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ADAPTATION OF PRESSURIZED IRRIGATION NETWORKS TO NEW STRATEGIES OF IRRIGATION MANAGEMENT: ENERGY IMPLICATIONS OF LOW DISCHARGE AND PULSED IRRIGATION

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ABSTRACT

This paper analyzes the consequences of adopting new on-farm irrigation management strategies (low discharge rates, long irrigation times and high frequencies) in an existing on-demand and sectorized pressurized irrigation system in eastern Spain. The sectorized behavior of the network was analyzed using two criteria: i) the operating sectors obtained in a first stage by arranging the hydrants depending on their altitude respecting the pumping station and ii) the operating sectors obtained by means of an optimization process. The Simulated Annealing combinatorial metaheuristic optimization technique was employed to find the best solution. Random on-demand patterns were generated using a Montecarlo simulation. The hydraulic requirements of the network were analyzed in every scenario by the Epanet 2.0 engine. The effect on energy consumption, power requirements and energy costs was assessed taking into account the electricity tariff billing structure. It was found that reductions in emitter discharge (q_e) and Energy consumption (E)-Energy Cost (EC) savings are not inherently related to each other. Certain amounts of E and EC could be saved when the number of sectors and operating time parameters were properly selected. Pulsed irrigation in the current scenario showed an energy saving potential of 10.67, 6.43 and 6.99% for power capacity, E and EC, respectively.

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Keywords: Energy optimization; on-demand and sectorized performance; pressurized irrigation network; Continuous irrigation irrigation; pulsed irrigation.

HIGHLIGHTS

- Consequences of adopting new on-farm irrigation management strategies on energy consumption and electric costs in a pressurized irrigation network were analyzed.
- Reductions of emitter discharge and energy consumption or energy cost savings are not inherently related to each other.
- Pulsed irrigation in the current scenario showed an energy saving potential.

LIST OF TABLES

LSIT OF FIGURES

1. Introduction

In many Mediterranean countries traditional irrigation schemes have been modernized during the last two decades. This updating of the irrigation facilities consisted of substituting ancient open-cannals-based transport, distribution, and surface watering systems by pressurized piping systems (Plusquellec 2009) in an attempt to achieve several advantages: a) reduce water losses during transport and application, b) overcome topographic constraints, c) avoid uncontrolled water withdrawals, and d) invoice the exact amount of water consumed on each farm (Lamaddalena and Sagardoy, 2000; Daccache et al., 2010). In addition, pressurized irrigation networks make it possible to implement new and more efficient on-farm irrigation systems, mainly drip and sprinkler irrigation. This entire process has derived in an increase of the water use efficiency but simultaneously it involves a notably increase in energy consumption (IDAE, 2008), especially in sprinkler irrigation. Many studies can be found in the literature aimed at assessing the behavior of pressurized irrigation networks in order to improve their energy consumption (Fernandez et al., 2013, 2014, 2015; Diaz et al., 2009; García-Prats, 2012; Gonzalez et al., 2014; Jimenez-Bello et al., 2010, 2015; Rodriguez Diaz et al., 2007, 2012; Tarjuelo et al., 2015;). The large number of these studies is an indication of the importance of this issue.

Drip irrigation has been traditionally recommended for row crops, vines and trees (Brouwer et al., 1988) although its many proven advantages has meant that its use has been extended to almost all types of crops. Its most significant advantages include: i) higher water use efficiency (Daccache et al., 2010), ii) lower energy requirements than other pressurized irrigation systems and iii) higher yields and better quality of harvested crops (Vyrlas and Sakellariou, 2005). The increased use of drip irrigation is seen as one way of improving the sustainability of irrigation systems around the world (Cote at al., 2003). The potential efficiency of drip irrigation is generally accepted to be around 90%, however we should not lose sight of the fact that this value is not an inherent property of the system, but a function of its management (Smith, 2010).

Discharge rates and irrigation times and frequencies are the most important management-related parameters.

Continuous irrigation (sometimes named microdrip irrigation in the literature) is defined as a drip irrigation system that supplies water at a rate close to that of plant water uptake in order to improve irrigation efficiency and yields and reduce water losses from drainage below the root zone (Assouline et al., 2002a, 2002b). However, soil moisture regimes similar to those resulting from continual low water application rates can be achieved by means of pulsed drip irrigation at higher discharge rates (Phogat et al., 2013). Pulsing involves the application of the same total amount of water and irrigation time but in a phased manner, i.e. fractioned into a series of *on-off* irrigation cycles.

Searching for the best management system to make the most of drip irrigation, several recent works deal with different management strategies in a combination of continuous and pulsed irrigation (Assouline, 2002; Assouline et al., 2002; Elnesr et al., 2015; Elnesr and Alazba, 2015; Segal et al., 2006; Vyrlas and Sakellariou, 2005; Phogat et al., 2012-2013; Skaggs et al., 2010; Elmaloglou and Diamantopoulos, 2007; and Cote at al., 2003). In several cases they found enhanced yields, efficiency, salt distribution and fertilizer leaching using low rates, high frequency and pulsed irrigation. In other cases they found no differences between management strategies, but in no case have worse results been reported from continuous or pulsed irrigation. Hence, both these methods are promising fields that should be considered in order to achieve more efficient use of irrigation water, but not only on the farms themselves, since overall efficiency is the product of all the efficiencies obtained from the entire network (storage, conveyance, distribution, application, etc).

Due to the interaction between the pressurized irrigation network, its pumping station and on-farm irrigation systems (Lamadalena et al., 2007; Daccache et al., 2010; Gonzalez et al., 2014), it could be expected that any change on the irrigation management strategy would have new associated scenarios with different headlosses in pipes and requirements for operating time, total discharge and pressure head in the pumping station in comparison to those one of the currently used system. In addition, every new scenario will have other associated energy implications, related not only to energy consumption, but also to the electricity billing structure. These consequences could be expected to be different if the pressurized irrigation network was planned to perform on-demand or sectorized.

Hence, the objective ofthis work was to analyze the consequences of adopting new strategies of on-farm irrigation management (low discharge rates, large irrigation times and high frequencies) in a pressurized on-demand and sectorized irrigation network in the east of Spain, taking into consideration the interaction all those new strategies with the electricity tariff billing structure.

2. Method

2.1. Discharge calculations of on-demand performance

A lot of pressurized irrigation networks have been scheduled to work on-demand; water is delivered from the network with enough pressure to meet the on-farm irrigation system requirements, and the farmer to decide the duration and frequency of operation. The number of hydrants that operates at the same time is determined using a stochastic process. Divers methods can be found in the literature to determine the network discharge when operates on-demand. We used the Clément's 1st formula method (Clément, 1966), in which the state of each hydrant (open or closed) is supposed to fit a binomial statistical distribution, tending to a normal-Gaussian statistical distribution whether the number of hydrants operating is sufficiently high.

