Energy optimization and micro-hydro solution in WSS: a case study

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Abstract

The use of renewable energy to generate electricity in water supply systems is innovative and has many advantages for the system itself and for the environment. The technical and financial evaluation of the implementation of generators with renewable energy are only part of the solution, once the optimization of the system operation also involves a reduction in costs of the water consumption and ensures a greater financial return to the authority administration. In this study the authors intend to demonstrate the gain in the energy efficiency applied to water supply systems (WSS) with the use of optimization algorithms in the operational pumping systems having the objective to minimize the costs due to the electricity tariff ensuring, at the same time, the hydraulic behaviour, the existing water demand and the installation of a micro-hydro solution for power generation. A case study was developed in a small WSS in Portugal, in the district of Ourém, where a micro-turbine is considered upstream of a reservoir and the payback, the net present value (NPV) and the internal rate of return (IRR) were estimated. For the optimization of the pumping system genetic algorithms (GA) are used, ensuring a less number of start-ups for the pumps' operation. Great savings are obtained when compared to the original system, also ensuring a good return of the investment with the implementation of a micro-hydro solution.

Keywords
Renewable energy systems; water supply systems; micro-hydro; genetic algorithms; operational optimization.

INTRODUCTION

In the last decades, the managers of water supply systems have been concerned with the reduction of energy consumption, as well as with the strong influence of climate changes on water patterns. The pumping system is the most energy consumer in a WSS and it operational optimization leads to costs reduction. The implementation of a hydropower micro-turbine in a WSS could bring more effort to reduce costs producing renewable energy using the excess of hydraulic energy presented in some WSS.

This work aims to present a renewable energy production in a WSS with an introduction of a hydropower micro-turbine and the benefits of its appliance in the WSS. A Genetic algorithm is used to optimize de number of starts of the pumps installed in the case study area and an economic approach is made to verify if the turbine introduction bring benefits to the WSS. The case study corresponds to a WSS of a small village in Portugal and the original system is called *status quo system* and was already used in other analyses.

BACKGROUND REVIEW

One of the bigger problems for the WSS managers is the energy consumption induced by the pump operation in the system. For that reason, the optimization of pump operation and the installation of hydropower micro-turbines in WSS could be a reasonable solution for saving and could be an alternative clean energy solution to reduce energy consumption and minimize the CO_2 emissions to the atmosphere. Kucukali [1] describe that in Switzerland 90 small hydropower plants were installed in municipal WSS. He also applied a study of an implementation of a small hydropower in Edremit WSS, in Turkey.

The constant growing of urbanisation and consumer demand, most water distribution systems (WDS) become increasingly complex and the pump operation scheduling is harder to execute. In the optimization field there are several types which have been used to find optimal pump schedules as the linear programing, dynamic programing, network flow programing and non-linear programing [2], but none of those methods are totally satisfactory [3]. The best optimization model to be used with those amounts of complicated systems constrains and huge calculations in pump scheduling operation is the Genetic Algorithms (GA) that treat discrete values used in pump scheduling models naturally and thus they seem well suited to this kind of optimization [3].

Shihu [4] uses genetic simulated annealing (GSA) to automatically determine the least cost pump operation for each pump station in large scale WSS satisfying the hydraulic behaviour of the system in a generic model city. Fang [5] developed an optimal scheduling of multi-storage tank using GA to optimize the pump operation. A modified GA called hyperplane real coding GA was developed to optimize the operation of a pump station instead of a traditional GA [6].

The simple GA (SGA) harnessses the power of implicit parallelism, but with a higher price of noisy evaluation of equivalence classes. Original messy GA (MGA) went to the other extreme, emphasizing the accurate evaluation of better classes by explicitly enumerating all-possible classes within the all possible relations at some order-*k* and evaluating them in the context of a locally optimal solution [7]. The fast messy GA (FMGA), initiated by Goldberg, Deb, Karagupta and Harik [8], takes a moderate strategy to balance both the ends and brings some of the benefits of implicit parallelism to the MGAs while retaining some degree of accuracy in detecting good relations.

