Chapter 8

Pumped-Storage and Hybrid Energy Solutions Towards the Improvement of Energy Efficiency in Water Systems

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Additional information is available at the end of the chapter

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1. Introduction

The needs of water consumption, environmental targets and energy savings have become the main concerns of water managers over the last years, becoming more and more important goals for the sustainable development and energy efficiency in water systems (Ramos & Covas, 1999). The needs for water consumption, environmental targets and saving energy have become ones of the world's main concerns over the last years and they will grow to be more and more important in a near future (Refocus, 2006). The objective of these systems is to guarantee the delivery of enough water with good quality to populations. Although, in order to achieve that, energy for pumping is needed, representing the main cost for water companies who operate the systems. The evaluation of the energetic potential in water systems may become a common procedure to achieve energy improvements on these systems. This can be done by taking advantage of the possible environmental and economical benefits from the instalation of a water turbine as a clean energy converter.

The optimization of operations energy consumer or production systems has been investigated for some decades. The interest in this area is not only related to the complexity of the problem but mainly by the environmental, economical and social benefits by adopting this type of solution. The implementation of energy production components in water supply systems is a solution that intends to increase the energy efficiency by using local available renewable resources. With this kind of systems the external energy dependence and their costs can be reduced. The adaptation of water supply systems to produce energy is an advantageous solution because most of the system components already exist (e.g. reservoirs, pipe system, valves) and there is a guaranteed discharge continuous flow along each day. Pump hydro storage systems are used as energy and water storage on systems' networks. These systems consist of two reservoirs, where one is located at a low level and the other at a higher elevation, with pump and hydropower stations for energy injection or conversion. During off-peak hours the water is pumped from the lower to the upper reservoir where it is stored. During peak hours the water is released back to the lower reservoir, passing through hydraulic turbines generating electrical power (Bose *et al.*, 2004).

When a wind park is combined with a pumped-hydro system, several advantages can be achieved:

- during low consumption hours, the wind energy that otherwise would be discarded, can be used to pump water to the upper reservoir and discharged whenever there is a need to produce energy;
- when the wind has high variability, these storage systems can be used to regulate the energy delivery;
- the energy stored in the pumped-hydro system can be utilized to generate electricity when wind power is not available;
- when there is a variable tariff applied, it is possible to achieve significant economical benefits by deciding optimal pumping / turbine schedules (Papathanassiou *et al*., 2003).

The optimization of pump/turbine-operation with energy consumption/production has been investigated over the last decade (Allen, G., McKeogh, F.J., Gallachóir, B., 2006; Anagnostopoulos, J., Papantonis, D., 2006). An optimization problem is a mathematical model in which the main goal is to minimize or maximize a quantity through an objective function constrained by certain restrictions. The optimization models can use several methods which nowadays are becoming more efficient due to the computer technology evolution. In Firmino *et al*. (2006) an optimization model using linear programming was developed to improve the pumping stations' energy costs in Brazil. The study revealed that the energy costs can be reduced by 15%. In Gonçalves et al. (2011) a best economical hybrid solution is applied and the study showed the installation of a micro hydro in a real small water distribution system using water level controls and pump operation optimization by using genetic algorithms shows the improvement of the energy efficiency in 63%. In Castronuovo and Peças Lopes (2004) a model for the daily operation of a wind-hydro plant was developed using linear programming. They concluded that, for the test case presented, the predicted yearly average economic gain of including a pumped-hydro station in a wind farmer, is between 425.3 and 716.9k€.

In this paper an hourly discretized optimization model for the determination of operational planning in a wind pumped-hydro system is presented. Comparisons were made between cases with and without complementary wind energy. The economical profit for each case study is presented.

2. System description

A real case is analysed based on the "Multi-purposes Socorridos system" located in Madeira Island, Portugal. This system was designed to supply water to Funchal, Câmara de Lobos and Santa Quitéria, as well as to regularize the irrigation flows and produce electric energy.

In this system there is a pumping and a hydropower station located at Socorridos. It is a reversible type system which enables pumping (in one station) and power production (in a parallel station) of 40000 m^3 of water per day. Figure 1 depicts a scheme of Socorridos system. Figures 2 to 6 show the all elements of the system under real conditions.