When a network operates on-demand, its pumping station have to be prepared to provide the maximum discharge rate equivalent to the envelope of all possible discharge rates for a certain operation quality (Lamaddalena and Sargadoy, 2000; Moreno et al., 2007). At the same time has to provide enough pressure at the origin of the network (pumping station) to ensure that at the most unfavorable hydrant the pressure head is greater than the minimum required to operate the on-farm irrigation system. Nonetheless, the same discharge flow-rate Q_{di} could be obtained from many different open-hydrant combinations, each of them requiring their own pressure H_i. Hence, whilst the network is operating it is stochastically drawing a cloud of pairs of values Q_{di}-H_i, that depends on what hydrants are opened at that moment.

Therefore, each combination of opened hydrants involves a pump operating point (Q_{di}-H_i-η_i) with a specific energy consumption.

Clément Method

In the Clément's 1st formula method, the discharge flow-rate at the origin of the network associated to a certain probability P_q of not being exceeded (Clément, 1966) is obtained as follows:

$$Q_d = \sum_{i=1}^{n} p_i d_i + U(P_q)\sqrt{\sum_{i=1}^{n} p_i q_i d_i^2} \qquad (1)$$

where Q_d is the discharge flow-rate (L s^{-1}) at the origin of the network that supplies n hydrants associated to a probability P_q of not being exceeded (It should be noted that P_q is named supply guarantee or operation quality –*OQ*- as well, i.e. is the probability to meet the desired flow and pressure conditions in the network when the user decides to water); p_i is the probability of finding the hydrant i open; $q_i=1-p_i$ is the probability of finding the hydrant i closed; d_i is the nominal discharge (L s^{-1}) of hydrant i; and U (P_q) is the standard normal cumulative variable for probability P_q.

1st Clément's model is based on two hypotheses: (a) the state of the hydrant (open or closed) fits a binomial statistical distribution and each hydrant operates independently and at random. (b) Every hydrant has the same opening probability to each other at any time of the day and at any day of the week (Rodriguez Diaz et al., 2007; Monserrat et al., 2004). When enough hydrants downstream are operating, the discharge flow-rate fits a normal-Gaussian statistical distribution. Hence, the average opening probability of each hydrant i (Moreno, et al., 2007) can be calculated as:

$$\mathrm{p_i = \frac{N_s\, t_r}{OT\, IR} = \frac{t_d}{OT}} \qquad (2)$$

where N_s is the number of drip irrigation subunits per farm; *OT* is the network daily operation time (h d^{-1}); t_r is the irrigation time to meet the crop water needs (h); *IR* is theirrigation interval (d); and t_d is the average daily irrigation time (h d^{-1}).

For each hydrant, the nominal discharge d_i was calculated as follows(Alandi, et al*.,* 2001):

$$d_i = A_{rs} \frac{\mathrm{S_i}}{\mathrm{N_s}} 2.778 \qquad (3)$$

being 2.778 a coefficient to adapt units $\left(\frac{10{,}000\ \mathrm{m^2\ ha^{-1}}}{3{,}600\ \mathrm{s\ h^{-1}}} \right)$; A_{rs} is the average on-farm irrigation system application rate (L m^{-2} h^{-1}); S_i is theplot area (ha).

The irrigation time needed to meet the crop water needs was obtained as follows (Alandi, et al. 2001):

$$\mathrm{t_r = \frac{IR\ \ NT_r}{A_{rs}}} \qquad (4)$$

where NT_r is the peak period crop gross irrigation needs (L m^{-2} d^{-1}).

Montecarlo simulation

Following Moreno, et al. (2007), Clément's method can be transformed () to:

$$\mathrm{Q_d} = \mu + \mathrm{U(P_q)}\,\sigma \qquad (5)$$

where μ is the mean of normal density function equivalent in this case to the average discharge flow-rate, and σ *is the* standard deviation of discharge flow-rate.

Therefore, it was able to conduct a Montecarlo simulation in which the state (open or closed) of each hydrant was defined as a stochastic variable r_i with a binomial performance. The probability of finding a hydrant open, as was previously defined, is known and is equal to p_i. When in an iteration of the Montecarlo simulation, the random variable takes the value $r_i = 1$, hydrant *i* is open and produces a discharge equal to the nominal discharge d_i. When the random variable takes the value r_i=0, that hydrant is closed and any discharge will be done. In each iteration the discharge flow-rate at the origin of the network was calculated as:

$$Q_{di} = \sum_{i=1}^{n} r_i \, d_i \qquad (6)$$

After enough iterations (identified because the average discharge flow-rate μ does not change up to a specific tolerance with further iterations) is possible to obtain the average discharge flow-rate, the standard deviation (previously defined as σ in Eq.(5)), as well as the Q_d for all the percentiles without needing to apply Clément's 1st formula. Note that the result obtained when Eq.(5) is applied with a given operation quality (*OQ*) is tantamount to the one obtained in the Montecarlo simulation for a percentile equals to *OQ*.

The main benefit of using a Montecarlo simulation procedure instead of a single design discharge flow-rate, as it happens when the Clément's 1st formula is used, is that multiple scenarios of stochastically generated open-hydrant combinations can be derived. Each of these combinations can be further analyzed using Epanet and H_i values associated to each value of Q_{di} obtained.

Effect of pulsing irrigation

As previously mentioned, pulsed drip irrigation involves the same amount of water and time as continuous drip irrigation, but divided into a number of phases. To put it into practice, the network manager has to divide operation time by the number of irrigation cycles. For example, if t_d = 3 h and *OT*=15 h and pulsed irrigation is done in three pulses, the farmer has water three times a day with $1/3 \cdot t_d$ = 1 h per cycle: the first from 1 to 5 h, the second from 6 to 10, and the last from 11 to 15 h with total freedom in each period. The effect on the random pattern generation is related to the statistical concepts of the Central Limit Theorem and the Principle of

Diversification. Splitting *OT* into three independent periods, the behavior of a given hydrant throughout the day is the mean value of three independent random variables with the same opening probability ($p_i = \frac{t_d}{OT} = \frac{1}{5} = \frac{3}{15} = 0.2$) with binomial behavior. Consequently, a similar mean value of Q_{di} is obtained, but with a substantial reduction in the variance. Further information on the diversification principle can be found in Savage (2003) and Rachev et al. (2006).

