Renewable energy

Regarding the gross consumption of electricity in 2011 (Figure 1.2), Portugal was recognized as the fifth country in the European Union with greater integration of renewable energy, yet was considered the fifth country in the EU with greater energy dependence. This dependence led to the development of ways to minimized it, resulting in a strong focus on sector (DGEG, 2011).

Share of renewable energy in gross final energy consumption in EU-27 Member States (APREN, 2013)
Taking this situation into account, Portugal has set very ambitious goals in the energy sector. According to the National Energy Strategy (ENE 2020), Portugal aims to reduce energy dependence on the outside world from 83% in 2008 to 74% in 2020, which aims to incorporate 31% of renewable energy consumption while it reduces by 20% the consumption. The investment and development of renewable energy potential, which in Portugal is remarkable, especially for solar, wind, hydro and biomass, is therefore one of the main goals.

![Electricity generation in Portugal by technology, 2010 (REN)](image)

Electricity generation in Portugal by technology, 2010 (REN)

This figure shows the electricity generation in Portugal by the different sources and it is clear that water and energy are inextricably linked, and both are equally important for economic and population growth.
Energy and water efficiency

- The importance of the hydropower production is related to the profit of excess available energy in water and wastewater systems, namely, drinking and irrigation systems being a valorous alternative for energy production within renewable energy sources with low cost and clean energy source and with no significant environmental impacts (Ramos and Borga, 2000).

- On other hand the pumping are also very important, since every liter of treated water that passes through the system represents a significant energy cost, a cost that is magnified by every liter lost to leaks (Barry, 2007).
**Water-energy nexus** is based on the reality that every liter of water that passes through a system represents a significant energy value. This value can be translated into costs when it is referred to treating water for human consumption and moving it to the consumer or in profit when it is referred to energy production. In any case, most of the times the system is not working with its best efficiency due to:

- Inefficient pump/hydropower stations;
- Poor design or installation;
- Lack of maintenance or poor management;
- Old pipes with high loss;
- Excessive supply pressure and head losses;
- Leakage in the system;
- Inefficient use of water;
- Inefficient operation strategies.
Approaches to efficient water distribution

• Despite all the barriers to the efficiency in the WSSs there are several measures that can be taken. According to Barry (2007), the most promising areas for intervention within water supply systems are:
  • Improve pump/turbine system efficiency;
    – Efficient machines;
    – Variable speed drives;
    – Regular inspection & maintenance;
  • Manage Leaks
    – Leak detection;
    – Pressure management;
  • Automate controls;
  • Metering & monitoring;
    – Install and maintain water meters;
    – Regular monitoring protocol;
    – Metrics to track performance.
In the course of an economic analysis there are some concepts that is necessary to understand:

**Discount rate (r):** The present value of a future unitary monetary flux will be lesser through the years, which will generate different “appetencies” to transfer money from the present to the future and vice-verse. Theses “appetencies” can be expressed in terms of different discount rates. The values of these rates depend, among other factors, on the state of the economy, on the risk that involves the investment, the capital availability and on the expected future rate of inflation. One monetary unit of today will be changed in year $n$ by $(1+r)^n$ monetary units and one monetary unit of year $n$ will be change today by $1/(1+r)^n$ units.

**Net Present Value (NPV)** is the net sum of total discounted benefits and total discounted costs in period of time. This shows the excess (or shortfall) of benefits over costs in monetary terms.

**Benefit Cost Ratio (BCR)** is the ratio of total discounted benefits to total discounted costs. A BCR greater than one should indicate a viable project.

**Internal Rate of Return (IRR)** is defined as the discount rate at which the NPV is zero. It is the rate at which the project’s benefits are equal to the costs, and reflects the rate at which the project investment is just recovered. Since the IRR is a measure of efficiency it is the most widely used of the measures. It also has the advantage of not requiring a definite discount rate specified in advance. Usually donors and governments have a target rate or cut-off rate and projects with an IRR above the target rate are considered viable.
Pump water intake

- Entrained air and vortex shown in scale model test.
- Strong surface vortex with an air core will result in cavitation, uneven load, noise and vibration.
- Entrained air can cause reduction in discharge and loss of efficiency.
- Strong submerged vortex.
- CFD simulation of the flow distribution at the impeller plane.
- Uneven velocity into the pump inlet leads to noise, vibration and bearing wear.
- Rectangular sump with high side-entry inlet shown with dry-installed pumps.
- Centrifugal pump sump design verified through computational fluid dynamics (CFD).
Operating point of a pump (Chapallaz et al., 1992)
Hydropower