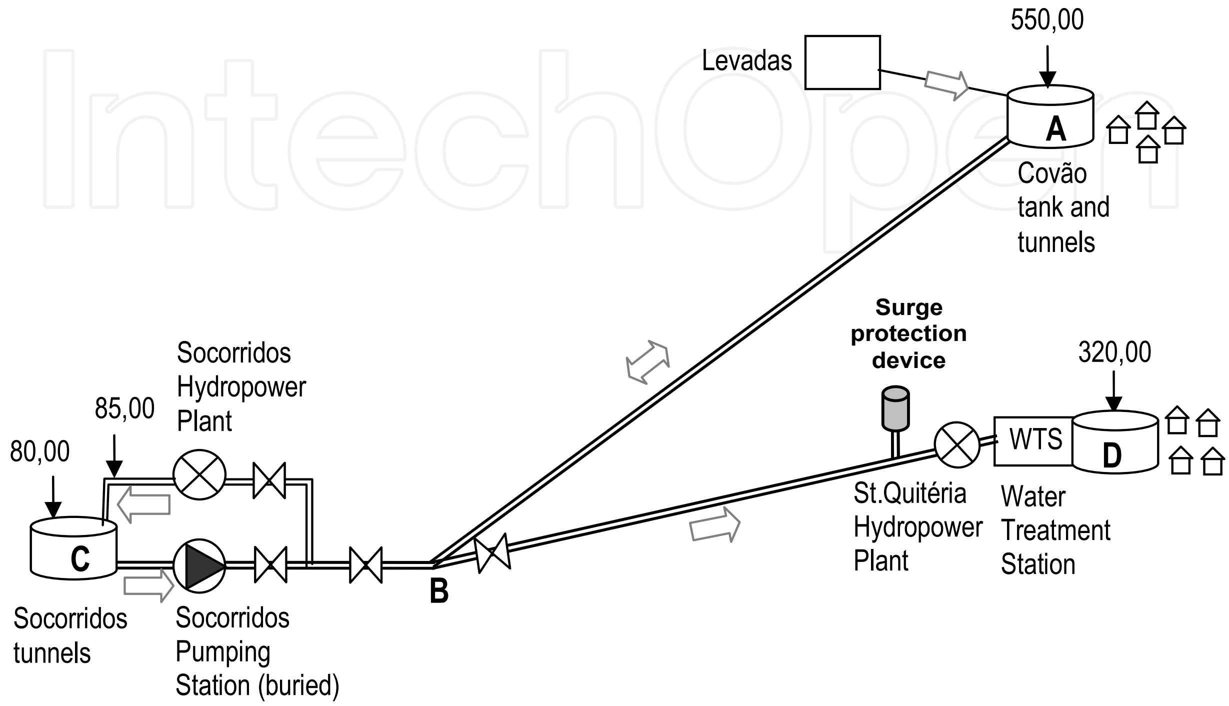

Figure 1. **Multi-purposes scheme of Socorridos system**

The system includes an upper reservoir (Covão) at 540 m, which is used to supply water for the Câmara de Lobos population. In addition to the tunnels, the Covão reservoir is used as storage for the water that flow from the mountains. In Socorridos, there is a tunnel located at 81 m that has the same capacity as the upper one.

Figure 2. Socorridos pumping station – outside view (on the left). Socorridos-St.Quitéria steel pipe (on the centre and on the right)

Figure 3. Socorridos pumping station: centrifugal pumps and control valves

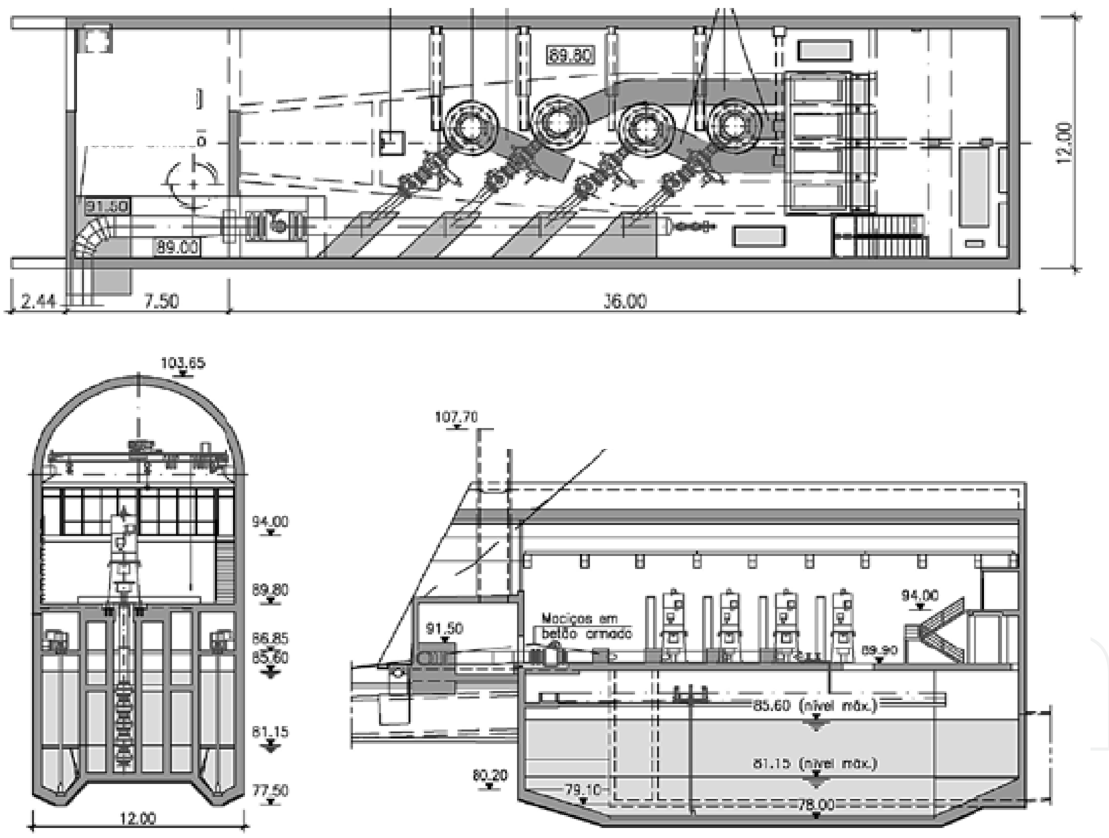

Figure 4. Socorridos pumping station: plant of the ground level (on the top) and transversal and longitudinal views (on the bottom)

St. Quitéria hydropower plant is located at the downstream end of St.Quiteria pipe branch, at immediately upstream a water treatment plant and a storage-tank. This hydropower station has a single Pelton turbine with a nominal flow rate of 1 m3/s and a by-pass to the water treatment plant (Figure 6).

Figure 5. Socorridos storage tank: inlet tunnel (on the left) and centrifugal pump (on the right)