2.2. Calculating discharge in operating-sector operations

Many studies have confirmed that on-demand pressurized irrigation networks have large energy requirements (García-Prats et al., 2012; Jiménez-Bello, 2015). An existing alternative to the on-demand performance is to divide the network into turns named operating sectors as well. A group of hydrants operating simultaneously at a given time form a turn or operating sector (García-Prats, 2012). As was aforementioned, the nominal discharge of each hydrant d_i could be derived from the Eq.(3). Hence,the total discharge flow-rate of an operating sector Q_{si} could be obtained by summing the discharges of those hydrants that operates simultaneously during a given period:

$$Q_{si} = \sum_{i=1}^{n} d_i \qquad (7)$$

NS is the number of turns or operating sectors and have to be consistent with the daily time required per hydrant to water *(t_d)* with the purpose to be capable of providing water to overall the network's hydrants along the daily operation time *(OT).*

$$OT \geq \mathrm{NS}\, t_d \qquad (8)$$

Effect of pulsing irrigation

In contrast to on-demand, in sectorized performance no effects were expected due to pulsed irrigation management. A turn or operating sector has been defined as a group of hydrants that operates simultaneously at a given time. Each time these hydrants work together, the same point

Q_{si}-H_i-η_i will be obtained, so that power capacity demand and energy consumption will also be the same.

2.3. Hydraulic Simulation: Pressure head requirements per scenario

Each open-hydrant combination do not only produces a turn or sector but a hydraulic scenario as well, regardless whether its type of performance is on-demand or sectorized. Therefore, each hydraulic scenario will require a certain value of pressure at the origin of the network H_i, in order to guarantee the minimum pressure condition in the worst-pressure hydrant. H_i was obtained using software of hydraulic simulation, specifically Epanet V2 model (Rossman, 2000). EPANET is public domain software developed by the Environmental Protection Agency (EPA) of the United States, which models pressurized pipe networks and performs extended period simulations of the water movement and quality behavior. The result of the hydraulic simulation is composed by pairs of values, Q_{si}-H_i or Q_{di}-H_i , as appropriate.

It should be noted that the worst-pressure hydrant for each scenario was selected among the opened hydrants. Non-operating hydrants only require positive pressures.

2.4. Energy Consumption and Pumping Station Regulation

The efficiency (Q-η) and characteristic (Q-H) curve of commercial pumps with fixed-speed at nominal revs can be approached as follows (Planells, et al., 2005):

$$\begin{cases} H = C + D\,Q^2 \\ \eta = E\,Q + F\,Q^2 \end{cases} \qquad (9)$$

where H is the pressure (m) produced by a pump unit when the discharge flow-rate is Q (L s^{-1}); η is the pump efficiency (%); C, D, E, F are the pump parameters derived from the characteristic curves provided by the pump manufacturer;

Eq.(9) can be adapted to work with pumps of variable speed using the affinity laws (Planells, et al., 2005):

$$\begin{cases} H = \alpha^2\, C + D\, Q_1^{\,2} \\ \eta = \dfrac{E}{\alpha} Q_1 + \dfrac{F}{\alpha^2} Q_1^{\,2} \end{cases} \qquad (10)$$

Where N_0 is the nominal pump revs; α is the pump relative speed *(*$\alpha = N_p/N_0$*);*, N_p is the pump revs at a given time; Q_1 is the discharge flow-rate of one variable-speed pump whether the pressure was H and the pump spins at α relative revs.

The required power capacity of each hydraulic scenario in a pumping station composed of N_{fs} equal fixed-speed pump units and N_{vs} equal variable-speed pump units arranged in parallel could be obtained as follows (Planells, et al., 2005):

$$P_{abs,i} = \frac{0.00981\, Q_{vs}\, H}{\dfrac{E}{N_{vs}\, \alpha} Q_{vs} + \dfrac{F}{N_{vs}^{\,2}\, \alpha^2} Q_{vs}^{\,2}} + \frac{0.00981\, Q_{fs}\, H}{\dfrac{E}{N_{fs}\, \alpha} Q_{vs} + \dfrac{F}{N_{fs}^{\,2}\, \alpha^2} Q_{fs}^{\,2}} \qquad (11)$$

where Q_{vs} is the total discharge flow-rate of variable speed pump units (L s^{-1}); Q_{fs} is the total discharge flow-rate of fixed-speed pump units (L s^{-1}); $P_{abs,i}$ is the power capacity required by pumping station (kW) in a given scenario; , ; being *(*$Q_{vs} + Q_{fp}$*)* equals to Q_{si} or Q_{di} as appropriate.

In order to control the pressure head, a programmable logic controller (PLC) and a pressure transducer is usually installed at the pumping station. Shared regulation is usually employed in variable-speed pump units, *i.e.* all of them spin at the same speed and are always in operation. Initially only variable-speed pumps operate until the required discharge flow-rate surpasses its discharge capacity. At that moment one fixed-speed pump unit starts up. At this point in time the discharge flow-rate of all the fixed-speed pumps Q can be derived using the Eq.(9) when the pressure head required at the origin of the network is H_i. In order to obtain the number of fixed-speed pump units to supply the discharge-pressure needs, the integer of this quotient has to be done:

$$N_{fs} = \frac{Q_{si}}{Q} \text{ or } \frac{Q_{di}}{Q} \text{ as appropriate} \qquad (12)$$

Thus,

$$Q_{fs} = Q\, N_{fs} \qquad (13)$$

The discharge flow-rate of each variable-speed pump unit will be derived as follows:

$$Q_1 = \frac{(Q_{si} - Q_{fs})}{N_{vs}} \quad \text{or} \quad Q_1 = \frac{(Q_{di} - Q_{fs})}{N_{vs}} \quad \text{as appropriate} \qquad (14)$$

Pump revs α could be obtained using the Eq.(10), after Q_1 is calculated.

N_{vs} have to be an attribute previously known of the pumping station.

Finally, the energy consumption when the network operates sectorized is given by:

$$E = \sum_{i=1}^{NS} P_{abs,i}\ t_d \qquad (15)$$

Where E is the daily energy consumption in the most water-demanding month, (July) in kW h d^{-1}.

However, to obtain the energy consumption in on-demand operating networks, it is necessary to calculate the time the pumping station is working into each Q_{di}-H_i point, using the relative frequency table derived from the Montecarlo simulation (Moreno et al., 2009). To this end, the discharge flow-rate range (0 to $Q_{di,max}$) was split in ten intervals (discharge deciles), and each one of them in ten pressure subintervals (pressure deciles $H_{i,min}$ to $H_{i,max}$). Calculating the relative frequency under which the pumping station works in each interval, was possible to infer the percentage of daily operation time –*OT*- the pumping station performs at a certain operating point Q_{di}-H_i-η_i, and so obtain its energy consumption (one day in the the most water-demanding month –July-, in kW h d^{-1}).