METHODOLOGY

In the system modelling it is used the WaterGems model, an hydraulic simulator module with genetic algorithm optimizer and an energy evaluator that calculates the hydraulic head and flow at the nodes in the water system network, to a set of levels in the reservoirs and in the tanks over a consumption variation. In each calculation step, the water levels and consumption in the nodes are updated according to the temporal pattern associated with them, while the height of water in the tanks levels is updated according to the flow output. The solution for the value of hydraulic head and flow at a particular point of the network at any moment is obtained by solving simultaneously the continuity equation (conservation of mass) for each node, and the equation of energy conservation for each section of the network. This procedure, called "hydraulic balance" of the network requires the use of iterative techniques for solving nonlinear equations involved.

The continuity and energy conservation equations and the relation between the flow and the head loss could be solved by the gradient method. Due the method developed by Todini and Pilati [9] is the simplest, this was chosen for the values of the flow and hydraulic grade line of the network. WaterGems uses EPANET to proceed those calculations and EPANET employs the "Gradient Method" to achieve those objectives [10].

The time interval used in hydraulic modelling is 15 minutes, making the interaction more detailed and the operation of the pumping system, thus avoiding the operation of the pumping in large periods (e.g. one hour). It is adopted the electricity tariff of winter, corresponding to the worst scenario for this modelling. The curves of the pumps are supplied by the system management and the curve of the turbine is a function of available energy at the network. The WaterGems model is used to guarantee that the hydraulic behaviour of the *status quo* system was exactly the same found in the field. After the *status quo* system was implemented and the hydraulic behaviour was fulfilled, which represents that the pump starts when the minimum level of tanks is achieved and the pumps stopped when the maximum level of tanks is reached, then the optimization starts.

The “Darwing Scheduler” module from WaterGems gives a GA optimization tool to optimize pumps’ operations, starting and stopping those, according to the electricity tariff and the hydraulic restrictions of the network. The GA optimization used is the FMGA – fast messy genetic algorithm. FMGA is used with a population size of 300, with an elite population size of 50, a mutation probability of 3%. The implementation is analysed and the level of all reservoirs was defined. GAs are stochastic global search methods based on the evolution of a population of individuals where each is a representation of a possible solution to the problem. The operating principle is based on Darwin's Theory of Evolution [11].

The optimization of the pumps is made according to objective functions to reduce the energy cost that are turn on or off to maintain the water tank level behaviour guarantying the demand to the network to an optimum hydraulic behaviour taking also into account the electricity tariff. In a second effort, the turbine is installed in the system and then another FMGA is implemented to verify the results with the introduction of a micro-hydro turbine in the system. The analysis of all data are developed and compared with the *status quo* and the first

FMGA optimization. It is developed an economic evaluation of the investment return period of the installation of a micro-hydro with a sell value of energy of 0,10€/kWh.

CASE STUDY

Espite water supply system (WSS) is hydraulically analysed to optimize the pump start-ups in order to minimise energy costs. The optimization applied was a Fast Messy Genetic Algorithm (FMGA) to determine the best pump operation to supply water depending on the reservoir levels' variation. This WSS system is located in Ourém, a small village of Portugal, with geographical coordinates 39° 46' 0" North, 8° 38' 0" West. This is a small system that distributes water to Couções and Arneiros do Carvalhal villages and the average flow in this pipe system is approximately 7 l/s. A simplified scheme of Espite system is presented in Figure 1. The micro hydro power plant will be installed in the gravity pipe system between node 5 and Tank Carvalhal. The water consumption (i.e. demand points) must be guaranteed and the water level variation of the tanks should be between recommended limits. The pipe profile of Espite system is: Reservoir 01 – 190 m; Pump R01 – 230 m; Node 1 – 240 m; Tank ASJ – 310 m; Node 2 – 244.50 m; Node 3 – 206 m; Node 4 – 185 m; Node 5 – 200 m; Turbine, Tanks Carvalhal1 & Carvalhal2, Pumps Carvalhal1 & 2 – 263 m; Node 6 – 348.80 m; Tank Couções – 349 m and Demand point Couções – 346 m.