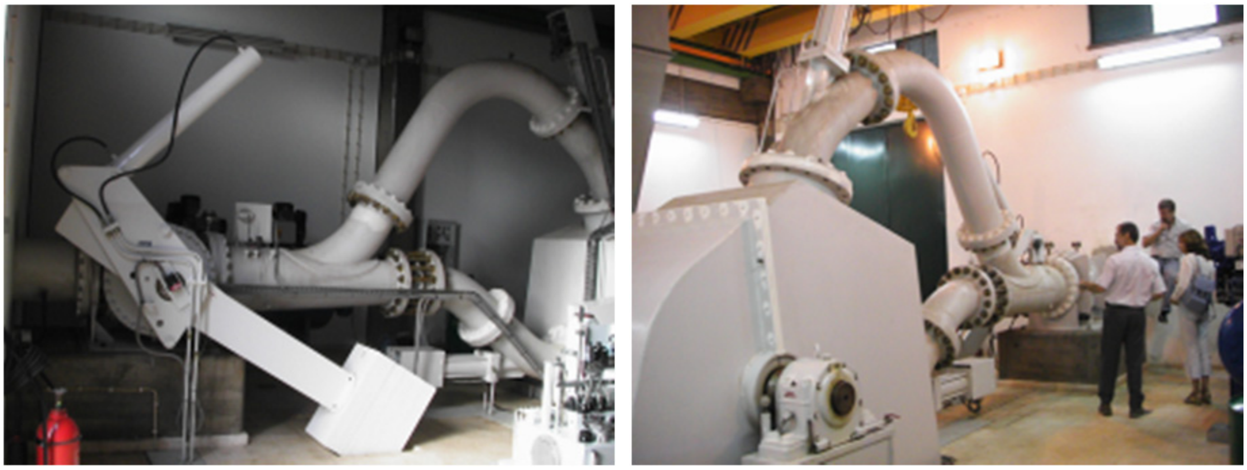

Figure 6. St. Quitéria hydropower station: inside view of Pelton turbine

The pump station is located at level 85 m and has four pumps with an installed power of 3750 kW each. The hydropower station is located at a topographic level of 89 m and has Pelton turbines installed with a nominal power of 8 000 kW and a maximum flow of $2m^3s^{-1}$ each. In Figure 7 the characteristic curves of the Pelton turbines and the pumps are presented.

The penstock between Covão and Socorridos has a total length of 1266.25 m. The characteristics are presented in Table 1.

pipe	L (m)	Φ (mm)	Material
AB	81.25	1000	Steel
BC	132.00	1200	Concrete
CD	303.00	1300	Concrete
DE	440.00	1400	Concrete
EF	310.00	1500	Concrete

Table 1. Covão-Socorridos penstock characteristics.

This pumping station was designed to pump 40000 m^3 of water stored in Socorridos reservoir during 6 h, for the electricity low peak hours (from 0 to 6 am). In the remaining hours of the day, the water is discharged from Covão reservoir to Socorridos hydropower station, in reverse flow direction, in order to produce energy. By the end of the day, the total volume of water in the system is in Socorridos reservoir.

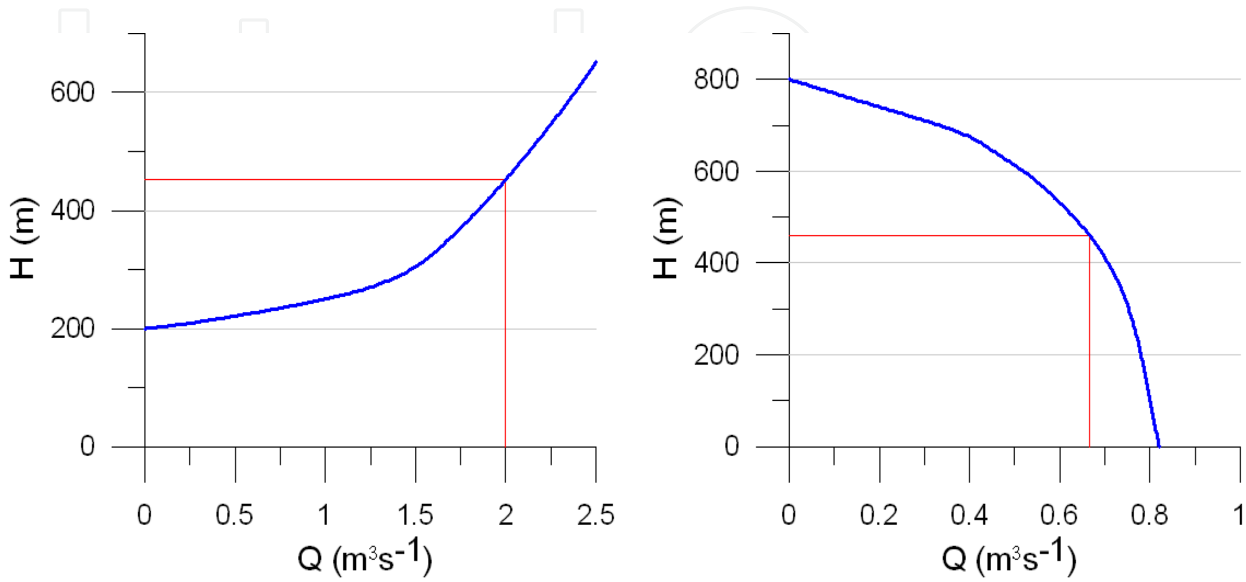

Figure 7. Turbine (Left) and Pump (Right) characteristic curves and operating conditions.

The electricity tariff used in this study, for Socorridos system, is based on the 2006 electricity tariff from Madeira Electricity Company (www.eem.pt), as presented in Figure 8.