2.5. Turn or Operating Sector arrangement

The turns or operating sectors could be obtainedin a first stage by sorting out the hydrants depending on their altitude in relation to that of the pumping station. The hydrants are placed from lowest to highest and their discharge flow rates are summed up, forming *NS* turns with similar Q_s. Each one of those turns or sectors requirescertain pressure to ensure that at the most unfavorable hydrant the pressure head is greater than the minimum required to operate the on-farm irrigation system. If variable-speed pump units exist, the pumping station might adapt its performance to the different turn pressure head requirementss. In this way some energy savings should be expected with respect an alternative arrangement in which both low and high altitude hydrants (which would require always high pressure). However, it is proved that this type of turn arrangement remains very inefficient if head losses were higher than the drop itself (García-Prats et al., 2012).

Studying all the possible configurations in order to select the best one involves an unacceptably high computational effort (Lamaddalena and Sagardoy, 2000). Since it is not likely to explore all the existing open-hydrant combinations, we needed a method to allocate the hydrants to the best turn or sector from an energy point of view. We used the Simulated Annealing (SA) algorithm. SA is a heuristic algorithm of combinatorial optimization. The daily energy consumption *E* (kW h d^{-1}) during one day of the peak demand month (July) (Eq.12) was employed as objective function. The kickoff scenario was an operating sector arranged according to the aforementioned method of the elevation criteria. In each iteration, the algorithm analyze a new configuration in the neighborhood of the previous one and its energy consumption is evaluated. The new configuration includes the whole set of hydrants working in the current turn or sector save one. One hydrant (from 1 to *n*) is selected at random, and one operating turn or sector (from 1 to *NS*) is selected at random as well. The chosen hydrant leaves the current turn and starts to operate in the selected one. This new scenario is simulated using the EPANET model with the purpose to obtain the energy consumption. When the new scenario is not hydraulically feasible or do not improve the objective function, will be immediately rejected and a new one is searched for. When a hydraulically feasible scenario is obtained, energy consumption has to be better than the one obtained in the previous scenario but may or may not be accepted depending on the Metropolis criterion. In case of acceptance, this combination was employed as the starting point for the next iteration, if not accepted the previous one was used to start a new iteration. Further information on this algorithm can be found in García-Prats et al. (2012).

In order to check the hydraulic feasibility, a turn or operative sector has to meet two criteria: a) all the links of the network have a velocity lesser than 3 m s^{-1}, b) the pressure is greater than zero in non-operating hydrants and greater than 25 m in the operating hydrants and other nodes.

2.6. Electricity tariff structure

The electricity tariff is divided in two terms: the first one is related to the energy consumption and the second one that considers the maximum demand of power capacity. Both of them have a different price, according to the time of day at which the energy consumption takes place. The energy term is a Time of Use (TOU) rate with three different usage periods: OFF-PEAK (8 h per day), MID-PEAK (10 h per day) and PEAK (4 h per day) with charges that vary accordingly. The power capacity term is a Demand Rate Tariff (DR). Users have to contract for a certain power capacity. The electricity meter registers the maximum value of instantaneous power capacity demanded during the entire usage period. If the maximum power capacity registered takes a value less than 105% of the contracted capacity, the bill will be for the contracted power capacity, otherwise a high penalty will be applied on the off-contract power used. This means that customers normally contract for a sufficient capacity to meet their normal maximum requirements. Power capacity demanded during each usage period is invoiced to its specific price.

2.7. Case Study

The area chosen to test the energy effect of new strategies of on-farm irrigation management was a traditionally irrigated citrus-growing area in the Valencian Community, region located in the east of Spain . Since 1998, when the collective irrigation facilities were modernized, the system employed to distribute irrigation water is a flow-driven pipeline distribution network. The on-farm irrigation system installed was drip irrigation. This method substituted the previous canal and the on-farm surface irrigation system. The total irrigated area is 191.15 ha with a total of 382 hydrants in individual plots, clustered in 47 control units. The pumping station has three N_0=2900 rpm and 63 kWpumps. Only one pump is variable-speed –i.e. equipped with an adjustable frequency drive- being the others fixed-speed pump units. The pump coefficients derived taking into account the characteristic curves supplied by the manufacturer were: F=-0.021631; E=2.546664; D=-0.007729; C=120.228854.

Peak gross crop irrigation requirements (calculated as average of July) was 3.95 L m^{-2} d^{-1}. Since the landscape is high parceled, a single subunit N_s per plot was found, and therefore $t_r = t_d$. The irrigation interval (*IR)* was fixed at 1 due to the fact that in drip irrigation watering usually take place on a daily basis.

A_{rs} was defined as the average on-farm irrigation system application rate (L m^{-2} h^{-1}). The crop pattern encountered in this area is the one typical used for Citrus trees with 375 plants per hectare and 8 drippers with an emitter discharge q_e=4 L h^{-1}. Therefore A_{rs}:

$$A_{rs} = 375x8x4 = 12{,}000 \text{ L h}^{-1} \text{ ha}^{-1} = 1.2 \text{ L h}^{-1} \text{ m}^{-2}$$

Irrigation-related variables t_d and d_i were derived as follows:

$$t_r = \frac{NT_r\ IR}{A_{rs}} = \frac{3.95x1}{1.2} = 3.29 \text{ h} \qquad d_i = 2.778 A_{rs} \frac{S_i}{N_s} = 3.336\ S_i$$

The pressurized irrigation network currently works on-demand with an operation time OT = 16 h d^{-1} in order to avoid paying the peak-rate tariff. Five operating sectors (*NS*) are close to 16 h d^{-}

^{1} because 3.29 h x 5 = 16.45 h d^{-1}. In order to compare homogeneous results between on-demand and sectorized performance, in on-demand performance scenarios *OT* was adapted to the sectorized *OT* obtained for each simulated scenario. Hence, when the current on-demand performance was compared with sectorized operations, on-demand *OT* was fixed at 16.45 h d^{-1} in order to compare the results for all the analyzed scenarios.

Table 1 summarizes the 2015 electricity tariffs.

Please Insert Table 1 here

Finally, applying Eq. (4) we obtain the last related irrigation parameter p_i:

$$p_i = \frac{N_s\ t_r}{OT\ IR} = \frac{1x3.29}{16.45x1} = 0.2$$

2.8. Continuous and pulsed irrigation scenarios

As the analyzed network and its pumping station were designed to work as described above, we did not search for more demanding scenarios (with lower *NS*-*OT* and higher p_i) as they would not have been hydraulically feasible. However the network is able to work with lower emitter discharges and higher *NS*-*OT* values when the discharge is maintained at the current value (q_e=4 L h^{-1}). As pulsed irrigation was only expected to affect on-demand performance, the scenarios analyzed were those shown in Table 2. Each scenario was simulated under 5 different performance conditions: 1) SecElv: sectorized operation by first arranging the hydrants according to their elevation, 2) SecSA: sectorized following the above-described SA optimization procedure in order to obtain the best hydrant arrangement, 3) Dem1: operating on-demand under continuous irrigation (one pulse), and 4) Dem2 - 5) Dem3: operating on-demand under pulsed irrigation with two and three pulses, respectively.