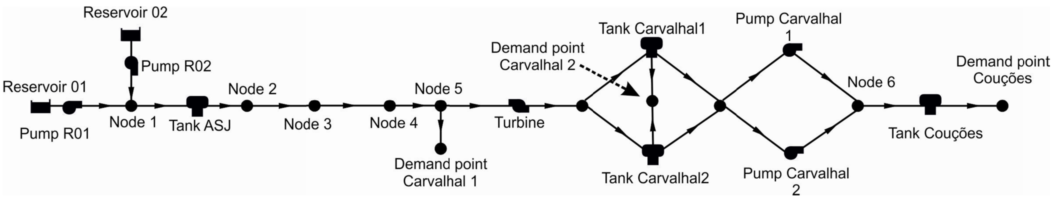


Figure 1. Scheme of Espite water pipe system.

It was important to verify all hydraulic parameters and the system behaviour when a hydropower turbine is also installed. Rule-based controls are defined in the optimization process to guarantee in the *status quo* system the limit tank levels are always met. In order to determine the most adequate hydro turbine in this WSS, regarding the importance to always maintain a good system operation management and the demand flow satisfaction, the evaluation of the available energy and the performance turbine curves compatible with the operating and hydraulic restrictions must be developed. Previously, a head loss device (e.g. a flow or a pressure control valve) is placed at the possible turbine site and it is verified the higher head loss that do not compromise the good operation of the system in terms of flow and pressures. According to Araújo [12] and Ramos et al. [13] these data found the best turbine characteristic curve to define the most adequate turbine selection.

The system is then analysed using the electricity tariff for the season with higher costs of energy or the worst economy conditions, whose in that case is the winter electricity tariff. The energy report of the *status quo* in this case study is shown in Table 1 which demonstrates that pumps R01 and R02 are the largest consumers of energy, responsible for the supply of Tanks ASJ1, Carvalhal1 and Carvalhal2 and also the demand points of Carvalhal1 and Carvalhal2.

Table 1. Pumping cost at *status quo* situation.

Energy Report (statu quo)			
Pump Station	Use	Consumption kWh/d	Total cost day
R01	58.33%	123.20	9.79 €
R02	58.33%	102.20	8.12 €
Carvalhal1	79.17%	43.70	3.26 €
Carvalhal2	79.17%	43.70	3.26 €

Figure 2 shows the system behaviour in the *status quo* operation and Figure 3 shows the system behaviour with GA implementation without turbine installed in the system (model a system) and with the turbine installed (model b system).

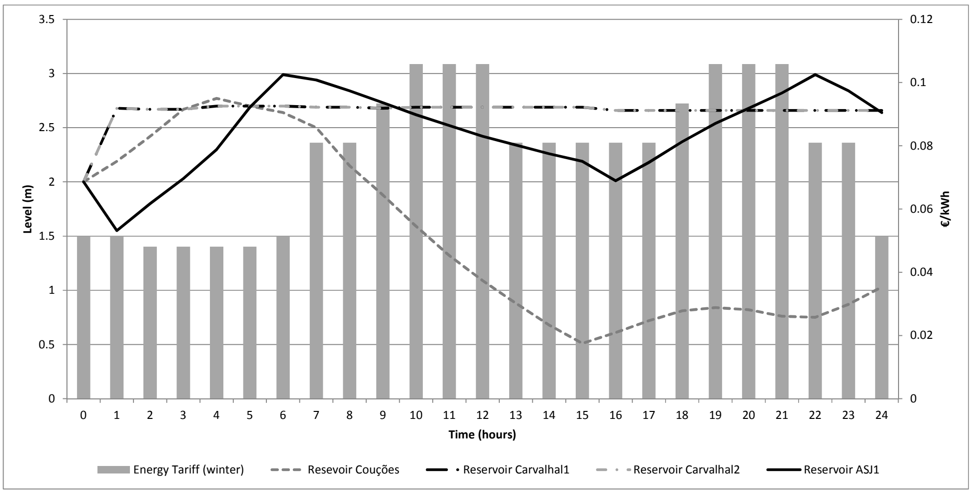
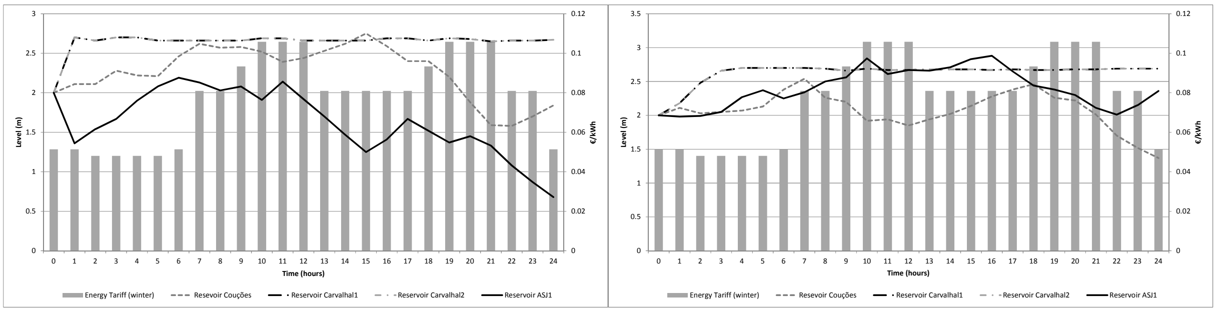