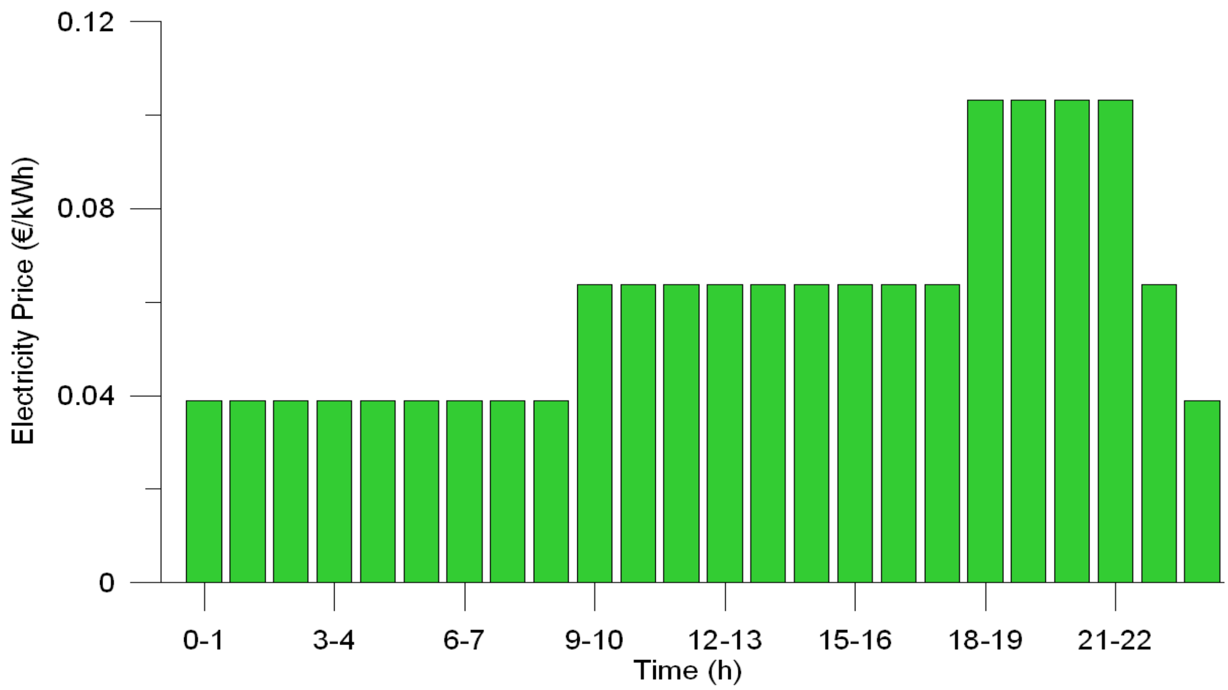

Figure 8. Electricity tariff used in the model (Source: www.eem.pt).

The water consumption in Câmara dos Lobos follows the Manual of Basic Sanitation pattern (DGRN, 1991) and the inflow to Covão reservoir was assumed to have a constant value throughout the day. In Figure 9. the consumption in Câmara dos Lobos and discharge inlet in Covão for one day are presented.

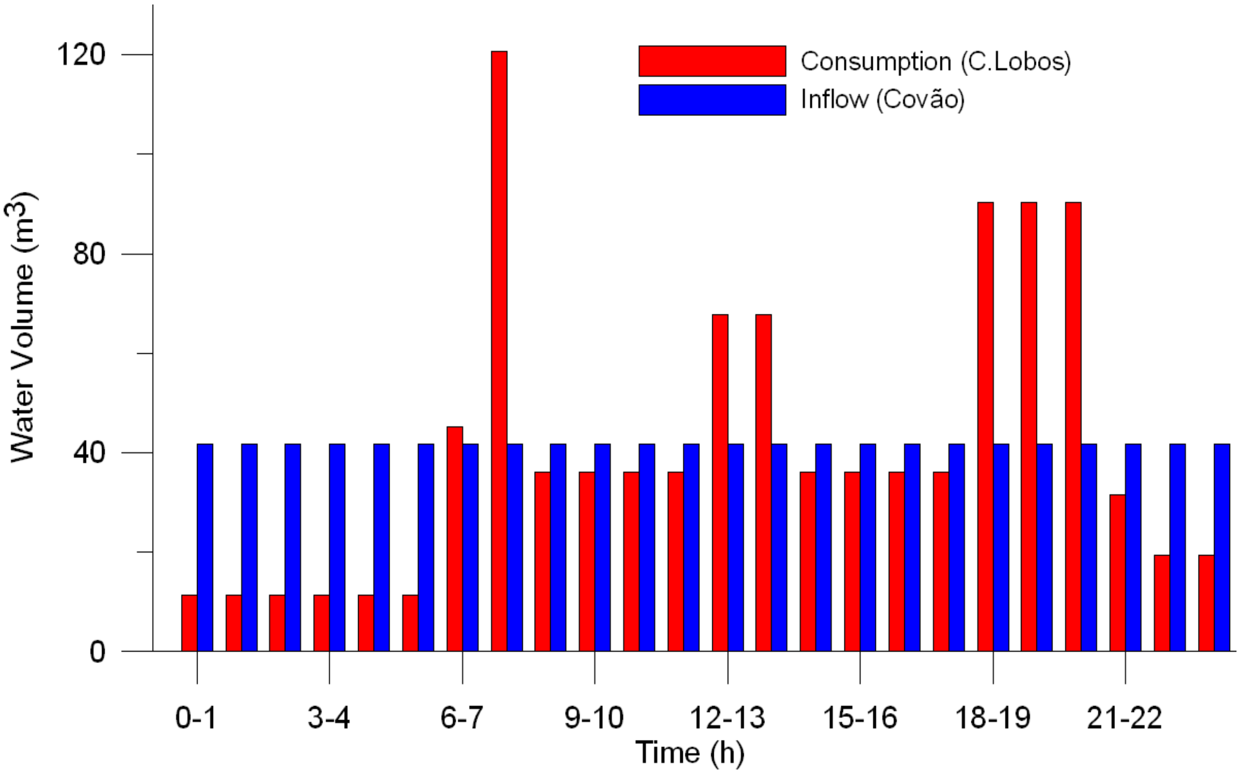

Figure 9. Water volume consumption (Câmara de Lobos) and inlet volume (Covão), in m3, for one day.

For modelling purposes, several assumptions were made to this system:

- the connection to Sta.Quitéria was neglected. This was due to two factors - the energy production is low when compared to the Socorridos hydropower station and the hydropower station does not operate all year;
- the three pumps in the pumping station of Socorridos and the turbines have the same nominal discharge (2 m^3s^{-1});
- it was considered that Socorridos and Covão the reservoirs are cylindrical. Then Socorridos reservoir has a maximum water level of 5 m and a diameter of 101 m. Covão reservoir has a maximum water level of 7 m and a diameter of 85.4 m. The minimum water levels in both reservoirs are 0.5 m.

3. Optimization procedure

Costs associated with the operation of pumping systems represent a significant amount of expenses of a water supply system (Ramos and Covas, 1999). For this reason, it is desirable to optimize the operation of pumps such that all demands are met and, simultaneously, the total pumping cost is minimized.

Typically, pump operation in water supply systems is controlled by water levels at the downstream storage tanks: upper and lower operating water levels are set up in storage tanks such that when these levels are reached, pumps start-up or stop.

The problem consists of defining the hourly operations for the pumps and turbines in the previous presented system, for a period of one day. The goal is to establish a sequence of decisions, for a determined time period, in order to obtain the most economical solution and, at the same time, the better social and environmental solution in terms of guarantee of water supply to populations. The intention is to obtain the pumps and turbines operation time for each hour, so that the maximum benefit from hydropower production and the minimum costs from the pumping station energy consumption are attained.

The problem was solved in terms of water level variation in Covão reservoir. The rules from the optimization model are directly implemented in EPANET model. This procedure is possible since the water level variations are directly proportional to the amount of energy produced or consumed, when the flow and head are considered constants along the simulation time. The time period considered is one day with an hourly time step.

