irrigation in Mediterranean greenhouses". Renewable Energy 85 (2016) 1143-1154.

Peer-reviewed version available at *Sustainability* **2018**, *10*, 4203; doi:10.3390/su10114203

18. Wazed, S., Hughes, B., O'Connor, D. and Calautit, J.K.S. (2018). "A review of sustainable solar irrigation systems for sub-Saharan Africa". Renewable and sustainable Energy reviews 81, Part 1:1026-1225. doi: 10.1016/j.rser.2017.08.039

19. Wettstein, S, Muir, K., Scharfy, D. and Stucki (2017). "The environmental mitigation Potential of Photovoltaic-Powered Irrigation in the production os Soth African Maize". Sustainability, 2017, 9, 1772; doi: 10.3390/su9101772

20. Rossman, L. A. (2000). EPANET 2: User´s manual, U.S. Environmental Protection Agency, Cincinnati.

21. Pardo, M.A., Manzano, J., Cabrera, E. and García-Serra, J. (2013). "Energy Audit of Irrigation Networks" Biosystems Engineering, 115(1), 89-101.

22. Duffle, J.A., and Beckman (2013) "Solar Engineering of Thermal Processes". 4th Edition Wiley ISBN: 978-0-470-87366-3

23. Betka, A. and Attali A. (2010). "Optimization of a photovoltaic pumping system based on the optimal control theory" *Solar Energy* 84(7) (2010) 1273-1283

24. Amer, E.H. and Younes,M.A. (2006). "Estimating the monthly discharge of a photovoltaic testing of a solar PV pump based drip system for orchards", *Energy Conversion and Management* 47 (15):2092-2102

25. Allen, R. G., Pereira, L. S., Raes, D., and Smith, M. (1998). "*Crop evapotranspiration; Guidelines for computing crop water requirements".* FAO Irrigation and Drainage Paper No. 56, Roma.

26. Hamlyn G. Jones (2004) "Irrigation scheduling: advantages and pitfalls of plant-based methods". *Journal of Experimental Botany*, Volume 55, Issue 407, 1 Pages 2427–2436 .

27. Courault, D., Seguin, B. & Olioso, "A. Review on estimation of evapotranspiration from remote sensing data: From empirical to numerical modeling approaches". *Irrig Drainage Syst* (2005) 19: 223. https://doi.org/10.1007/s10795-005-5186-0

Peer-reviewed version available at *Sustainability* **2018**, *10*, 4203; doi:10.3390/su10114203

28. Hoffman, G.J. Evans, R.G., Jensen, M.E., Martin, D.L., Elliot, R.L. (2007). "Design and Operation of Farm Irrigation Systems", 2nd edition. American Society of Agricultural and Biological Engineers. ISBN 1-892769-64-6

29. Jiménez Bello, MA.; Royuela Tomás, Á.; Manzano Juarez, J.; García Prats, A.; Martínez Alzamora, F. (2015). "Methodology to improve water and energy use by proper irrigations scheduling in pressurised networks". *Agricultural Water Management*. 149:91-101. doi:10.1016/j.agwat.2014.10.026

30. Replogle, J.A., Gordon, E., (2007). "Delivery and distribution systems". *Design and Operation of Farm Irrigation Systems*, 2nd edition. American Society of Agricultural and Biological Engineers. ISBN 1-892769-64-6

31. McGovern, J. (2011)." Technical Note Friction Factor Diagrams for pipe Flow". Dublin Institute of Technology, 2011.

32. Castel, J.R., (2000). "Water use of developing citrus canopies in Valencia, Spain". *Proceeding International Society Citriculture*, IX Congress:223-226