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Energy efficiency in a water supply system: Energy consumption and CO_2 emission

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Abstract: This paper presents important fundamentals associated with water and energy efficiency and highlights the importance of using renewable energy sources. A model of multi-criteria optimization for energy efficiency based on water and environmental management policies, including the preservation of water resources and the control of water pressure and energy consumption through a hybrid energy solution, was developed and applied to a water supply system. The methodology developed includes three solutions: (1) the use of a water turbine in pipe systems where pressures are higher than necessary and pressure-reducing valves are installed, (2) the optimization of pumping operation according to the electricity tariff and water demand, and (3) the use of other renewable energy sources, including a wind turbine, to supply energy to the pumping station, with the remaining energy being sold to the national electric grid. The use of an integrated solution (water and energy) proves to be a valuable input for creating benefits from available hydro energy in the water supply system in order to produce clean power, and the use of a wind source allows for the reduction of energy consumption in pumping stations, as well as of the CO_2 emission to the atmosphere.

Key words: *multi-criteria optimization; energy efficiency; water supply; renewable energy sources; CO_2 emission*

1 Introduction

Nowadays, energy and water play vital roles in the economic growth of any country. Some regions are facing energy and water scarcity due to unprecedented economic and social development. This economic growth is not sustainable if most of the energy has to come from fossil fuels. Increasing fossil fuel consumption will significantly increase greenhouse gas emissions, resulting in dangerous levels of global warming. Thus, an integrated policy dealing with water and energy efficiency, reliability, and environmental issues through appropriate water supply system management must be developed in order to encourage water and energy companies to implement new environmental hybrid energy solutions with guaranteed flow throughout the day in these types of water systems.

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The efficient use of conventional energy and proper use of renewable energy sources have received more attention in the European Union (EU) over the past decade, and climate policies that focus on these goals particularly help in the reduction of CO_2 emission in order to meet international obligations. This is particularly relevant when viewed in light of the Kyoto Agreement to reduce CO_2 emission, as improved energy efficiency will play a key role in meeting the EU Kyoto target in an economic way. This will contribute to the following: (1) promoting the development of energy production from national clean and renewable resources; (2) fostering increasingly rational energy use; (3) reducing the external dependence of the national power system; (4) promoting the diversification of energy supply sources; (5) ensuring energy supply under efficient and safe conditions; (6) reducing oil dependency; and (7) minimizing the environmental impacts resulting from energy production by endogenous sources and high levels of energy consumption.

The EU leaders have made commitments to increase the use of renewable energy, which can replace fossil fuels, diversify the energy supply, and reduce carbon emissions. Increasing the investment in renewable energies and new technologies and strategies to promote energy efficiency will allow countries to implement sustainable and safe development, and push up their economic growth. Moreover, the preservation of water resources, control of energy consumption, and implementation of water management policies bring about a series of priority problems that are important to integrated water supply and energy efficiency management (Vieira et al. 2007).

Water supply systems should guarantee the delivery of enough water of good quality to the population (Ramos et al. 2004). In these systems, energy is needed for water pumping and treatment. This represents an important part of operation and maintenance (O&M) costs for water utilities (Hiremath et al. 2007). Nowadays, decision makers cannot be driven only by economic concerns, since it is necessary to consider other factors, such as performance, reliability, and risk, leading to new solutions for integrated non-conventional analysis (Rossman 2000; Vieira and Ramos 2009).

Efficient measures can be taken if the available resources are used in an optimized way. The main motivations of the new challenge process are based on an integrated vision that comprises reliability and energy components in order to guarantee good service levels throughout the system’s life cycle.

2 Objectives

The control of energy consumption associated with water management is a priority in this new era of water and energy utilization. It is because of these concerns that new methodologies must be defined and solutions must be achieved.

The integration of energy production in water supply systems is one of the most advantageous solutions, comprising analyses to increase energy and water efficiency according to the following basic goals: the rational use of existing resources and the satisfaction of consumers' needs, the reduction of external energy dependence, the promotion of the use of renewable energy sources, and the increase of the effectiveness and efficiency of each system (Vieira and Ramos 2008).

According to the typical load curves (dimensionless consumption factors) for both water consumption and energy consumption (Fig. 1), the periods of highest consumption of water and energy occur at approximately the same time. This fact allows for the definition of a new mutual water and energy strategy.

