Optimal Management of Water and Energy in Irrigation Systems: Application to the Bardenas Canal

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Abstract: This paper presents a methodology for the optimal management of water and energy in irrigation systems. A two-layer management scheme is proposed. In the upper layer, an optimal control strategy is used to plan how to serve the demanded water within a prediction horizon of five days ahead in order to minimize electricity costs associated to pumping satisfying the physical limitations of the pipes. At the lower layer, a scheduling algorithm decides how to schedule the different pumps of the pumping stations in order to supply the desired flow with the maximum efficiency and minimum cost. A part of the Bardenas irrigation system in Spain is used as the case study to illustrate the proposed approach.

Keywords: Irrigation system, water optimization, energy cost optimization.

1. INTRODUCTION

Agriculture sector used 30% of the total water consumption in Europe, but reaches up to 70% of total water consumption in several European southern countries. In recent years, most of the efforts have been focused on water efficiency, without taking care of energy aspects, resulting in some cases on a significant increase in energy consumption, both per irrigated surface and per volume unit of water. Thus, the goal is to develop techniques for resource efficiency in irrigation systems such that allow saving water, improving the €/kWh ratio and the minimization of the operational cost of water supply infrastructures. The application of automatic control techniques to manage irrigation systems has widely researched in the literature. See for e.g. (Mareels et al. 2003; Mareels et al. 2005). Most of the existing works have focused on the design of controllers that maintain the desired levels in the irrigation canals while serving the water irrigation demands. In practice, additional important problems appear: How to serve the water demand in order to minimize the electrical costs by optimally scheduling the pumping stations. This problem has already started to be investigated in the literature just from pumping station point view as e.g. in (Moradi-Jalal, 2004) that proposed the optimal scheduling of a pumping station using genetic algorithms. A more general management structure is proposed in (Duviella et al., 2007; Duviella et al, 2011), where the decision how to serve the water demands is planified at a global level providing the set-points to the low level control elements.

This paper presents a methodology for the optimal management of water and energy in irrigation systems. A two-layer management scheme is proposed. In the upper layer, an optimal control strategy is used to plan how to serve the demanded water within a prediction horizon of five days ahead to minimize the electricity costs associated to pumping taking into account the physical limitations of the pipes. At the lower layer, a scheduling algorithm decides how to schedule the different pumps of the pumping stations in order to supply the desired flow with the maximum efficiency and minimum cost. A part of the Bardenas irrigation system in Aragon (Spain) is used as the case study to illustrate the proposed approach.

The work presented in this paper has been developed in the context of the WEAM4i (Water & Energy Advanced Management for Irrigation: http://weam4i.eu/). The aim of the project is to improve the efficiency of water use and reduce the costs of power irrigation systems.

The structure of the paper is as follows: In Section 2, the proposed methodology is described. Section 3 describes a software tool that implements the proposed methodology. Section 4 presents the case study used to illustrate it. Section 5 summarizes the main results obtained. Finally, Section 6 the main conclusions are drawn and the future work is outlined

2. PROPOSED METHODOLOGY

2.1 Component-oriented model

Several modelling techniques have been proposed for operational control of irrigation systems in the literature, see as e.g. (Mareels et al. 2003; Mareels et al. 2005) for a review, among others. Here, a control-oriented modelling approach is outlined, which follows the principles presented by the authors in (Ocampo, 2013). The extension to include the pressure- model can be found in (Brdys, 1994). An irrigation system generally contains pools, which store the water that comes from the dams, a network of pressurized pipes and a number of sinks. Pumping stations are elements that allow to manipulate the water flow according to a specific policy and to supply water requested by the farmers. The flows are chosen by a global management strategy. The irrigation system model can be considered as composed of a set of constitutive elements, which are presented and described next.