The complexity of the problem is related to:

- the effects of time propagation when an operation is carried, because this will influence the next hours;
- the hydraulic restrictions of the system, like the maximum flow in the pipes, the water level in the reservoirs and the water consumption by the population, have to be completely fulfilled.

An integrated software tool has been developed together with EPANET model (Rossman, 2000) to evaluate the results of the optimization model, in order to verify if the behaviour of the hydraulic components of the system (reservoir levels, flow) is maintained between the desired maximum and minimum limits. To solve the problem several variables are identified, as well as the objective function, which represents the quantity that should be minimized or maximized, the problem constraints associated to the physical capacities of the hydraulic system, and the water demands.

Hence the variables of the optimization process are the following ones:

- Hourly water consumption in Covão (m) - N_{CC}
- Hourly water inlet in Covão (m) - N_{IN}
- Maximum flow in the penstock (m^3s^{-1}) - Q
- Electricity tariff (€) - c
- Initial water level in Covão reservoir (m) - N_{IC}
- Initial water level in Socorridos reservoir (m) - N_{IS}
- Maximum water level in Covão reservoir (m) - N_{MAXC}
- Maximum water level in Socorridos reservoir (m) - N_{MAXS}
- Minimum water level in Covão reservoir (m) - N_{MINC}
- Minimum water level in Socorridos reservoir (m) - N_{MINS}

- Maximum water level rise/decrease for each time step - N_{Qmax}
- Reservoirs diameter (m) - *D*
- Wind speed curve;
- Wind turbine power curve.

3.1. Pump-storage/hydro

For this situation, two optimization programs were developed: one using linear programming (LP) and the other using a non linear programming (NLP).

For the linear programming case (LP), it is assumed that the water pumping occurs during the first six hours of the day (from 0 to 6 am) and in the remaining hours the system can only produce energy by hydropower. This is to simulate the normal operation mode. The objective function to minimize is the following:

$$f = \sum_{h=1}^{6} \left(\frac{c_{B,h}}{\eta_B} \cdot dN_h \right) + \sum_{h=7}^{24} \left(c_{T,h} \cdot \eta_T \cdot dN_h \right) \tag{1}$$

where c_B represents the electricity tariff for each hour; *dN* is the water level raise or decrease in Covão reservoir, for each hour; c_T is the produced hydroelectricity selling price for each hour; $\eta_{B,T}$ are the pump and turbine efficiency; and *h* is the hour of the day.

The above function represents the sum of the water level variation in Covão multiplied by the electricity costs/selling price, throughout one day. Meaning that if there is a raise in Covão reservoir water level ($dN>0$), the pump station is operating and has a cost c_B associated for each hour. If, on the other hand, there is a decrease in Covão reservoir water level ($dN<0$), the system is discharging water from Covão to Socorridos and consequently, producing energy that can be sold at a price c_T. With this function it is possible to provide the electricity costs for the pumping hours and the selling price for the electricity production hours.

The hourly limits relatively to the pipe flow restrictions are presented in Table 2.

Hours	Lower	Upper
0 to 6	0	N_{Qmax}
6 to 24	$-N_{Qmax}$	0

Table 2. Hourly restrictions LP.

From 0 to 6 am it is only possible to pump water since the lower bound is zero. From 6 am forward only turbine operation is allowed.

For the non linear programming case (NLP) there is no need to impose pumping and power hours because the program will choose which solution is the best in order to obtain the major benefits. Then the objective function to minimize is:

$$f=\sum_{h=1}^{24}\left[\frac{c_{B,h}}{\eta_B}\cdot\left(\frac{dN_h+\left|dN_h\right|}{2}\right)+c_{Th}\cdot\eta_T\cdot\left(\frac{dN_h-\left|dN_h\right|}{2}\right)\right] \quad (2)$$

Hence, if the water level variation in Covão reservoir is positive (pumping situation), the term related to the turbine operation is zero. The opposite is also verified. The hourly limits relatively to the pipe flow restrictions are presented in Table 3.

Hours	Lower	Upper
0 to 24	$-N_{Qmax}$	N_{Qmax}

Table 3. Hourly restrictions NLP.

This means that, for this case, the only restriction is that the water level variation for each time step cannot be greater than N_{Qmax}.

3.2. Pump-storage/hydro with wind power

For this case the non linear programming (NLP Winter and NLP Summer) was used since the objective function is also non-linear:

$$f=\sum_{h=1}^{24}\left\{\left[\frac{\left|\frac{Nv_h}{dN_h}-1\right|-\left(\frac{Nv_h}{dN_h}-1\right)}{2}\right]\cdot\frac{c_{B,h}}{\eta_B}\cdot\left(\frac{dN_h+\left|dN_h\right|}{2}\right)+c_{T,h}\cdot\eta_T\cdot\left(\frac{dN_h-\left|dN_h\right|}{2}\right)\right\} \quad (3)$$

where N_v is the water level rising to Covão reservoir due to wind power for each hour.

With the former function, the electricity cost for each hour is not the same as the tariff, but it varies according to the contribution of wind available energy. The wind energy is assumed to have a null cost since no energy from the grid is necessary for its generation. Therefore, for each hour, if all of the energy for pumping water is provided by the wind turbines, it has a null cost; if one part of the energy comes from the electrical grid and the other from the wind turbines, the cost is a fraction of the tariff. For example, if one third of the energy for pumping is provided by the wind turbines for one time step, the cost of energy to pump water in this time step is two thirds of the original tariff.

The hourly limits related to the pipe flow restrictions of the system are the same as the previous case (NLP) where the wind component was not considered.

The wind data used for this case is presented in Figure 10. The curves represent typical winter and summer situations for a weather station in Portugal.

The wind turbine chosen was a *Fuhrländer FL2500* (www.friendly-energy.de) with a power curve presented in Figure 11. It was assumed that the system has five of these turbines, so that the maximum power demand by the water pumps in one hour could be provided.