Please Insert Table 2 here

3. Results and discussion

As can be seen in Table 2, 46 different scenarios were considered to show the effect on energy consumption of new irrigation management strategies (Continuous and pulsed irrigation) in pressurized irrigation networks.

3.1. Continuous irrigation

All the scenarios under continuous irrigation management were assessed first (SecElv-SecSA-Dem1 in Table 2). Figures 1a, b and c show the evolution of P_{abs} (kW), power capacity, E (kW·h), daily energy consumption in the most water-demanding month (July) and EC (€) electricity costs for the same period in the different scenarios.

Please Insert Figure 1 here

Comparing the different scenarios: Scenarios 1, 2 and 3 represent the current on-farm irrigation system with increased OT and NS. Scenarios 4, 5 and 6 have different emitter discharge rates from Scenarios 1, 2 and 3. Now q_e=3 L h^{-1} instead of q_e=4 L h^{-1}. Irrigation time thus needs to be longer, and three different scenarios could be created, keeping OT near the $16<OT<24$ h range, as can be seen in Table 2. Scenarios 7 and 8 were formed using q_e=2 L h^{-1}. Scenarios 9 and 10 were obtained for q_e=1 L h^{-1} and q_e=0.8 L h^{-1} respectively.

As can be seen in Figure 1, when all the performance types were compared, the following rule can be derived regardless of the scenario analyzed: P_{abs} in both sectorized performance types (SecElv and SecSA) showed similar behavior, requiring considerably less power capacity than Dem1. Focusing on the energy consumption E, Dem1 was characterized by a high-energy demand, followed closely by SecElev, while SecSA required significantly less energy.

However, when *E* was translated into energy costs *EC,* this effect became more pronounced and SecElev and Dem1 showed similar very high *EC* while SecSA showed lower *EC* values.

It can be seen that, as a general rule, irrigation networks in on-demand or sectorized operations in which the operating sectors have been designed without any or with incorrect criteria leads to a high-energy demand and energy costs. However, if optimization techniques are used to organize hydrant performance, considerable energy and cost savings can be achieved (García-Prats et al., 2012; Jimenez-Bello et al., 2015).

In the analysis of specific scenarios, comparing the current on-farm irrigation system (Scenario 1 compared to itself *i.e.* compared to Scenarios 2 and 3, the observed abatement of capacity P_{abs} obtained by increasing *NS* and *OT*, only gave energy savings in SecSA performance, but in no case showed cost savings. We can therefore see that the decision of the network managers to limit the *OT* to OFF-PEAK and MID-PEAK to avoid the PEAK period was a good choice.

In Scenarios 4, 5 and 6, as regards P_{abs} , increasing *OT* and *NS* lowered the required capacity in all types of performance. However, *E* only decreased in SecSA and increased in the other two types. *EC* increased in all types of performance. The same trend was observed in Scenarios 5 and 6. All the performance types tend to converge in Scenarios 9 and 10, due to the lack of freedom to irrigate.

However, comparing the scenarios that use the current emitter discharge rate of q_e=4 L h^{-1} (Scenarios 1, 2 and 3) with those that use the lower rate of q_e=3 L h^{-1}etc. (Scenarios 4, 5 and 6) we see that the results depend on *OT* and *NS.* Table 3 summarizes the maximum differences obtained by comparing the current Scenario 1 with the most efficient scenario, expressed in absolute values and percentages, excluding Scenarios 2 and 3, which belong to the current on-farm irrigation system (q_e=4 L h^{-1}).

Please Insert Table 3 here

Reductions in q_e and *E-EC* savings are not inherently related to each other. A certain amount of *E* and *EC* could be saved when *NS* and *OT* parameters are properly selected, especially when the network operates on-demand. In addition, the interaction between the energy variables *OT* and *NS* with the power company's billing structure must be taken into account, since energy savings are not always translated into cost savings. For example, for Dem1, Scenarios 7 and 8 showed *E* savings over Scenario 1, but only Scenario 7 had *EC* savings. On the other hand, Scenario 8 showed a considerable increase in *EC* due to the use of power during the peak time.

To sum up, as the best results were obtained by using optimization techniques (SecSA scenarios) to organize operating hydrants, and similar *EC* could be obtained with different emitter discharges. Hence, the main potential for savings in *E* and *EC* could be related to on-demand performance.

3.2. Pulsed irrigation

This section gives the results of the pulsed-irrigation scenarios (Dem1-Dem2-Dem3) with one, two or three pulses (see Table 2). Table 5 summarizes the P_{abs} - *E* – *EC* obtained in these scenarios. Figures 2a, b and c show the evolution of P_{abs} - *E* - *EC* in the different scenarios.

Please Insert Figure 2 here

As can be seen in Figure 2, when the number of pulses is compared the following rule can be derived: P_{abs} in all cases (Dem1, Dem2, and Dem3) showed similar behavior and the higher the pulse rate the less the P_{abs} required. Focusing on energy consumption *E*, performance was characterized by a decrease in energy consumption, *i.e.* energy demand dropped with more pulses. When *E* was translated into energy costs *EC,* this effect still remained. We can thus claim that, as a general rule, in irrigation networks operating on-demand, pulsed irrigation leads to savings in power capacity, energy demands and electricity costs. In Scenario 1 pulsed irrigation showed an energy saving potential of 10.67, 6.43 and 6.99% for P_{abs}, *E* and *EC,* respectively.

Analyzing specific scenarios, starting with the current on-farm irrigation system (Scenario 1) compared to itself, and Scenarios 2 and 3: increasing *OT* in all cases showed a drop in P_{abs}, but in no case resulted in *E* or *EC* savings. Hence, the decision made by the network managers to limit *OT* to OFF-PEAK and MID-PEAK usage periods to avoid the PEAK period is also seen to be a good choice in pulsed irrigation. Exactly the same behavior was observed for Scenarios 4-5-6 and 7-8.

Nevertheless, comparing the scenarios formed by the current emitter discharge rate of q_e=4 L h^{-1} (Scenarios 1, 2 and 3) with those at the lower discharge rate of q_e=3 L h^{-1} etc. (Scenarios 4, 5 and 6), we observe that the most important parameter was *OT* and its interaction with the billing structure. Scenarios with similar *OT* had similar *E* and *EC*, regardless of emitter discharge rate, *e.g.* Scenario 1 *vs* Scenario 4. As happened in the continuous irrigation scenarios, increasing *OT* reduced P_{abs} but increased *E* and *EC*.