Dams/pools. They provide the irrigation network with the storage capacity of water at appropiate elevation levels to provide adequate pressure service to consumers. The mass balance expression for i-th dam/pool can be written in discrete-time as follows

$$v_i(k+1) = v_i(k) + \Delta t\left(\sum_i q_{in,i}(k) - \sum_j q_{out,j}(k)\right) \quad (1)$$

where v_i is the stored volume, $q_{in,i}$ are the manipulated inflows, $q_{out,j}$ the manipulated outflows, Δt is the sampling time and k is the discrete time. The capacity of the dam/pool add some physical constraints as follows

$$\underline{v}_i \le v_i(k) \le \overline{v}_i \quad (2)$$

where $\underline{v}_i$ and $\overline{v}_i$ denote the minimum and the maximum volume, respectively, given in m^3

Canal reaches. The i-th canal reach can be approximated using the IDZ model proposed by Litrico (2004) as a first order plus time delay (FOPTD) model that in discrete-time can be expressed as

$$q_{out,i}(k+1) = \alpha q_{out,i}(k) + \beta q_{in,i}(k-\tau_d) \quad (3)$$

where, $q_{out,i}$ and $q_{in,i}$ are respectively the downstream and upstream flows. α and β are parameters that are related to the constant time and static gain of the reach canal, while τ_d is the transport delay in samples.

Nodes. They correspond to the irrigation network points where water flows are merged or split. Thus, the nodes represent mass balance relations, being modelled as equality constraints related to inflows (from other pools/dams through gates or pumps) and outflows, these latter being represented not only by manipulated flows but also by demand flows. The expression of the mass conservation in these elements can be written as

$$\sum_i q_{in,i}(k) = \sum_j q_{out,j}(k) \quad (4)$$

Gates/pumps. Two types of control actuators are considered: gates and pumps (more precisely, complex pumping stations). The manipulated flows through the actuators represent the manipulated variables, denoted as qu. Both pumps and gates have lower and upper physical limits, which are taken into account as system constraints. As in (2), they are expressed as

$$\underline{q}_{u,i} \le q_{u,i}(k) \le \overline{q}_{u,i} \quad (5)$$

where $\underline{q}_{u,i}$ and $\overline{q}_{u,i}$ denote the minimum and the maximum actuator flow capacity, respectively, given in m^3/s.

Irrigation demands. They represent the water demand made by the network users of a certain physical area. It is considered as a measured disturbance of the system at a given time instant. The water demand can be anticipated by a forecasting algorithm that is integrated within the optimal planning algorithm.

2.3 Control-oriented model

For a given irrigation system composed with a particular number of components and interconnections between them, using the component models presented in the previous section, the model can be expressed in discrete-time state space form as follows

$$\begin{aligned} \boldsymbol{x}(k+1) &= \boldsymbol{A}\boldsymbol{x}(k) + \boldsymbol{B}_u\boldsymbol{u}(k) + \boldsymbol{B}_d\boldsymbol{d}(k) \\ 0 &= \boldsymbol{E}_u\boldsymbol{u}(k) + \boldsymbol{E}_d\boldsymbol{d}(k) \end{aligned} \quad (6)$$

considering that the states $\boldsymbol{x}$ are the volumes of dams/pools and flows in canal reaches, the control inputs $\boldsymbol{u}$ are the flows manipulated by the actuators (gates/pump stations) and that the disturbances $\boldsymbol{d}$ are the demands. The dynamic equation of the model (6) comes from dam/pool model (1) and canal reaches (3), while the static one come from the mass balance in the nodes (4). The dimensions and values of the system matrices involved (6) depend on the number of elements and their interconnections.