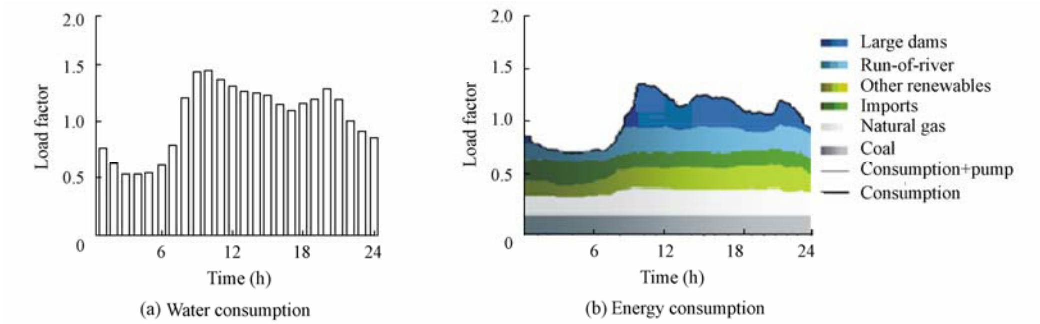


Fig. 1 Typical dimensionless consumption curves over a day in Portugal

As for water production and supply, coal makes up the highest percentage of the primary energy sources for electric energy consumption (Fig. 2, REN 2007). Although the tendency is toward reducing this contribution, it is necessary to consider new and innovative energy solutions. The percentages of different energy sources used for water production and supply by the Lisbon Water Company (EPAL 2006) are: 46.6% for coal, 18.7% for gas, 24.6% for fuel, and 10.1% for renewable sources (mainly hydroelectric).

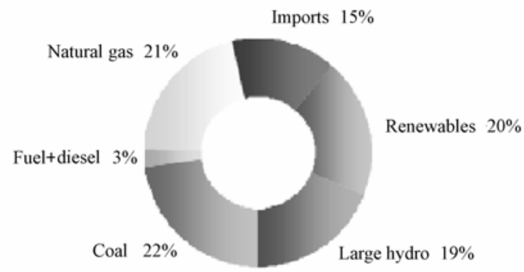


Fig. 2 Percentage of total energy injected in national electric grid by power type

However, renewable sources are not always part of the main objectives for energy production in many developed countries. The amount of CO_2 in the atmosphere has been rapidly increasing over the last 100 years.

In order to better support the integration of these combined solutions, an analysis should be developed based on the following: (1) evaluation of the available potential energy in water supply systems or the establishment of favorable conditions for energy exploitation, on the basis of global performance analysis of the system (e.g., pressure control, energy consumption, etc.), by means of multi-objective optimization algorithms; (2) more efficient use of water and energy; and (3) minimization of energy use and water loss.

3 Methodology

In water supply systems, the pressure must be controlled as shown in Fig. 3 to avoid pipe bursting and carry out leakage management. Fig. 3 presents an example of a possible pressure control solution (Ramos et al. 2004), where the differences between the solutions, without any control and with a pressure-reducing valve (PRV) or a power converter device (PT) installed (i.e., a water turbine), are quite visible, for all nodes of the network system during one day.

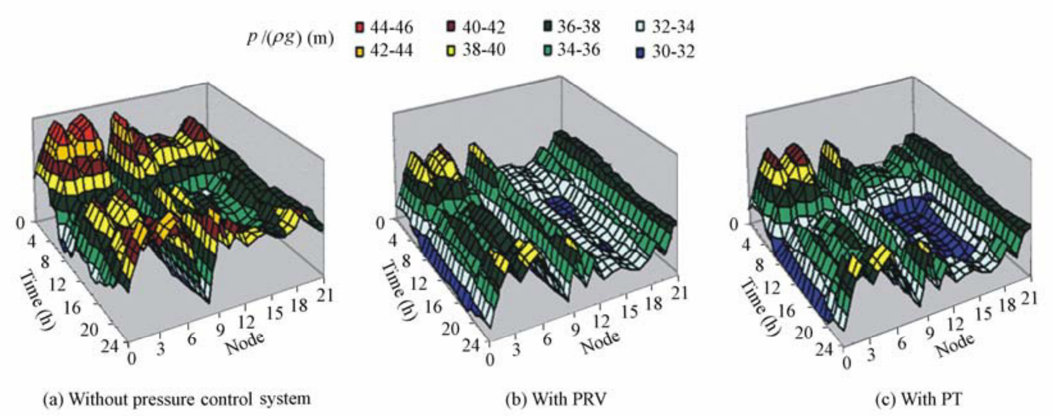


Fig. 3 Pressure variation in nodes of pipe network during one day

(p is pressure, ρ is water density, and g is acceleration of gravity)

The methodology proposed in this paper can be easily implemented in existing water supply systems. It consists of three complementary measures: (1) the installation of turbines in gravity pipes with excess pressure, (2) the optimization of pump schedules in pumping branches, and (3) the use of other available renewable sources to supply pumping systems or the national electric grid (e.g., wind energy).