4. Conclusions

In this work forty-six different scenarios were considered to illustrate the effect on energy requirements of new irrigation management strategies (Continuous and pulsed irrigation) in pressurized irrigation networks.

Continuous irrigation in networks operating on-demand or sectorized with sectors created without any criteria lead to high energy demands and thus high energy costs. However, significant energy and cost savings can be achieved by employing optimization techniques to organize hydrants performance that proved to be crucial. These savings can be consolidated when new strategies of on-farm irrigation management are implemented. However reduced q_e and *E-EC* savings are not inherently related to each other. A certain amount of *E* and *EC* can be saved when *NS* and *OT* parameters are carefully selected, especially operating on-demand. It is also crucial to take into account the interaction between the *OT* and *NS* energy variables with the electricity billing structure, since energy savings are not always translated into cost savings, especially when peak time electricity is used.

Pulsed irrigation in networks operating on-demand leads to savings in power capacity, energy demand and electricity costs. The most important parameter related to energy savings was *OT* and its associated interaction with the billing structure. Scenarios with similar *OT* showed similar *E* and *EC*, regardless of emitter discharge rate.

To conclude, the adoption of new on-farm irrigation management techniques (low discharge rates, long irrigation times and high frequencies or pulsed irrigation) have been shown to have energy saving potential, especially in networks operating on-demand. However, the new scenarios have to be analyzed taking into account the interaction of the billing structure with the irrigation performance parameters in order to prevent the opposite effect to that intended.

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TABLES

Table 1. Usage period-related 2015 electricity tariffs.

	OFF-PEAK	MID-PEAK	PEAK
Capacity (€·kW^{-1}·d^{-1})	0.0229	0.0997	0.1622
Energy (€·kW·h^{-1})	0.0684	0.1120	0.1267

Table 2. Scenarios analyzed under continuous and pulsed irrigation

Scenario	#Scenarios	Performance type	q_e (L h^{-1})	*NS*	t_d (h)	*OT* (h)*	p_i
1	5	SecElv-SecSA-Dem1-Dem2-Dem3	4	5	3.29	16.45	0.20
2	5	SecElv-SecSA-Dem1-Dem2-Dem3	4	6	3.29	19.74	0.17
3	5	SecElv-SecSA-Dem1-Dem2-Dem3	4	7	3.29	23.03	0.14
4	5	SecElv-SecSA-Dem1-Dem2-Dem3	3	3	4.39	13.17	0.33
5	5	SecElv-SecSA-Dem1-Dem2-Dem3	3	4	4.39	17.56	0.25
6	5	SecElv-SecSA-Dem1-Dem2-Dem3	3	5	4.39	21.95	0.20
7	5	SecElv-SecSA-Dem1-Dem2-Dem3	2	2	6.58	13.08	0.50
8	5	SecElv-SecSA-Dem1-Dem2-Dem3	2	3	6.58	19.74	0.33
9	3	SecElv-SecSA-Dem1*	1	1	13.17	13.17	1.00
10	3	SecElv-SecSA-Dem1*	0.8	1	16.45	16.45	1.00
	46						

q_e=emitter discharge; NS=number of sectors; t_d=average daily irrigation time; OT=network daily operation time and p_i = probability that hydrant *i* is open.

* $OT = NS\, t_d$

* With this low emitter discharge rate only one pulse is possible per day.

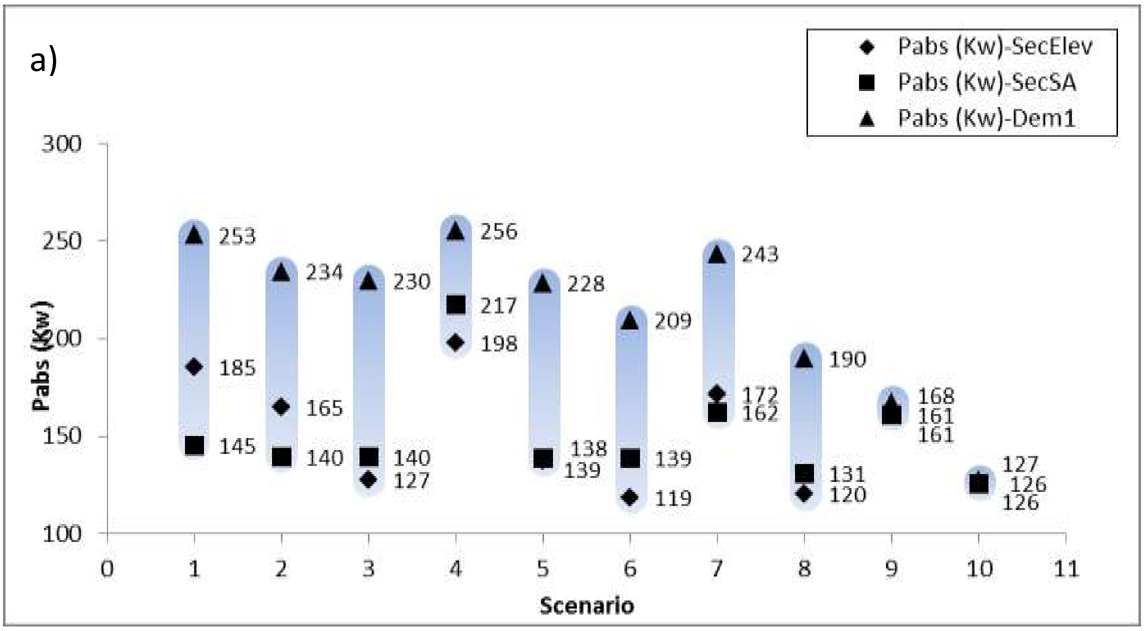
Table 3. Increase in P_{abs} (kW), *E* (kW h) and *EC* (€) over Scenario 1, excluding Scenarios 2 and 3.

	P_{abs} (kW)			*E* (kW·h)			*EC* (€)		
	SecElv	SecSA	Dem1	SecElv	SecSA	Dem1	SecElv	SecSA	Dem1
B.S.	6	10	10	10	6	10	9	4	10
Δ*	66.8	19.91	125.7	358.96	98.75	225.43	40.82	2.17	36.75
Δ%	36.03	13.69	49.66	14.81	4.82	9.71	16.83	1.06	15.14
W.S	4	4	4	6	7	6	6	6	6
Δ*	-12.42	-71.95	-2.6	-33.08	-78.08	-29.33	-34.06	-28.59	-49.1
Δ%	-6.70	-49.48	-1.03	-1.37	-3.81	-1.26	-14.04	-14.02	-20.23

Δ*: Saving as absolute value, Δ% Saving as percentage, B.S=Best Scenario, W.S=Worst Scenario

P_{abs}=power capacity; E=energy consumption for one day of irrigation in the peak month and EC=electricity costs for the same period in the different scenarios.