2.4 Upper layer: Optimal planning problem

The main control goal of an irrigation system is to meet the water demands at consumer sites with appropriate flows at the required elevation (pressure) according to users' needs. This problem can be formulated using optimal predictive control techniques that include as main objectives:

Pumping cost reduction. Delivering the water through the irrigation network involves important electricity costs in pumping stations. This control objective can be described by the expression at each time instant k

$$J_e(k) = \boldsymbol{W}_e(\gamma^T(k)\boldsymbol{u}(k)) \quad (7)$$

where $\boldsymbol{\gamma}(k)$ is a vector of suitable dimensions associated to the economic cost of the flow through certain actuators (pumps only) and their control cost (pumping). Note the k-dependence of $\boldsymbol{\gamma}$ since the pumping effort has different values according to the time of the day (electricity costs). Weight matrix $\boldsymbol{W}_e$ penalizes the control objective related to economic costs in the optimization process.

Safety storage term. The satisfaction of water demands should be fulfilled at then of the planning period H_p. However, some risk prevention mechanisms should be introduced in the dam/pool management such that the stored volume is preferably maintained over safety limit as follows:

$$J_s(k) = \begin{cases} 0 & if \quad \boldsymbol{x}(k) \ge \boldsymbol{x}_s \\ (\boldsymbol{x}(k)-\boldsymbol{x}_s)^T \boldsymbol{W}_s(\boldsymbol{x}(k)-\boldsymbol{x}_s) & if \quad \boldsymbol{x}(k) \le \boldsymbol{x}_s \end{cases} \quad (8)$$

where $\boldsymbol{x}_s$ is the safety volume and matrix $\boldsymbol{W}_s$ defines the weight of the objective in the cost function. Thus, optimal control strategy can be formulated as follows using a prediction ahead horizon H_p

$$\min_{\boldsymbol{u}(0),\cdots,\boldsymbol{u}(H_p-1)} \sum_{k=0}^{H_p} \left(J_e(k) + J_s(k)\right) \quad (9)$$

subject to:

$$x(k+1) = Ax(k) + B_u u(k) + B_d d(k) \quad k = 0,\cdots,H_p$$
$$0 = E_u u(k) + E_d d(k) \quad k = 0,\cdots,H_p - 1$$
$$\sum_{k=0}^{H_p-1} d_i(k) = d_{i,total} \quad i = 1,\cdots,n_d$$
$$u(k) \in \mathbb{U} \quad k = 0,\cdots,H_p - 1$$
$$x(k) \in \mathbb{X} \quad k = 1,\cdots,H_p$$

where:

$$\mathbb{U} = \left\{ u \in \mathbb{R}^m \middle| \underline{u} \le u \le \bar{u} \right\} \qquad \mathbb{X} = \left\{ x \in \mathbb{R}^n \middle| \underline{x} \le x \le \bar{x} \right\}$$

Note that in (9) the total water demanded by each consumer $d_{i,total}$ should be satisfied at the end of the prediction horizon H_p, not being necessary to satisfy it at each time instant k. This provides additional degrees of freedom when distributing the pumping requited to provide this demand along the horizon H_p. If the water demand should be delivered exactly at each time k, it would not be possible to optimize the electricity consume associated to pumping.

2.5 Lower layer: Optimal pump scheduling problem

Once optimal set-points per each pumping station have been decided at the upper layer, the detailed scheduling of the pumps should be computed. Typically, the pumping stations include several units running a fixed and/or variable speed. The goal of the optimal pump scheduling algorithm is to decide how many units, of which type and for how long they should be activated to pump the set-point flow decided at the upper layer. This problem can be formulated as a mixed-integer optimization problem where the decision variables are a set of binary variables deciding if a given pump unit is *on* or *off* and the speed of the variable speed pumps or the on-time of the fixed speed pumps to achieve the desired flow set-point. Considering that in the pump station there are n_p^f fixed speed pumps and n_p^v variables speed pumps, the optimal pump scheduling problem can be formulated as follows

$$\min_{\substack{s(0),\cdots,s(N-1)\\ v(0),\cdots,v(N-1)\\ q^v(0),\cdots,q^v(N-1)}} \sum_{i=1}^{n_p^f}\sum_{k=0}^{N-1} c_i^f(k) q_i^f(k) + \sum_{i=1}^{n_p^v}\sum_{k=0}^{N-1} c_i^v(k) q_i^v(k) \qquad (10)$$