- Small dam
- Canal
- Forebay
- Powerhouse
- Penstock
- Low pressure pipe
- Surge tank
- Reservoir
- Total singular losses (curves, bends and valves)
- Conveyance system (low pressure pipe and penstock)
- Generator
- Turbine
- Net head
- Gross head
- Headgate
- Draft tube
- Tailrace
The graphs illustrate the relationship between head (H) and flow rate (Q) for different speeds (N) and closed coefficients (C). The graphs show how the head changes with varying flow rates at specific speeds and closed coefficients.
Pumped-storage power plants

Nowadays, to guarantee the stability of electrical networks it is becoming increasingly important to manage the balance between energy production and consumption levels. With this, a very big interest in Pumped-Storage Power Plants (PSPP) is taking place worldwide. Pumped hydroelectric storage is one of the most established technology for utility scale electricity storage. Storage allows to face the major problem of renewable energies, which is the intermittency and at the same time, assures the energy efficiency and environmental sustainability.

The main difference from these facilities and the normal hydropower systems is that instead of only generating electricity they use it as well. The operation of a PSPP is based on the storage of energy in form of water pumped from a lower elevation tank to a higher one during off-peak hours. The stored water can later be used to generate electricity to cover temporary peaks in demand from consumers or unplanned outages at other power plants. When the price of energy is low, the system pumps water and can buy energy from the grid, but it generates and sells this same energy later in high demand hours, where electricity prices are high creating profit.
Daytime: Water flows downhill through turbines, producing electricity

Nighttime: Water pumped uphill to reservoir for tomorrow's use
PUMPED-STORAGE OPTIMIZATION OF HYBRID (Hydro-Wind) RENEWABLE ENERGY PRODUCTION IN WATER SUPPLY SYSTEMS

Helena M. Ramos

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1. INTRODUCTION

- Energy and hydraulic efficiency are important goals for the sustainable development of water supply systems
- Water supply systems have high energy costs which depend on the water consumption and the daily tariff

  - Pumped-hydro storage systems are being used as energy and water storage on water supply systems
  - Daily programming of pump-storage operations
Pumped-hydro storage systems

Two reservoirs, where one is located at a lower 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 is stored. During peak hours the water is released back to the lower reservoir, passing through hydraulic turbines generating electrical power.

When wind energy is combined with a pumped-hydro system, several advantages can be achieved: during low consumption hours, the wind energy can be used to pump;

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 used 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 optimal pumping / turbine schedules
Multi-purposes Socorridos system (Madeira island, Portugal)

In Socorridos the power and pump stations enable pumping and turbining in a diary cycle of 40 000 m3 of water.

Designed to:
- Supply water to population
- Regularize the irrigation flows
- Produce electric energy
System components:

• Upper reservoir (Covão) at level 540 m (storage tunnels) with capacity for 40 000 m³
• Socorridos tunnel at level 81 m that has the same capacity as the upper one
• Pump station located at level 85 m
• Hydropower station located at level 89 m
• Penstock of 1266.25 m length
PUMPED-STORAGE OPTIMIZATION OF WIND-HYDRO RENEWABLE ENERGY PRODUCTION IN WATER SUPPLY SYSTEMS

Helena Ramos

1. INTRODUCCION

2. SYSTEM DESCRIPTION

3. OPTIMIZATION

4. RESULTS

5. CONCLUSIONS

Electricity tariff

Water Consumption and Inflow
Assumptions for modelling purposes:

- The connection to Sta.Quitória was neglected due to two factors:
  (i) it has low energy production when compared to the Socorridos hydropower station;
  (ii) and, the hydropower station does not operate all year.

- It was considered an equivalent cylindrical reservoir (instead of tunnels) in Socorridos and Covão (EPANET):
  - the Socorridos reservoir has a maximum water level of 5 m and a diameter of 101 m; the 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.
Objectives

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 reservoirs, being the rules from the optimization model directly implemented in the hydraulic simulator.