A water turbine can be installed in systems that already have excess pressure, most of the times with already installed PRVs. However, an evaluation of the potential of energy production is necessary in order to assess whether this solution is feasible or not, and to estimate associated costs and benefits. Micro-hydro systems can control the pressure and provide an effective way to produce clean energy.

The improvement of the system efficiency can also be achieved by planning water pumping operations according to the daily electricity tariff. The operations can be managed in such a way that the daily costs are reduced by choosing the off-peak hours to pump whenever possible. This requires the application of numerical optimization methods and information on the expected water consumption so that the operations can be planned in advance. The main objective of this solution is to assure the reliability of the water supply at the minimum operational costs.

Another proposed solution that deals with hybrid energy systems comprises two or more sources of energy production (Ramos and Ramos 2008). The combination of different energy sources has the main advantage of coping with intermittencies in the production of energy from complementary sources, stabilizing the energy efficiency and offering the necessary flexibility and significant environmental benefits (Anagnostopoulos and Papantonis 2007). For instance, energies from the electric grid (usually produced from fossil fuels) and wind turbines (which have the advantage of being renewable) can augment the energy supply. Besides, an energy storage solution (e.g., pump-storage) is necessary to enable later use.

The production and control of wasted energy using combined solutions or the integration with existent water supply systems allows for approaches to new challenges, low cost, and clean and environmentally acceptable and alternative solutions. This methodology will help the EU reach the goal of reducing overall greenhouse gases emissions by 20% by the end of 2020.

4 Case study

4.1 System description

A water supply system is considered, which is composed of a water source (*A*) and a gravity pipe with a bifurcation (*B*) that supplies two populations (*C* and *D*) with storage tanks (Fig. 4). One of these populations (*C*) is located at a higher site than the water source, requiring a pumping system. The other population (*D*) is supplied by gravity and needs a PRV at the upstream end of the storage tank. The upstream tank *A* has a constant water level of 130 m; the two storage tanks, *C* and *D*, have levels of 177 m and 17 m and diameters of 27 m and 29 m, respectively, and both have minimum water depths of 0.5 m and maximum water depths of 3.0 m.

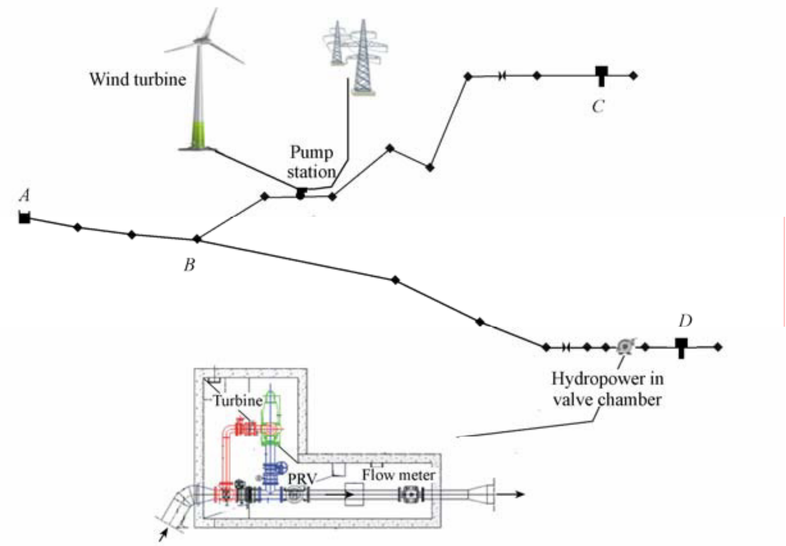


Fig. 4 Sketch of water supply system

The pump, located in the *BC* pipe branch, has a manometric head of 116 m and an average efficiency of 75%.

The pumping station is supplied by the national electric grid or wind energy whenever it is available. The turbine is installed in the valve chamber, a bypass of the existing pipe, as shown in detail in Fig. 4. It is assumed that water demand and energy cost vary throughout the day as presented in Vieira and Ramos (2009).