subject to:

$$q_i^f(k) = q_{i,on}^f s_i(k) \quad k = 0,\cdots,H_p - 1 \qquad i = 1,\cdots,n_p^f$$
$$q_i^v(k) = q_{u,i}^v(k) z_i(k) \quad k = 0,\cdots,H_p - 1 \qquad i = 1,\cdots,n_p^v$$
$$\sum_{i=0}^{n_p^f}\sum_{k=0}^{N-1} q_i^f(k) + \sum_{i=0}^{n_p^v}\sum_{k=0}^{N-1} q_i^f(k) = q_{total}(k)$$
$$s_{i+1}(k) + (1 - s_i(k)) \le 1 \quad k = 0,\cdots,H_p - 1 \qquad i = 1,\cdots,n_p^f$$
$$z_{i+1}(k) + (1 - z_i(k)) \le 1 \quad k = 0,\cdots,H_p - 1 \qquad i = 1,\cdots,n_p^v$$
$$s_i(k) \in \{0,1\} \quad k = 0,\cdots,H_p - 1 \qquad i = 1,\cdots,n_p^f$$
$$z_i(k) \in \{0,1\} \quad k = 0,\cdots,H_p - 1 \qquad i = 1,\cdots,n_p^v$$
$$0 \le q_{u,i}^v(k) \le \bar{q}_{u,i}^v \quad k = 0,\cdots,H_p - 1 \qquad i = 1,\cdots,n_p^v$$

where: s_i and z_i are binary variables that are used to decide if the i-th fixed speed pump and the i-th variable speed pump are in operation. c_i^f and c_i^v are the coefficients that takes into account the efficiency and the cost associated the i-th fixed speed pump and the i-th variable speed pump, respectively. q_{total} is the total flow determined by the upper layer that should be pumped by the pump station.

3. HYDROPTIM TOOL

The proposed approach presented in previous section has been implemented using a software tool that is called HYDROPTIM. It is a graphical decision support tool for the integral optimal operational planning of irrigation systems. HYDROPTIM is developed using standard GUI (graphical user interface) techniques and object oriented programming. HYDROPTIM allows to graphically modelling the irrigation network using a component oriented approach. Each component is modelled according the model presented in Section 2. From this graphical model, the mathematical model of the irrigation is system is generated in GAMS optimization modelling language. One the model has been generated, HYDROPTIM can solve the optimization problems presented in Sections 2.4 and 2.5 using numerical solvers that can be called from GAMS. As result of solving such problems the optimal irrigation plan is obtained as well as the optimal scheduling of the pumps.
The tool has four modes of operation: edition, simulation, monitoring and reproduction modes:

3.1 Edition mode

This mode allows graphically building and parameterizing the network using a palette of building blocks, defining the control objectives and generating the optimization model equations. HYDROPTIM has different element libraries which allow the user to easily model the network. Elements include reservoirs, tanks, water demands, sensors and actuators. The user may place these elements in the model using drag and drop and then connect using pipes, aqueducts, etc. Each element in HYDROPTIM has a number of properties, which are grouped in trees. These identify the element, parameterize its characteristics, provide goals to the optimizer, define SCADA data links and database presence, etc. Once the network has been built, HYDROPTIM tests it for consistency and creates the set of optimization equations using the goals and constraints defined in each element.

3.2 Simulation (or off-line) mode

This mode allows network optimization in simulation, using the demands from the HYDROPTIM database corresponding to a recorded real scenario as inputs, HYDROPTIM generates the optimal controls, which are applied to the same network model (as a substitute of the real network). Graphical evolution of the main network variables and controls can be represented and registered in HYDROPTIM database for further study.