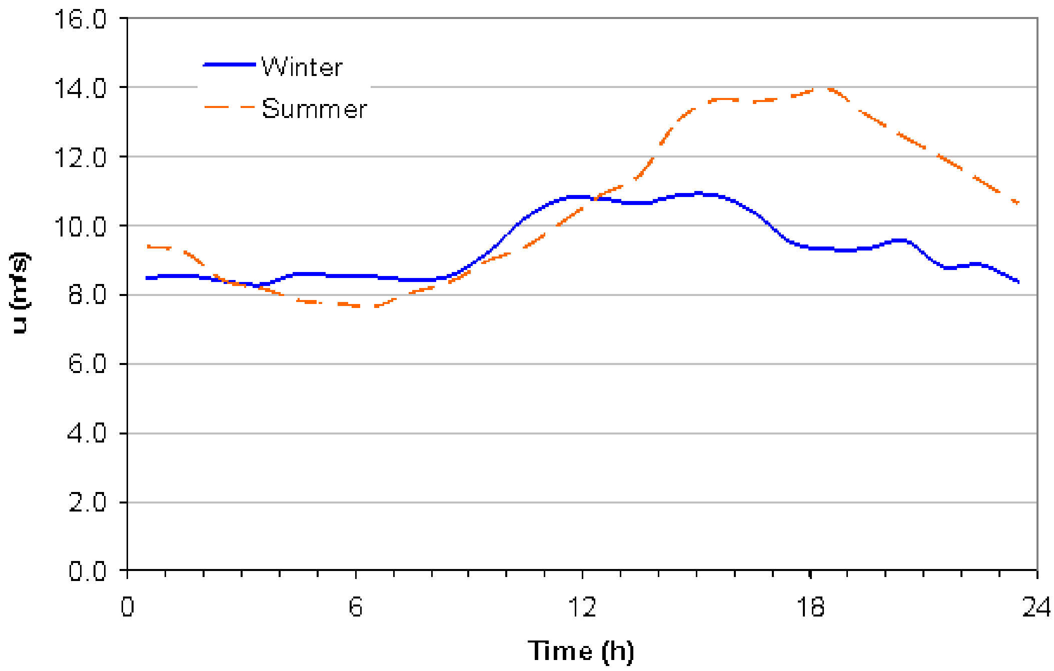

Figure 10. Wind speed average values for typical winter and summer conditions, 100 m above the ground.

The constraints for all of the cases presented, linear and non linear programming, are the following:

1. The guaranty of water supply to the Câmara de Lobos population must be provided, maintaining a minimum water level in both reservoirs;
2. The water in the reservoirs can not exceed the maximum level;
3. The maximum water flow, in each time step, depends on the systems characteristics and the electromechanical equipment.

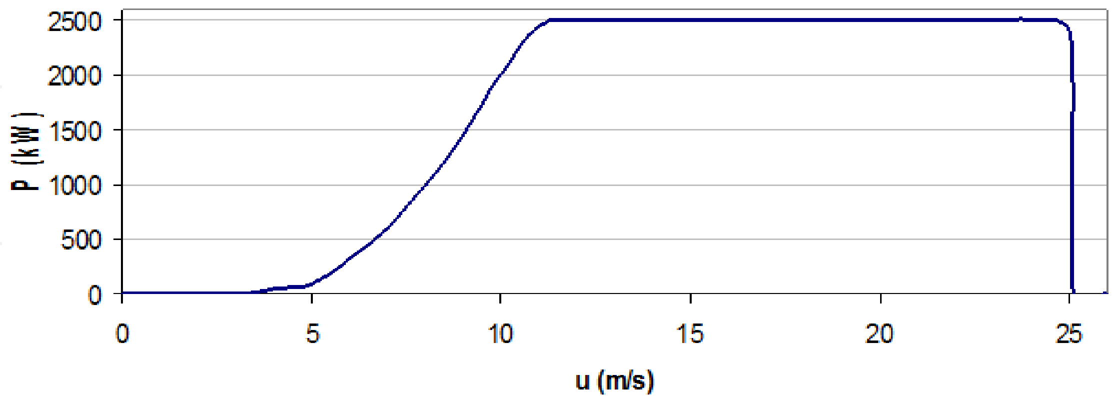

Figure 11. Typical FL2500 power curve.

4. Hydraulic model implementation

An integrated software tool has been developed for determining the optimum pump and turbine schedules and reservoirs water levels, that minimize pumping costs (i.e., maximize off-peak electrical energy consumption) and maximize energy production. This tool incorporates a 'hydraulic simulator' that describes the hydraulic behaviour of the system during 24 hour simulation (EPANET), and an 'optimization solver' based on Linear and Non-linear programming to determine the optimal solution without violating system constraints (e.g., minimum and maximum allowable water levels in the storage reservoirs) and ensuring that downstream demands are satisfied. In Figure 12 the model scheme of Socorridos-Covão system is presented.

As for Covão as for Socorridos the storage reservoirs are tunnels made in rocks. However during modelling implementation these tunnels are approximated by regular cylindrical reservoirs of variable levels with the same volume of the real case. For modelling purposes a discharge control valve, with 2 m^3/s as the control parameter, was implemented in order to simulate the hydropower installed at topographic level 89 m. The pump station is installed at 85 m.