Figure 2. System behaviour in *status quo* operation and energy tariff applied in the winter.



model (a) model (b)

Figure 3. System behaviour with GA optimization without turbine (a) and with turbine installed in the system (b) and the energy tariff applied in the winter.

In the simulation it could be observed tanks' level of Carvalhal1 and Carvalhal2 do not change with the GA optimization and the only level changes just occurred in tanks ASJ1 and Couções. The pump operation is an important issue, and in GA optimization the number of pump start-ups is limited to 5 start-ups at maximum to avoid unnecessary expenditure of energy, causing a reduction of the consumption of reactive energy and to avoid the wear of the pumps. In Figure 4 is showed the operation of pump R01 in the tree scenarios (the original system called *status quo*, system optimized without the insertion of hydropower turbine called "model a" and the optimized system with the insertion of hydropower turbine called "model b") and it could be observed that pump R01 starts less one time in model b than in model (a) and avoid one time approaching the high value of electricity tariff. The costs of pumping in the model (a) and (b) systems are demonstrated in Table 2.

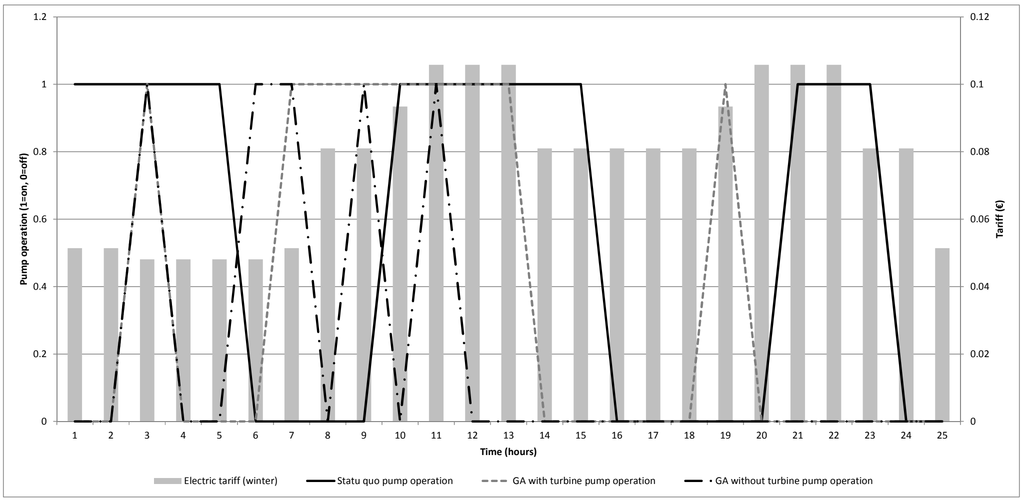


Figure 4. Pump R01 operation in *status* quo, model a and b systems.

Table 2. Pumping costs with GA optimizations.

Energy Report (Optimization without turbine)				Energy Report (Optimization with turbine)			
Pump Station	Use	Consumption kWh/d	Total cost day	Pump Station	Use	Consumption kWh/d	Total cost day
R01	20.83%	44.00	2.94 €	R01	37.50%	79.20	6.74 €
R02	29.17%	51.10	3.38 €	R02	29.17%	51.10	4.85 €
Carvalhal1	45.83%	25.30	1.93 €	Carvalhal1	29.17%	16.10	1.38 €
Carvalhal2	41.67%	23.00	1.76 €	Carvalhal2	29.17%	16.10	1.41 €

model (a) model (b)

Even the model (b) system consume more energy than model (a), there is an advantage in model (b) system, the hydropower turbine installed compensate the higher consumption given a general reduction in costs as shown in **Erro! Auto-referência de marcador inválida.**. The energy production of turbine is demonstrated in Table 4 and the value of benefits is based in the sell value of 0.10€/kWh.