3.3 Monitoring (or on-line) mode

Network optimization in real time is carried out in monitoring mode, using the demands and measurements from network real state coming from the telemetry system, provided by the SCADA system. HYDROPTIM generates the optimal controls, which are applied to the real network only after confirmation by an operator. Graphical evolution of the main network variables and controls can be represented and registered in HYDROPTIM database for further study.

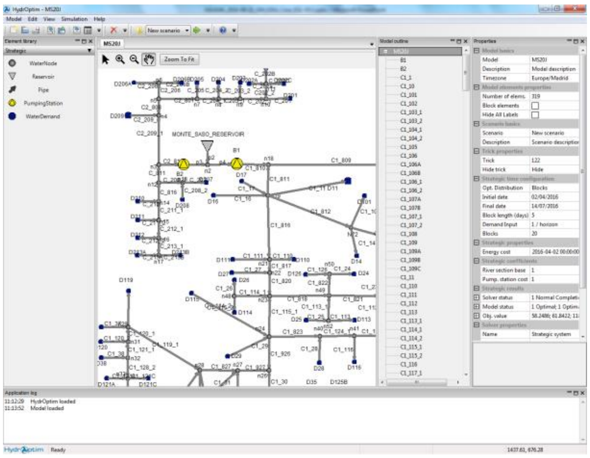


Fig. 1. HYDROPTIM: Edition mode

4. CASE STUDY

The considered case study for illustrating the proposed approach is located in Spain, in the Comunidad de Regantes del Canal de Bardenas. The considered area in this paper is the Monte Saso sector (Irrigation District V) . The district is located in the Ebro Valley, North Eastern Spain (Fig. 2).

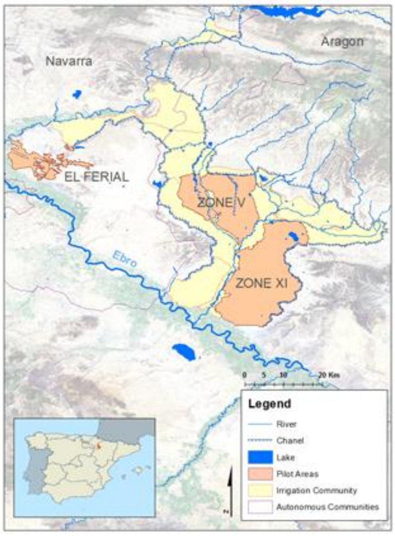
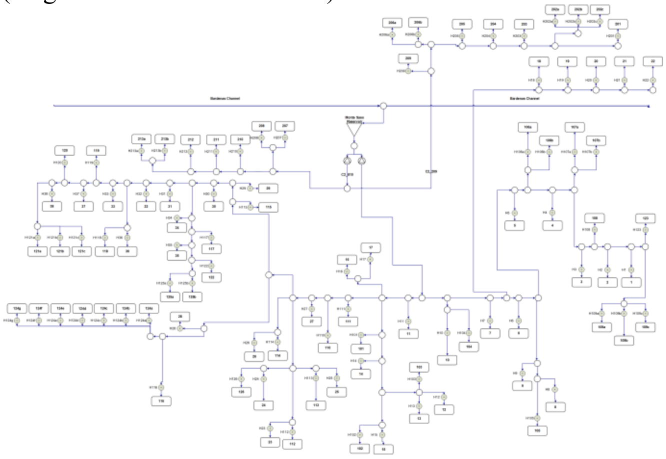


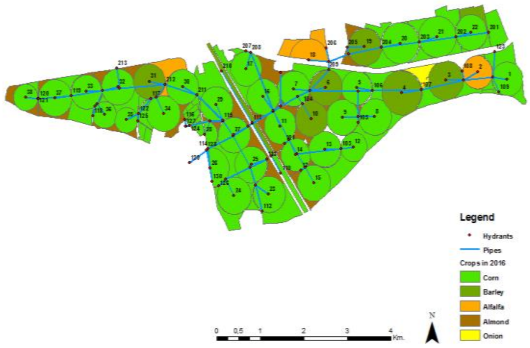
Fig. 2. Irrigation District V (name Zone V in the figure) in the Bardenas Canal

The total irrigated area is 1200 ha. Figure 3 shows the 94 hidrants located inside the district (37 using sprinklers: 40 ha, 38 using pivots: 860 ha, 19 using drips: 100 ha). The district is included in the Bardenas Canal, which started operation in 1959, after completion of the construction of the Yesa dam in the Aragón river. The canal provides water for about 80000 ha in the provinces of Zaragoza and Navarra.