FIGURES


a)
◆ Pabs (Kw)-SecElev
■ Pabs (Kw)-SecSA
▲ Pabs (Kw)-Dem1
Pabs (Kw)
300
250
200
150
100
0
1
2
3
4
5
6
7
8
9
10
11
Scenario
253
185
145
234
165
140
230
140
127
256
217
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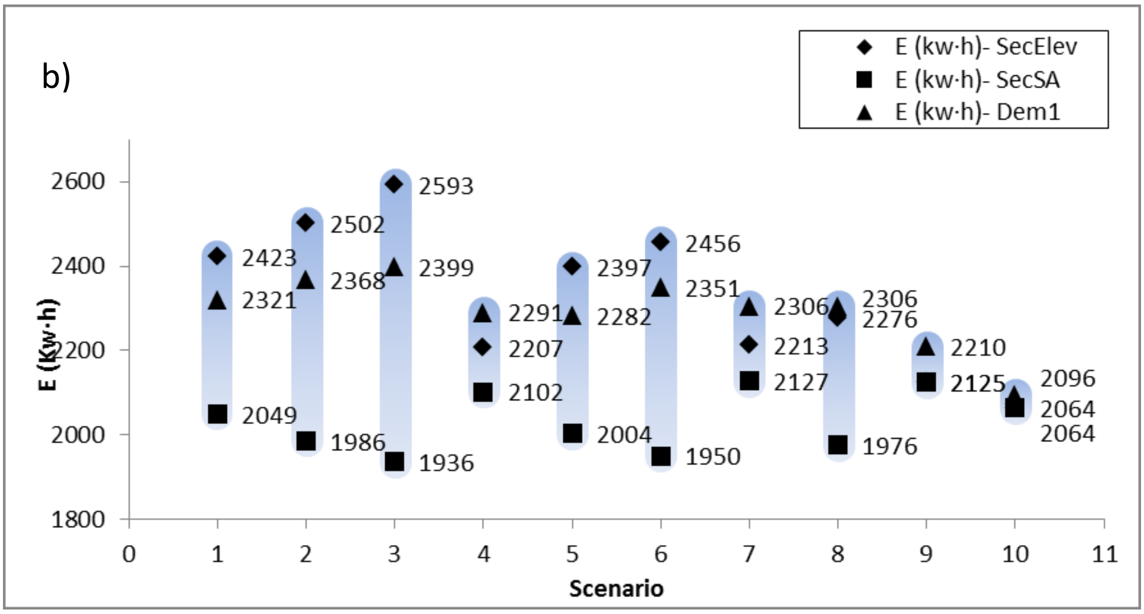
131
120
168
161
161
127
126
126


b)
◆ E (kw·h)- SecElev
■ E (kw·h)- SecSA
▲ E (kw·h)- Dem1
E (Kw·h)
2600
2400
2200
2000
1800
0
1
2
3
4
5
6
7
8
9
10
11
Scenario
2423
2321
2049
2502
2368
1986
2593
2399
1936
2291
2207
2102
2397
2282
2004
2456
2351
1950
2306
2213
2127
2306
2276
1976
2210
2125
2096
2064
2064

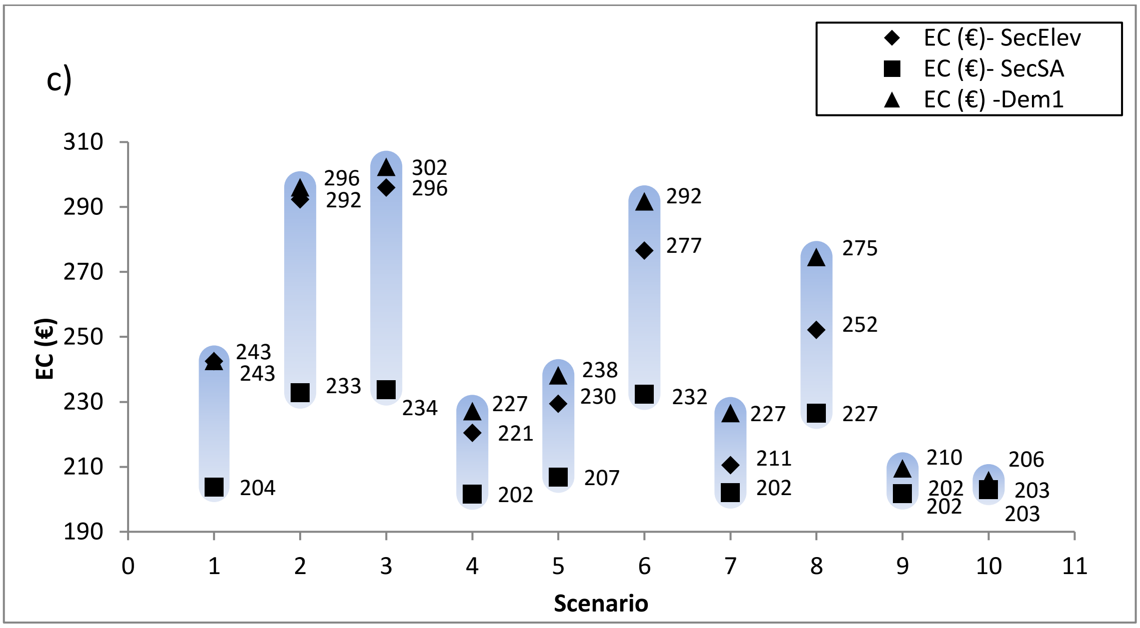
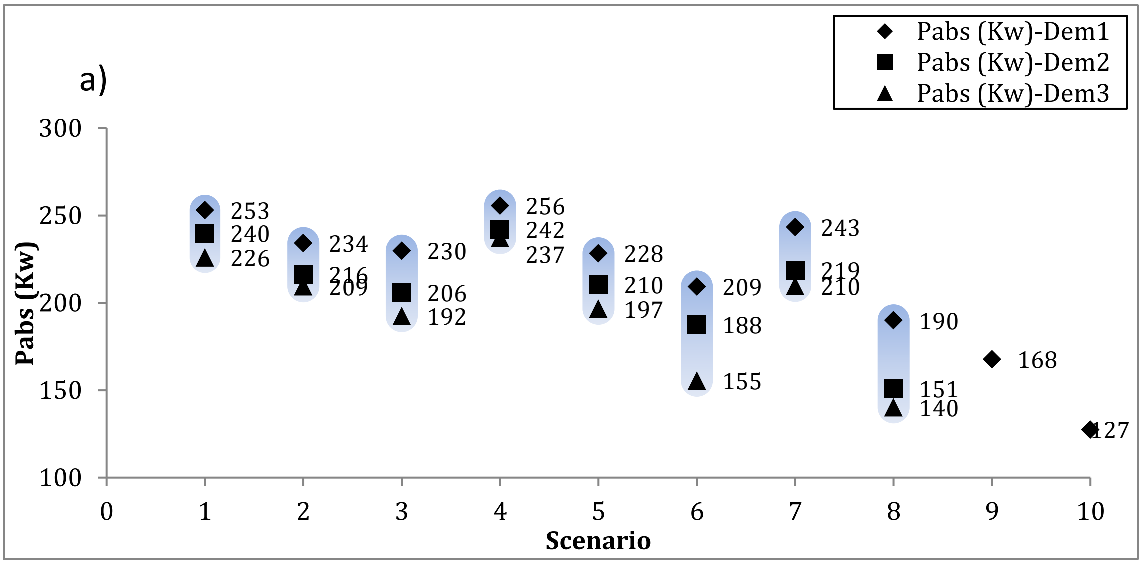