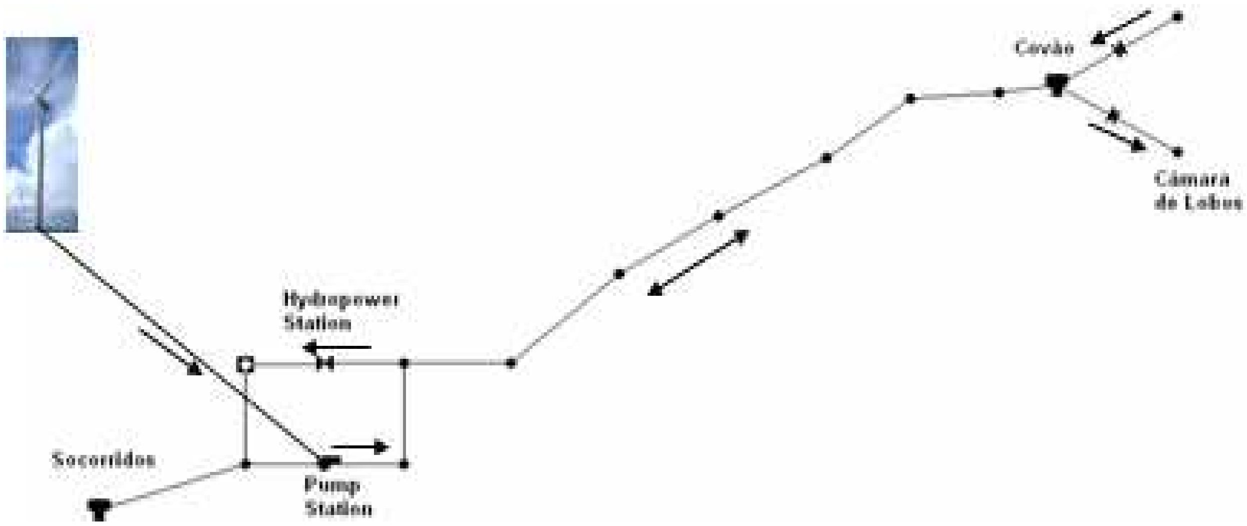

Figure 12. Model scheme of hydraulic system used in the optimization process.

5. Discussion

The four modes of operation (i.e. linear and non-linear programming without wind turbines: LP and NLP; and non-linear programming with wind turbines for summer and winter conditions: NLP Summer and NLP Winter) were compared in terms of water reservoirs levels, pump and turbine operation time and final costs/profits.

In Figure 13, the discharge volumes through the analysis of water levels in Socorridos and Covão reservoirs are presented. It can be seen, that for all modes, the initial and final water levels are imposed to be the same. Then, an adequate comparison in terms of energy production and consumption can be made.

Figure 14 depicts the pumping and turbine operation time for each hour of the day. It can be seen that for the LP mode of operation, the pump station only operates during the first six hours of the day, and in the remaining hours, the hydropower station is working. In the last two hours of the day there is no more water available to power because the Covão reservoir has reached the minimum water level.

For the NLP modes, with and without wind turbines, the behaviour of pump and turbine operation is quite different from each other. The results vary due to the non linearity of the objective function and also according to the wind availability for each hour.

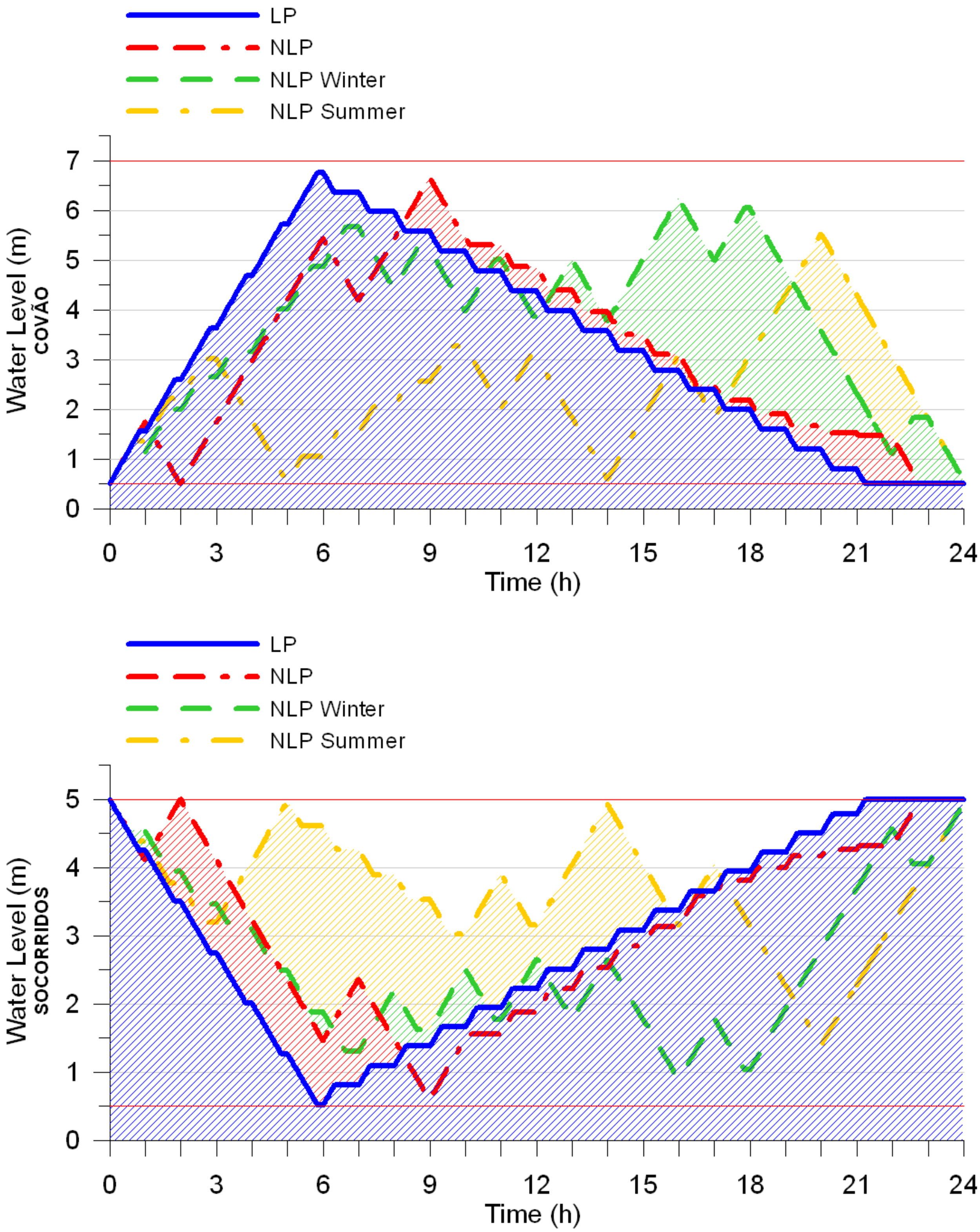

Figure 13. Water level variation in Covão and Socorridos reservoirs.

	$E_{Produced}$ kWh	$E_{Consumed}$ kWh	Cost €/day	Benefit €/day	Profit €/day
LP	37247	60107	2342	2754	411
NLP	51110	82747	3224	3734	510
NLP Winter	73344	7012	273	5470	5197
NLP Summer	72933	5009	195	5356	5161

Table 4. Energy produced and consumed, and daily costs, benefits and profits.