Table 3. Profit achieved with all optimizations scenarios.

Energy Report (total cost day)		
System	Total cost	Saving
Statu Quo	24.43 €	0.00%
Optimization with turbine	9.05 €	62.98%
Optimization without turbine	10.02 €	59.00%

Table 4. Turbine energy production and benefits.

Energy Report (Turbine)			
Turbine	Use	Production kWh/d	Production/day (0.10€/kWh)
Carvalhal	100.00%	53.26	5.33 €

After these evaluations a payback analysis is developed to verify how many years are taken to return the investment in the micro-turbine installation. The market price of this micro-turbine is stipulated in approximately 2,000€ with an annual maintenance costs of 10% of the investment price. It could be verified in

Table 5 that in 3 years the investment is paid and the micro-turbine starts to get profits. In Table 6 could be verified the net present value (NPV) and Internal Rate of Return (IRR) of this investment for updates rates of 6%, 8% and 10% for 10 years of the micro-turbine exploitation.

Table 5. Hydropower micro-turbine payback analysis.

Base year	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Year	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Micro-turbine production (kWh/d)	0	53.26	53.26	53.26	53.26	53.26	53.26	53.26	53.26	53.26	53.26
Micro-turbine investiment	2,000.00 €	0.00 €									
Gross revenue	0.00 €	1,943.99 €	1,943.99 €	1,943.99 €	1,943.99 €	1,943.99 €	1,943.99 €	1,943.99 €	1,943.99 €	1,943.99 €	1,943.99 €
Maintenance expenditures	0.00 €	200.00 €	200.00 €	200.00 €	200.00 €	200.00 €	200.00 €	200.00 €	200.00 €	200.00 €	200.00 €
Net revenue	-2,000.00 €	-256.01 €	1,487.98 €	3,231.97 €	4,975.96 €	6,719.95 €	8,463.94 €	10,207.93 €	11,951.92 €	13,695.91 €	15,439.90 €
Present value 6%	-2,000.00 €	-241.52 €	1,324.30 €	2,713.62 €	3,941.43 €	5,021.54 €	5,966.74 €	6,788.86 €	7,498.78 €	8,106.59 €	8,621.56 €
Present value 8%	-2,000.00 €	-237.05 €	1,275.70 €	2,565.64 €	3,657.48 €	4,573.49 €	5,333.72 €	5,956.23 €	6,457.25 €	6,851.36 €	7,151.66 €
Present value 10%	-2,000.00 €	-232.7364	1229.736	2428.227	3398.648	4172.56	4777.673	5238.2821	5575.6589	5808.4028	5952.7498

Table 6. Hydropower micro-turbine NPV and IRR results.

Net present value (NPV)	
Update rate 6%	47,741.90 €
Update rate 8%	41,585.49 €
Update rate 10%	36,349.20 €
Internal Rate of Return (IRR)	**86.32%**

CONCLUSIONS

Based on the optimization and payback analysis, the GA optimization of the *status quo* system and the implementation of a micro-hydro turbine in the Espite WSS could brought a cost reduction of approximately 63% and an investment return in the beginning of the third year of exploitation. It is worth remembering that the system studied is a small system with an average consumption of 7 l/s and the micro-hydro power is about to 2.13 kW.

The GA optimization for the number of pump start-ups and the micro-hydro installation in WSS, even for cases of small consumptions and low power production installed, it leads to a viable and environmentally friendly solution, using clean energy exploited during 24 hours per day during the whole year.

ACKNOWLEDGEMENTS

This work was supported by FCT through the project PTDC/ECM/65731/2006, CEHIDRO, the Hydro-systems Research Centre from the Department of Civil Engineering, at Instituto Superior Técnico, Lisbon, Portugal and the Brazilian Research Support Agency (CAPES).

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