TECHNICAL DESIGN AND OPERATION OF A PUMPED-STORAGE HYDROELECTRIC POWER PLANT LOCATED ON A REHABILITATED AREA OF PUERTOLLANO´S COALFIELD, IN SPAIN.

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Abstract
This paper develops the technical design and operation of a hydroelectric plant, with pumping storage, using mining holes at the Puertollano´s (Ciudad Real, Spain) coalfield as water reservoirs.

The project describes a technical solution and its economic and financing cash-flow study for an optimal combination of water turbination and pumping between reservoirs at different levels. Cash-flow model is based on the Spanish electricity market.

It is not only a matter of just minimizing environmental effects of a degraded coalfield, but also generating renewable energy and economical profits.

Keywords: pumped storage; mine reclamation; electricity market; hydroelectric energy

Resumen
El artículo se centra en el diseño técnico y explotación de una central hidroeléctrica reversible para el aprovechamiento de los huecos creados en los terrenos de la cuenca minera de Puertollano (Ciudad Real) y su uso como embalses de la propia central.

El proyecto describe además de una solución técnica, el estudio económico para generar ingresos a partir de la combinación óptima de turbinado y bombeo de agua entre embalses a distinto nivel, vendiendo y comprando energía en el contexto del mercado eléctrico español.

Se trata, no solamente de recuperar terrenos degradados por la actividad minera, sino también de utilizar la orografía artificial para su aprovechamiento energético y explotación comercial.

Palabras clave: bombeo; restauración de terrenos; mercado eléctrico; energía hidroeléctrica
1. Introduction

1.1. Mine reclamation in open-pit mining

In the process of open-pit mining the damage to the surrounding environment is remarcable. This is due to the large amount of ground movements that are necessary for its activity. Current operating tasks facilitate the mine reclamation, such as “Transfer Mining”. Transfer Mining is a process that consists in covering the gap using ground material extracted from another area of the mine. By this method, an exploited area is recovering simultaneously to exploitation process.

At the first steep, ground is extracted from an initial gap and deposited in a external dump. The gap is dragged along mining progress (direction of advance) until it stops, where the final gap will be left empty.

Figure 1: Mine reclamation in progress of exploitation

![Image](image)

The order of soil’s different layers is very important for mine reclamation. Ground must be deposited by layers or substrates in such a way that make possible the mine reclamation, therefore, we use the upper land or topsoil areas that are being exploited to deposit in landfills as the final (upper) layer, thus leaving a surface suitable for plants and allowing the introduction of crops such as olives.

On the other hand, when the exploitation ends, final gap will not be filled because there is normally not enough land and due to the cost of transport from the initial dump would be high. In addition, if there has been a successful mine reclamation at the beginning of the activity, the initial dump will have become a land restored and adapted to the environment.

Besides, we must minimize the environmental impact of final gap. We will do it by placing a vegetal cover to avoid the landslide. Another complementary option is to create an artificial lake that would be filled by rain and underground water flows.

Finally, we have a reservoir with water and a significant difference in height (with respect to the original level of the area), adding the upper reservoir, we can use them to create a hydroelectric plant, with pumping storage facilities.
1.2. Pumped storage hydro power station

Pumped storage hydro power station is a special kind of power plant. This power station usually has, at least, two reservoirs. The water contained in the lower reservoir (lowest level) can be raised by pumps to the upper reservoir (highest level) and the water in the upper reservoir may be discharged to the lower reservoir through a turbine. The objective is to harness the difference in electricity prices (peak and off-peak) to make a profit.

![Figure 2: Pumped storage hydro power station](image)

These plants produce electricity during peak hours of consumption (high prices). Energy production is done by channeling water from the upper to the lower reservoir through a turbine coupled to a generator that produces electricity. On the other hand during off-peak hours of consumption (low prices) water is pumped to upper reservoir. Reversible turbines or pumps up the water purchasing energy from the electricity market. In this way the water can be reused in a new period.

1.3. Spanish electricity market

Companies that produce electricity make offers to sell a certain amount of electricity at a certain price for each hour. At the same time consumers make purchase offers. Tender offers may be made directly (to be a special consumer) or through trading companies.