Variables

- Hourly water consumption in Covão (m) - \( NCC \)
- Hourly water inlet in Covão (m) - \( NIN \)
- Maximum flow in the penstock (m\(^3\)s\(^{-1}\)) - \( Q \)
- Electricity tariff (€) - \( c \)
- Initial water level in Covão reservoir (m) - \( NIC \)
- Initial water level in Socorridos reservoir (m) - \( NIS \)
- Maximum water level in Covão reservoir (m) - \( NMAXC \)
- Maximum water level in Socorridos reservoir (m) - \( NMAXS \)
- Minimum water level in Covão reservoir (m) - \( NMINC \)
- Minimum water level in Socorridos reservoir (m) - \( NMINS \)
- Maximum water level rise/decrease for each time step - \( NQ_{\text{max}} \)
- Reservoirs diameter (m) - \( D \)
- Wind speed curve
- Wind turbine power curve
Pump-Storage/Hydro (Without wind power)

Two optimization programs:

- **Linear programming** (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.

- **Non linear programming** (NLP) there is no need to impose pumping and turbining hours because the program will choose which solution is the best in order to obtain the major benefits.
Pump-Storage/Hydro (Without wind power)

Objective function (LP):

\[ f = \sum_{h=1}^{6} \left( \frac{c_B^h}{\eta_B^h} \cdot dN_h \right) + \sum_{h=7}^{24} \left( c_T^h \cdot \eta_T^h \cdot dN_h \right) \]

\( CB \) represents the electricity tariff for each hour; \( dN \) is the water level raise or decrease in Covão reservoir, for each hour; \( CT \) 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.

This objective function represents the sum of the water level variation in Covão multiplied by the electricity costs/selling price, throughout one day.

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. But if there is a decrease in Covão reservoir water level (\( dN < 0 \)), the system is discharging water from Covão to Socorridos and consequently, produces energy that can be sold at a price \( c_T \).

**Hourly restrictions (LP) due to maximum flow limitation**

<table>
<thead>
<tr>
<th>Hours</th>
<th>Lower</th>
<th>Upper</th>
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<tbody>
<tr>
<td>0 to 6</td>
<td>0</td>
<td>( N_{Q_{max}} )</td>
</tr>
<tr>
<td>6 to 24</td>
<td>(-N_{Q_{max}})</td>
<td>0</td>
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</table>
Pump-Storage/Hydro (Without wind power)

Objective function (NLP):

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

When the water level variation in Covão reservoir is positive (pumping), the term related to the turbining is zero.

Hourly restrictions (NLP) due to maximum flow limitation

<table>
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<tbody>
<tr>
<td>0 to 24</td>
<td>( - N_{Q_{max}} )</td>
<td>( N_{Q_{max}} )</td>
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the only restriction is the water level variation for each time step that cannot be greater than \( NQ_{max} \)
Pump-Storage/Hydro (With wind power)

Objective function (NLP-S and NLP-W):

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

The electricity cost for each hour varies according to the contribution of wind available energy. For each hour, if all of the energy for pumping water is provided by the wind turbines, it results 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.

Hourly restrictions (NLP-S and NLP-W) due to maximum flow limitation

<table>
<thead>
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<th>Hours</th>
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<td>0 to 24</td>
<td>$-N_{Q_{max}}$</td>
<td>$N_{Q_{max}}$</td>
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</table>
Common constraints (for all cases)

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

Wind Speed

Wind turbine power curve
Hydraulic Model Implementation

- For modelling procedure it was implemented a discharge control valve, with 2 m$^3$/s as the control parameter, in order to simulate the hydropower installed at topographic level 89 m
- At level 85 m the pump station is installed
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.

It can be seen that for all modes, the initial and final water levels are imposed to be the same (for an adequate comparison in terms of energy production and consumption).
1. INTRODUCTION

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For the LP mode of operation, the pump station only operates during the first six hours of the day, while in the remaining time the hydropower station is working. In the last two hours of the day there is no more water available to turbine 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.
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 energy** as a supplier of 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.
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 developed is very flexible in terms of input data: wind speed, water demands, reservoir volumes, maximum flow and electricity tariff, and the numerical computations take less than few minutes. The results is then introduced in an 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 obtained with LP, maintaining the hydraulic restrictions and water delivery to the population.

When wind turbines are added to the system, the profits are much higher (in this case approximately 5200 €/day) for winter and summer wind conditions.