The Monte Saso (part of District V) has a pool that is filled on-demand. The pool has a capacity of 150000 m^3 and fills up by communicating vessels through a 1025 l/s pipe (see Figure 4). Anti-return valves keep the water in the pool. From that pool two pumping stations at different levels supply the water to the hydrants. One pumping station with 8 pumps with capacity of 1538 l/s (irrigates 88% of the total area) and the second pumping station with 5 pumps with of 229 l/s (irrigates 12% of the total area).



(a)



(b)

Fig. 3. (a) Monte Saso hydraulic scheme. (b) Hydrants of the Irrigation Monte Saso sector in the Bardenas Canal

Fig. 4. Pool and one of the Pumping Stations of the Irrigation VMonte Saso sector in the Bardenas Canal

The infrastructure is not capable of supplying water to hydrants all the same time, thus the water supply is organized in shifts. Currently, the irrigation infrastructure is fully managed by the District V technicians when decide when to water each field (depending on the crop, need, water availability, allocation bottlenecks, electricity tariffs ... etc.)

5. RESULTS

To test the proposed methodology and tool several scenarios have been considered using real water demand data obtained from the system in two irrigation periods: from 1 April to 30 September 2015 and from 1 April to 2 October 2016. As a baseline strategy, the water and electricity consume in this period has been considered. Figure 5 presents the electricity consumes associated to pumping the required water demand for irrigation presented in Figure 6.

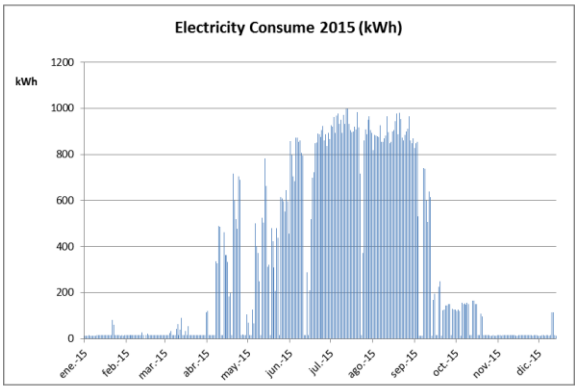


Fig. 5. Electricity consume associated to pumping corresponding to 2015

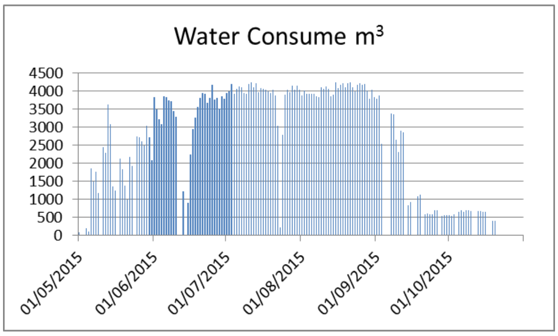


Fig. 6. Water irrigation demand corresponding to 2015

5.1 Scenario 1: Optimization using fixed prices

In this scenario, electrical cost optimization using the approach described in Section 2.4 and 2.5 considering a fixed six period electricity tariff will be compared against the current strategy based on the heuristic decision based on how to pump. Figure 7 shows that currently (baseline scenario) most of the water is pumped at the the period of cheapest price (period *p6*). However, since the limited capacity of the pipes not all the water can be pumped during this period (see Figure 7). Figure 8 shows the reduction of pumping costs when using the optimized strategy proposed in this paper compared to the baseline heuristic that tries to pump as much flow as possible in the period of cheapest tariff. Figure 9 shows the comparison of how the water in case of the proposed approach is pump most of the time in the period of cheapest tariff, while this is not the case with the heuristic approach. This is possible because the proposed approach plans ahead the pumping to serve the demand required by the consumers with a time window of five days. This timeframe (120 hours) was set in the Weam4i framework like a reasonable period from an agronomic point of view without impact in the crop production.