All the bids form an aggregate purchase curve, demand curve or demand function. On the other hand, the sum of the offers for sale constitutes a sale aggregate curve called supply function. The intersection of two curves in each hour, determines the total energy and the marginal price accepted.

In short, the price of electricity is built basically through what is called the acceptance of supply and demand. However, in the final price are added also by factors that form the total price that consumers pay (taxation, nuclear moratorium, tolls...).

- **Daily market:** it has the purpose of carrying out energy transactions for the next day. The System Operator communicates the characteristics of demand, generation and transmission system status to the agents of production and consumption. Later, the agents of production launch their offers for sale, and consumer agents launch their purchase bids. Once offer and demand have accepted, the marginal price and the amount of energy for a certain period are determined. Finally, the System Operator analyzes the feasibility of the solution and determines the Final Viable Day Program.
• Intraday market: it is, in fact, an adjustment of the market. The new market is divided into six sessions where Daily Market participants can sell and buy energy. The Intraday Market is intended to manage the generation or demand’s deviations that may occur throughout the day. Finally, Red Eléctrica reviews the solutions to ensure compliance with safety criteria and will determine Final Schedule Program.

2. Objectives

The global objectives of this project can be summarized as follows: recovery of the natural landscape, reintroduction of fauna, creating an income from energetic, creating an income from agriculture and recovery of the original appearance.

This document refers to the optimal commercial operation process, combining energy generation and pumping depending on hourly prices.

An optimization model has been developed and tested using GAMS® software.

3. Nomenclature

The nomenclature used in the model is as follows:

- Input parameters

  \[\lambda^k\] Market price (€/MW) in period k

  \[V_{\text{upper}}^{\text{max}}\] Upper reservoir’s maximum volume (Hm³)

  \[V_{\text{upper}}^{\text{min}}\] Upper reservoir’s minimum volume (Hm³)

  \[V_{\text{low}}^{\text{max}}\] Lower reservoir’s maximum volume (Hm³)

  \[V_{\text{low}}^{\text{min}}\] Lower reservoir’s minimum volume (Hm³)

  \[V_{\text{top}}^0\] Upper reservoir’s initial volume (period k-1) (Hm³)

  \[V_{\text{low}}^0\] Lower reservoir’s initial volume (period k-1) (Hm³)

  \[P_{\text{turbine design}}\] Turbine design power (MW)

  \[P_{\text{pump design}}\] Pump design power (MW)

  \[Q_{\text{turbine}}^{\text{design}}\] Turbine design flow (Hm³)

  \[Q_{\text{pump}}^{\text{design}}\] Pump design flow (Hm³)

  \[Q_{\text{turbine}}^{\text{min}}\] Minimum turbination flow (Hm³)

  \[Q_{\text{pump}}^{\text{min}}\] Minimum pumping flow (Hm³)

  \[C_{\text{fix k}}^{\text{plant}}\] Plant fixed costs in period k (€/hour)

  \[C_{\text{turbine variable}}^{\text{k}}\] Turbination variable costs in period k (€/MW)

  \[C_{\text{pump variable}}^{\text{k}}\] Pumping variable costs in period k (€/MW)

  \[Q_{\text{turbine med}}^{\text{med}}\] Midpoint of turbine piecewise power function (Hm³)

  \[Q_{\text{pump med}}^{\text{med}}\] Midpoint of pump piecewise power function (Hm³)

  \[a_1\] Turbine curve’s first slope (MW/Hm³)
• Variables

- $V_{\text{top}}^k$: Upper reservoir’s volume in period $k$ (Hm$^3$)
- $V_{\text{low}}^k$: Lower reservoir’s volume in period $k$ (Hm$^3$)
- $Q_{\text{tur}}^k$: Turbined flow in period $k$ (Hm$^3$)
- $Q_{\text{pump}}^k$: Pumped flow in period $k$ (Hm$^3$)
- $B$: Turbine / pump binary variable.
- $Z$: Turbine curve’s section binary variable.
- $P$: Pump curve’s section binary variable.
- $L$: No operation binary variable.

• Outputs

- $P_{\text{tur}}^k$: Turbine power in period $k$ (MW).
- $P_{\text{pump}}^k$: Pump power in period $k$ (MW).