The main objective was to assess potential benefits resulting from the installation of a water turbine in the *BD* pipe branch, replacing the PRV or installing it in series with the PRV, depending on the system characteristics. The water turbine has an efficiency of 83% at the highest efficiency point, and a characteristic curve (net head *H* versus discharge *Q*) as depicted in Fig. 5.

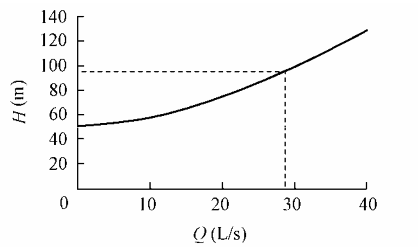


Fig. 5 Net head-discharge curve for water turbine

4.2 Model restrictions

The optimization of the pump operation in the *BC* pipe branch should be analyzed in terms of water level variation in the downstream tank. Thus, an increase of the water level in tank *C* corresponds to an increase of energy consumption necessary for pumping the corresponding volume of water. Unlike for tank *D*, a rise of the water level corresponds to an increase in energy production. Thus, for the optimization of the water pump, a sequence of decisions throughout a day is made in order to reduce the total electricity costs, and, whenever possible, the use of available wind power can also be considered. The time step used for the optimization model is one hour for a total daily period. The goal is to achieve the best solution for each hour, considering that each action influences those that follow. The water supply has to be guaranteed and all hydraulic restrictions have to be fulfilled. The output of the optimization routines is then introduced into a hydraulic simulator to verify the system behavior.

For the normal operation mode (without the optimization algorithm) of the *BC* pipe branch, the pumping station is switched on when the water level in tank *C* is less than the minimum value, and switched off when the water level in tank *C* is higher than the maximum value. The result of this optimization model is the duration of pumping for each hour throughout the day, considering the following restrictions: (1) adequate water supply for the population is guaranteed, while maintaining a minimum imposed water level in the tank for emergencies; (2) the water inflow to tank *C* depends on its capacity; (3) the maximum water flow, in each time step, depends on the system characteristics and the electromechanical equipment; and (4) the water level variation in tank *C* cannot be negative, i.e., the water cannot flow in a reverse direction (from *C* to *A*).

Whenever there is available wind, a hybrid solution with a complementary wind energy source should be considered along with the wind power curve, as presented in Vieira and Ramos (2009). Two wind speed curves were tested, one representing the winter condition and the other representing the summer condition.

Since CO_2 emissions are one important concern associated with the energy production process, an estimation of benefits of the implementation of an environmental hybrid solution based on available data (Spadaro et al. 2000) was also analyzed. The total CO_2 equivalent emissions for different energy sources are shown in Table 1. These include both direct emissions from burning and indirect emissions from the life cycle.

Table 1 CO_2 equivalent emissions for different energy sources

Energy source	CO_2 equivalent emission (g/(kW·h))		
	Maximum	Minimum	Average
Coal	1 306	966	1 136
Gas	688	439	564
Solar PV	280	100	190
Hydro	236	4	120
Wind	48	10	29
Nuclear	21	9	15

5 Discussion of results

Results for an initial water depth of 1.5 m for the downstream tanks *C* and *D* are presented in this section, since the operations, both pumping and turbining, depend on this parameter. By installing a water turbine in the *BD* pipe branch, 370 kW·h of energy were produced during one day when the initial water depth in tank *D* was 1.5 m. This energy production caused an average of 44 kg of CO_2 emissions (when using the average value for hydropower production from Table 1). If the same amount of energy was produced by coal and gas (assuming an average value between the two sources from Table 1, 850 g/(kW·h) of CO_2 equivalent), 315 kg of CO_2 equivalent were emitted to the atmosphere.

By combining the pumping optimization operations and the introduction of a wind turbine for providing energy to the water pump, both economic benefits and reduction in CO_2 equivalent emission were achieved. Table 2 presents the total energy consumed during one day by the energy source and CO_2 equivalent emission for the normal operation of the system without the wind turbine and for two scenarios of operation with the wind turbine in summer and winter. It can be observed that there was much less energy provided by the electric grid when the wind turbine was included in the system in both summer and winter in comparison with the normal operation. This is because the optimization model allows for all available energy from wind power to be used for water pumping.