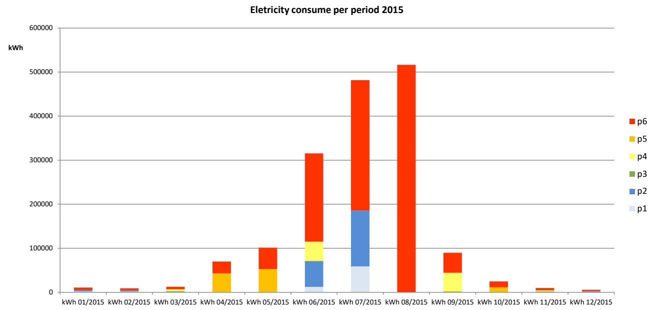


Fig. 7. Electricity consume per period

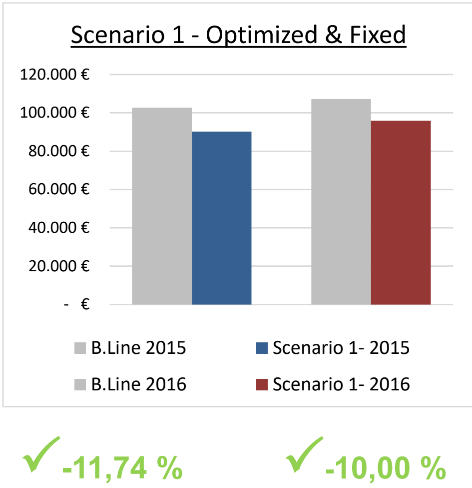


Fig. 8. Scenario 1: Pumping electricity costs

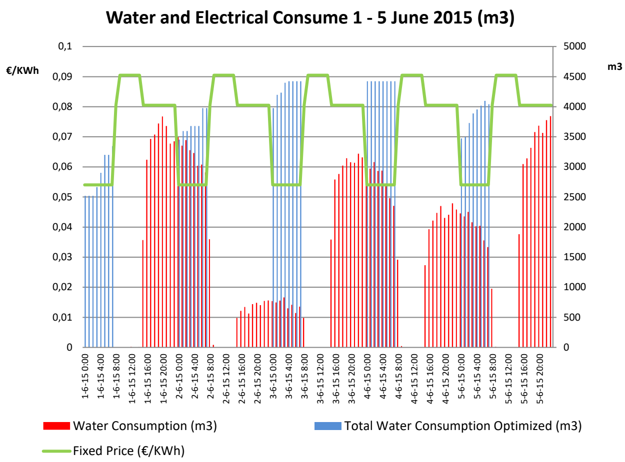


Fig. 9. Scenario 1: Comparison of the water consumption when heuristic and optimized strategies are used.

5.2 Scenario 2: Optimization using index prices

In this scenario, electrical cost optimization considering an index electricity tariff will be compared against the current strategy based on the heuristic decision based on how to pump. Figure 10 shows how the electricity prices vary with time when using an indexed tariff. It also shows the comparison with the fixed tariff prices. Figure 11 shows the reduction of pumping costs when using the optimized strategy proposed in this paper compared to the baseline heuristic with fixed tariffs. From this figure, it can be seen that in 2016, the used of the optimized strategy with indexed electricity costs outperform the baseline heuristic approach based on fixes electricity costs.