4. Optimization model

The optimization model’s main objective is to maximize profit by the optimal combination of turbining and pumping water between reservoirs according to the market’s price behavior and variable and fix costs.

The developed model is described by the following equations, that are explained afterwards:

Maximize:

\[
\sum_{k=0}^{168} \left( (P_{\text{tur}}^k (\lambda^k - C_{\text{tur}}^k)) - (P_{\text{pump}}^k (\lambda^k + C_{\text{pump}}^k)) - C_{\text{plant}}^k \right)
\]  

Subject to:

\[ P_{\text{tur}}^k = a_{1\text{tur}}^k * Q_{\text{tur}}^k + b_{1\text{tur}}^k \quad (Q_{\text{tur}}^{\text{min}} \leq Q_{\text{tur}}^k \leq Q_{\text{tur}}^{\text{med}}) \]  

\[ P_{\text{tur}}^k = a_{2\text{tur}}^k * Q_{\text{tur}}^k + b_{2\text{tur}}^k \quad (Q_{\text{tur}}^{\text{med}} \leq Q_{\text{tur}}^k \leq Q_{\text{tur}}^{\text{design}}) \]
\[ P_{pump}^k = a_{1pump}^k Q_{pump}^k + b_{1pump}^k (Q_{pump}^{\text{min}} \leq Q_{pump}^k \leq Q_{pump}^{\text{med}}) \]  
(4)

\[ P_{pump}^k = a_{2pump}^k Q_{pump}^k + b_{2pump}^k (Q_{pump}^{\text{med}} \leq Q_{pump}^k \leq Q_{pump}^{\text{design}}) \]  
(5)

\[ V_{\text{upper}}^{\text{min}} \leq V_{\text{top}}^k \leq V_{\text{upper}}^{\text{max}} \]  
(6)

\[ V_{\text{low}}^{\text{min}} \leq V_{\text{low}}^k \leq V_{\text{low}}^{\text{max}} \]  
(7)

\[ Q_{\text{tur}}^{\text{min}} \ast (1 - L) \ast B \ast Z \leq Q_{\text{tur}}^k \leq Q_{\text{tur}}^{\text{med}} \ast (1 - L) \ast B \ast Z \]  
(8)

\[ Q_{\text{tur}}^{\text{med}} \ast (1 - L) \ast B \ast (1 - Z) \leq Q_{\text{tur}}^k \leq Q_{\text{tur}}^{\text{design}} \ast (1 - L) \ast B \ast (1 - Z) \]  
(9)

\[ Q_{pump}^{\text{min}} \ast (1 - B) \ast L \ast P \leq Q_{pump}^k \leq Q_{pump}^{\text{med}} \ast (1 - B) \ast L \ast P \]  
(10)

\[ Q_{pump}^{\text{med}} \ast (1 - B) \ast L \ast (1 - P) \leq Q_{pump}^k \leq Q_{pump}^{\text{design}} \ast (1 - B) \ast L \ast (1 - P) \]  
(11)

\[ V_{\text{upper}}^k = V_{\text{upper}}^{k-1} + Q_{pump}^k - Q_{\text{tur}}^k \]  
(12)

\[ V_{\text{low}}^k = V_{\text{low}}^{k-1} + Q_{\text{tur}}^k - Q_{pump}^k \]  
(13)

\[ L, B, Z, P \in [0,1] \]  
(14)

The objective function (1) of the optimization problem is based on taking advantage from the maximum differences in prices of energy. Fixed and variable costs of production are also added in the objective function.

The performance of a turbo-pump is nonlinear, so that a linearization is required. The power-flow curves are linearized using piecewise approximations. Two sections and two equations are used for each operation mode. Figures 3 and 4 show this linearization is done. Note that the linearization process needs some new parameters and variables. The mean flows are used to divide sections of linearization.
Equations (2) and (3) show the expressions of the turbine power for both sections. Equations (4) and (5) show idem for pumping use.

Restrictions of minimum and maximum volume are reflected in equations (6) and (7), these restrictions are very important because if we have excess volume could cause a flood, or otherwise, lack of water can damage the machinery used to produce electricity.