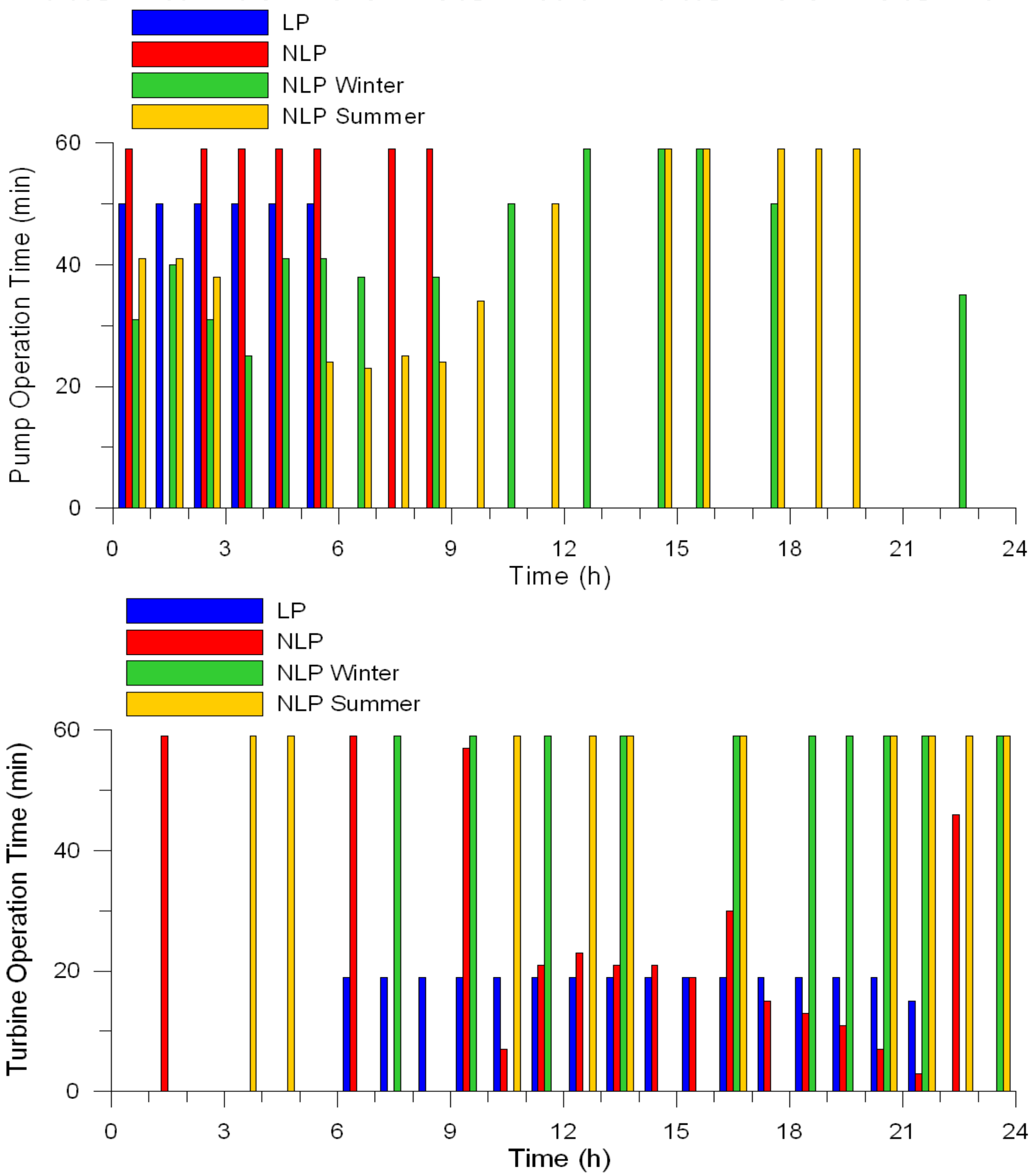

Figure 14. Pump and turbine operation time for the four modes.

In Table 4, a summary of the energy production and consumption, as well as the total costs, benefits and profits are presented.

It can be verified that although, with *NLP* the daily profit is higher than the *LP* case, there is more energy consumption but also more energy production. The profits are approximately 100 €/day higher for the *NLP*.

When considering the wind park as energy supplier for the pump station, the energy consumption from the electrical grid is much lower and the energy production higher. There is not a relevant difference in the profits between summer and winter wind conditions. The costs of installation, operation and maintenance of the wind park are not considered here since it was a component out of the purpose of this work.

6. Conclusions

In the last decades, the managers of water distribution systems have been concerned with the reduction of energy consumption, and the strong influence of climate changes on water patterns. The subsequent increase in oil prices has increased the search for alternatives to generate energy using renewable sources and creating hybrid energy solutions, in particular associated to the water consumption. Renewable energy includes hydro, wind, solar and many others resources. To avoid problems caused by weather and environment uncertainties that hinder the reliability of a continuous production of energy from renewable sources, when only one source production system model is considered, the possibility of integrating various sources, creating hybrid energy solutions, can greatly reduce the intermittences and uncertainties of energy production bringing a new perspective for the future. These hybrid solutions are feasible applications for water distribution systems that need to decrease their costs with the electrical component. These solutions, when installed in water systems, take the advantage of power production based on its own available flow energy, as well as on local available renewable sources, saving on the purchase of energy produced by fossil sources and contributing for the reduction of the greenhouse effect.

An optimization model for determining the best pump and turbine hourly operation for one day was developed. The model was applied to the "Multi-purposes Socorridos" system located in Madeira Island, Portugal, which is a pumped storage system with water consumption and hydropower production.

The model is very flexible in terms of input data: wind speed, water consumption, reservoirs volume, maximum flow and electricity tariff, and the numerical computations take less than a minute. The results can immediately be introduced in EPANET hydraulic simulator in order to verify the system behaviour.

With non linear programming, the results showed that a saving of nearly 100 €/day can be achieved when compared to the normal operation mode, maintaining the hydraulic restrictions and water delivery to the population. When a wind park is added to the system, the profits are much higher, approximately 5200 €/day, for winter and summer wind conditions.

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