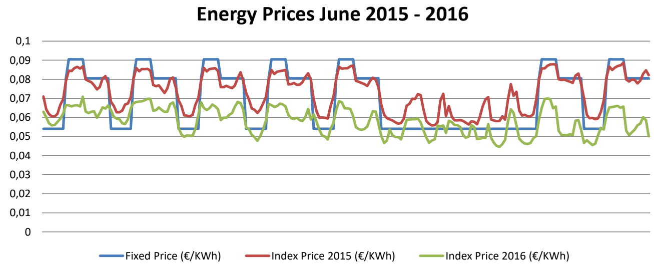


Fig. 10. Indexed versus fixed prices

5.4 Discussion

Finally, the comparison of the electricity costs associated to pumping when heuristic approaches using either fixed six period and indexed tariffs are used compared to the case that the optimized are strategies obtained using the proposed approach are used (see Figure 12). From this figure, it can be seen that the optimized strategies outperform the heuristic strategies either with fixed or indexed electricity costs. The use of indexed electricity costs with the optimization tool in case of 2016 provides an improved with respected to fixed electricity costs, being the contrary in case of 2015.

6. CONCLUSIONS

This paper has presented a methodology for the optimal management of water and energy in irrigation systems. A two-layer management scheme has been proposed. In the upper layer, an optimal control strategy has been used to plan how to serve the demanded water within prediction horizon of five days ahead taking into account minimizing the electricity prices associated to pumping and taking into account the physical limitations of the pipes. At the lower layer, a scheduling algorithm decides how to schedule the different pumps of the pumping stations in order to supply the desired flow with the maximum efficiency. A part of the Bardenas irrigation system in Spain has been used as the case study to illustrate the proposed approach considering two different scenarios. The results have been promising showing the validity of the proposed methodology and tool for the optimal management of irrigation systems. As future work, the proposed approach will be coupled with water demand forecasting module that will be able to estimate the right amount of water required in each sector taking into account the soil moisture and the type of crop that is being grown.

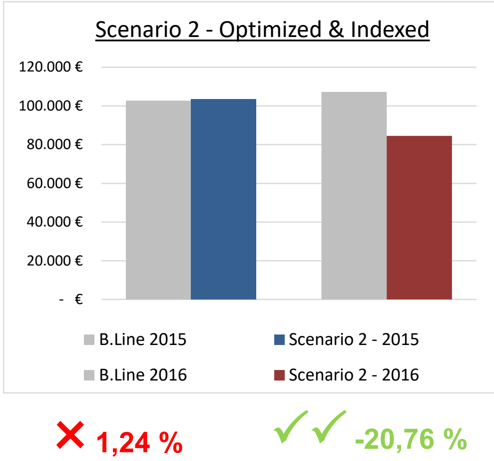


Fig. 11. Scenario 2: Pumping electricity costs

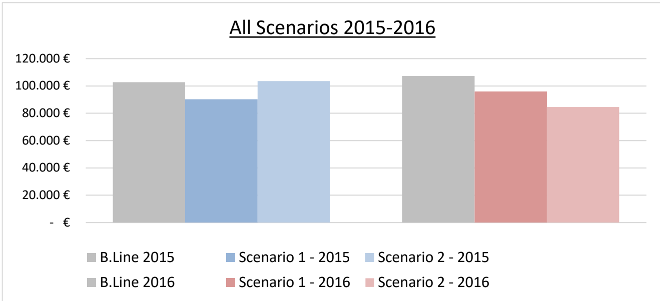


Fig. 12. Comparison of the different scenarios.

ACKNOWLEDGMENTS

The authors want to thank "Comunidad de regantes V de Bardenas" and "Comunidad General de Regantes del Canal de Bardenas" for their work and for the provided data that has allowed to model the scheme and feed the scenarios. Thanks to CREARA for providing the different energy cost time series. Thanks to Pablo Rodriguez Madroño for his collaboration in the development of the initial idea and his endeavour in the project at its first stage.

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