When water is pumped up, it flows up to the upper reservoir, during turbination water flows down to the lower reservoir. These equations are defined by the volume of the reservoirs and correspond to equations (12) and (13).

Operation will be controlled with binary variables (14). Inequalities (8), to (11) are used to distinguish between pumping, turbination and no operation. These restrictions change the water flow direction depending on the scenario.
5. Case study

In this paper we will make the study of the operation of a pumping station in the mining resort of Puertollano (Ciudad Real). The characteristics of the Puertollano mining area are reflected in Tables 1 and 2 and Figure 5.

### Table 1: Reservoirs' Data

<table>
<thead>
<tr>
<th></th>
<th>Lower reservoir</th>
<th>Upper reservoir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Useful volume</td>
<td>4.21Hm³</td>
<td>3.78Hm³</td>
</tr>
<tr>
<td>Nmax</td>
<td>555msnm</td>
<td>670msnm</td>
</tr>
<tr>
<td>Nmin</td>
<td>530msnm</td>
<td>655msnm</td>
</tr>
</tbody>
</table>

### Table 2: Height’s Difference

<table>
<thead>
<tr>
<th></th>
<th>Turbination</th>
<th>Pumping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum difference</td>
<td>140m</td>
<td>140m</td>
</tr>
<tr>
<td>Minimum difference</td>
<td>100m</td>
<td>100m</td>
</tr>
</tbody>
</table>

Market prices data have been obtained from OMEL webpage (see references) from 22 to 28 March 2010 because of its prices’ high volatility. The resolution of the problem has been carried out with the mathematical tool GAMS. The simulations are executed using the "solver" RMINL (Relaxed Mixed Integer Programming nonlinear).

![Figure 5: Pumped storage hydro power station for case study](image)

Case study’s parameters setup:

### Table 3: Input parameters

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{upper}^{max}$</td>
<td>3.78</td>
<td>(Hm³)</td>
</tr>
<tr>
<td>$V_{upper}^{min}$</td>
<td>0.23</td>
<td>(Hm³)</td>
</tr>
<tr>
<td>$V_{low}^{max}$</td>
<td>4.6</td>
<td>(Hm³)</td>
</tr>
<tr>
<td>$V_{low}^{min}$</td>
<td>0.4</td>
<td>(Hm³)</td>
</tr>
<tr>
<td>$V_{upper}^{0}$</td>
<td>3.78</td>
<td>(Hm³)</td>
</tr>
<tr>
<td>$V_{low}^{0}$</td>
<td>0.4</td>
<td>(Hm³)</td>
</tr>
</tbody>
</table>
6. Results

Figure 6 depicts the behavior of energy production according to variability of the electricity market price. The study has been done for that case in which the upper reservoir is completely filled and the lower one is empty. Figures 7 and 8 show the evolution of reservoirs, we can see that they never exceed the maximum and minimum limits.

Figure 6: Results in production time during one week
In this depicted case, the optimal solution is a profit contribution of **183.257€**

Two more scenarios have been simulated; their results are shown in Table 4. Simulations have been performed based on the initial of filling up percentage of upper and lower reservoirs.

**Table 4: Different study cases**

<table>
<thead>
<tr>
<th>Upper reservoir</th>
<th>Lower reservoir</th>
<th>Profit</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>0%</td>
<td>183,257,77€</td>
</tr>
<tr>
<td>50%</td>
<td>50%</td>
<td>171,298,63€</td>
</tr>
<tr>
<td>0%</td>
<td>100%</td>
<td>157,616,43€</td>
</tr>
</tbody>
</table>
7. Conclusions

In conclusion we can say that the model is adapted to the pattern of market prices, deciding to pump at lower prices and turbining when de prices are high enough, so that getting an optimal operation of a reversible hydro plant.

This approach allows the investor to asset this kind of projects. It could be a good decision-making tool for taking decisions between several investment projects.

In the future we will work in the model dividing the performance curves in more pieces and also spot prices’ uncertainty will be added to the stochastic problem.

Feed-in tariff and subsidies, described on Plan de Acción Nacional de Energías Renovables (PANER), will be also added to the model to study their impact on operation decisions.

Referencias


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