Figure 1. Evolution of P_{abs} (kW), *E* (Kh h) and *EC* (€) in different scenarios of continuous irrigation. P_{abs}=,power capacity; E=energy consumption for one day of irrigation in the peak month and EC=electricity costs for the same period in the different scenarios.


a)
Pabs (Kw)-Dem1
Pabs (Kw)-Dem2
Pabs (Kw)-Dem3
Pabs (Kw)
300
250
200
150
100
0
1
2
3
4
5
6
7
8
9
10
Scenario
253
240
226
234
216
209
230
206
192
256
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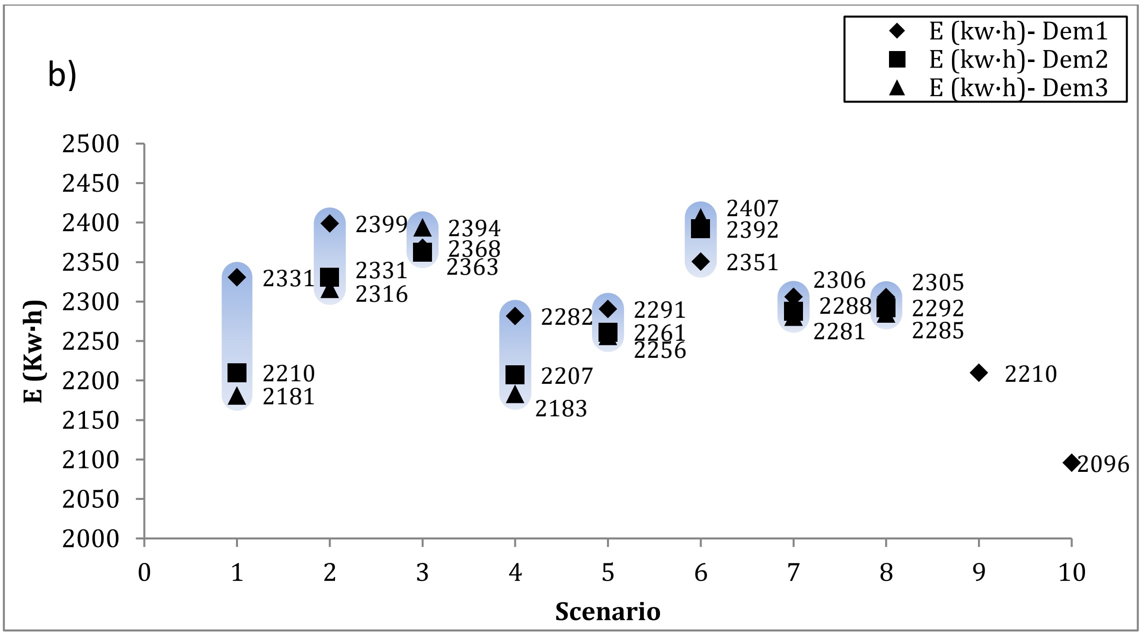
188
155
243
219
210
190
151
140
168
127


b)
E (kw·h)- Dem1
E (kw·h)- Dem2
E (kw·h)- Dem3
E (Kw·h)
2500
2450
2400
2350
2300
2250
2200
2150
2100
2050
2000
0
1
2
3
4
5
6
7
8
9
10
Scenario
2331
2210
2181
2399
2331
2316
2394
2368
2363
2282
2207
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2292
2285
2210
2096

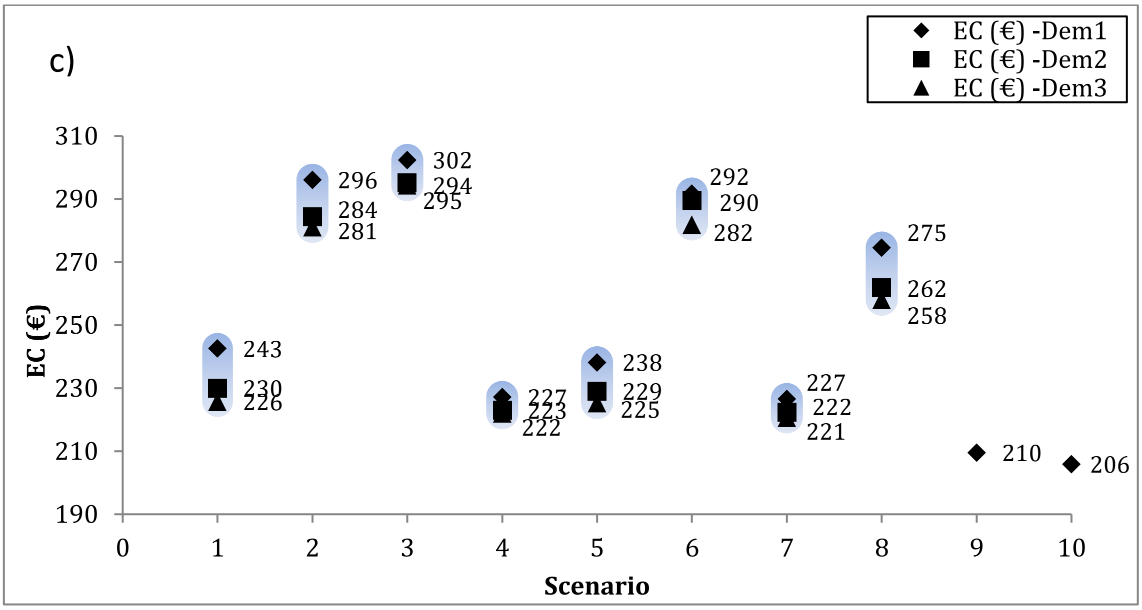

Figure 2. Evolution of P_{abs} (kW), E (kW h) and EC (€) in different scenarios of pulsed irrigation. P_{abs}=,power capacity; E=energy consumption for one day of irrigation in the peak month and EC=electricity costs for the same period in the different scenarios.