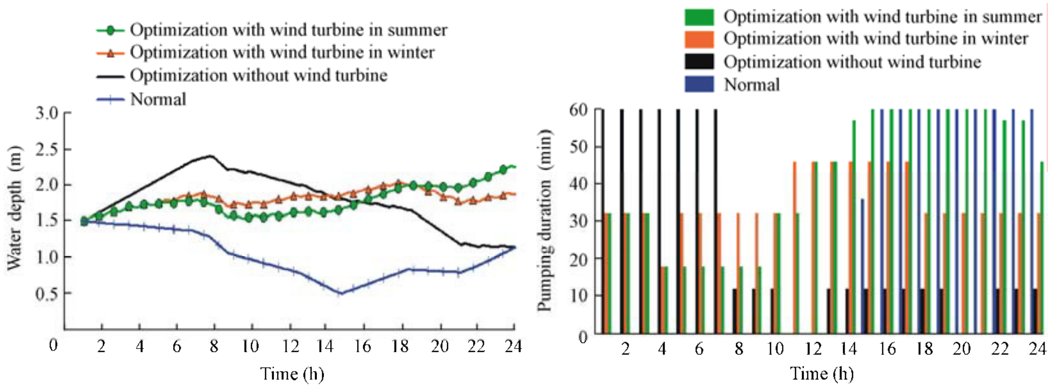
Table 2 Consumed energy by source and CO_2 equivalent emission

Energy source	Consumed energy (kW·h)			CO_2 emission (kg)		
	Without wind turbine	With wind turbine		Without wind turbine	With wind turbine	
	Normal	Summer	Winter	Normal	Summer	Winter
Electric grid	188	79	27	174	73	25
Wind turbine	0	246	251	0	7	7
Total	188	325	278	174	80	32

For normal operation (without optimization), more energy of electric grid is consumed when the initial water depth is lower because, according to the operating mode, the pump is switched on when the water level in tank *C* reaches the minimum value and switched off when the water level is at the maximum value. When the wind turbine was included, the maximum water depth in tank *C* was higher than that for the normal operation.

When the final water level for an initial water depth of 1.5 m in tank *C* was the same as for the summer and winter cases, an additional 178 kg and 117 kg of CO_2 equivalent were emitted.

The water depth variation in tank *C* and the duration of water pumping for each hour for normal mode and optimized modes without the wind turbine and with the wind turbine in summer and winter, during a period of one day are shown in Fig. 6.



(a) Water depth variation in tank C (b) Pumping duration

Fig. 6 Comparison of water depth variation in tank *C* and pumping duration with and without wind turbine for initial water depth of 1.5 m

In terms of the pumping duration, for the normal operation mode, the pump starts working as the water level reaches the minimum value, and keeps working until the end of the day, because the water level never reaches the maximum value, which is the condition for shutting down the pump. With the optimized procedure, the pump remains on without interruption for the first seven hours of the day, which correspond to the off-peak hours of the load pattern. During the peak hours the pump is not switched on, and during the rest of the day it is on for a certain period of time. Considering the optimization with the wind turbine, the pumping duration varies according to the wind power availability.

The amount of CO_2 equivalent was calculated under the assumption that the grid energy was generated by a mix of sources consisting of 46.6% coal, 18.7% gas, 24.6% fuel, and 10.1% renewable sources, resulting in a weighted average value of 926 g/(kW·h) of CO_2 for the calculation of the associated pollution.

6 Conclusions

The European Community has been working intensively to improve energy efficiency in all sectors while at the same time increasing the use of renewable energies. This can be a key issue for solving environmental, self-sufficiency, and cost problems, and adequately providing for increasing energy demand without major upheavals. This paper presents a procedure for improving the energy and environmental efficiency in a water supply system with pumping and gravity pipe branches. Optimization routines for the pump operation and the hybrid system operation (with a wind-pump solution) were also developed based on the following methods: (1) installation of a water turbine in pipes where the pressure must be controlled, (2) optimization of pumping operations according to the electricity tariff and the water demand, and (3) addition of a renewable energy source and a wind turbine in the pumping system.

The results show that, with the use of a water turbine to take on the available excess energy in the gravity pipe branch, which would be dissipated in a pressure reduction valve, 370 kW·h of energy are generated during a period of one day. The optimization of the pump operation does not affect the energy consumption but considerably reduces the costs. When a wind turbine is included in the system to provide power to the water pump, less energy from the national electric grid is consumed and CO_2 emission is reduced by more than half when compared with the normal operating mode.

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