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# Economic Viability of Pumped-Storage Power Plants Equipped with Ternary Units and Considering Hydraulic Short-Circuit Operation

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**Abstract.** This paper analyses the economic viability of pumped-storage hydropower plants equipped with ternary units and considering hydraulic short-circuit operation. The analysed plant is assumed to participate in the day-ahead energy market and in the secondary regulation service of the Spanish power system. A deterministic day-ahead energy and reserve scheduling model is used to estimate the maximum theoretical income of the plant assuming perfect information of the next day prices and the residual demand curves of the secondary regulation reserve market. Results show that the pay-back periods with and without the hydraulic short-circuit operation are significantly lower than their expected lifetime and that the pay-back periods can be reduced with the inclusion of the hydraulic short-circuit operation.

## 1. Introduction

Pumped-storage hydropower plants (PSHPs) are considered worldwide as a mature technology to store large quantities of energy and to improve the flexibility of the power systems [1]. Therefore, they can play an important role in the context of a high penetration of intermittent renewable energies such as wind and solar power. However, PSHPs are characterised by high capital costs and even higher if they are equipped with ternary units and the hydraulic short-circuit operation is enabled.

Several papers have been found in the technical literature analysing the economic viability of conventional PSHPs participating in the day-ahead energy market. [2] compares the profits and the investment costs in six electricity markets such as Great Britain or Nordpool, among others, using a heuristic algorithm based on the well-known price-arbitrage to operate the PSHP. Results obtained in [2] show that the recovery of the investment costs is not possible almost in all the analysed markets. Results in [3] show that PSHPs are profitable in almost all the seven real-time markets analysed in the United States, such as ERCOT (Texas) or NYISO (New York). However, results can be considered slightly optimistic as they are obtained for 2008, when there was a significant difference between peak and off-peak energy prices and also reaching in some months the highest average prices of the last decade. [4] analyses the economic viability of conventional PSHPs participating also in the regulation market. Results in [4] show that the considered PSHP cannot recover the investment costs if it only participates in the day-ahead energy market and can recover the investment costs only for a limited range of the storage size if it also participates in the regulation market. According to the best of our



knowledge, there is no published paper in which the economic viability of PSHPs equipped with ternary units and considering the hydraulic short-circuit operation (HSC-PSHPs) is analysed [5].

The main goal and contribution of this paper is to evaluate the economic viability of closed-loop and daily-cycle PSHPs equipped with ternary units and considering hydraulic short-circuit operation. The considered ternary unit is composed by a Pelton turbine, a fixed-speed pump and an electric machine. Closed-loop means that no natural water inflows are received in the upper reservoir and that no water outflows are released from the lower reservoir of the hydro system.

The economic viability is evaluated using the so-called pay-back period, i.e. the number of years that the investment costs are expected to be recovered. The pay-back period is estimated from the maximum theoretical income (MTI) and the investment costs of the PSHP. The MTI is obtained from the results of a deterministic day-ahead energy and secondary reserve scheduling model, based on mixed integer quadratic programming. The model is sequentially run day by day for a time period of one year (2014). The investment costs of the PSHP are estimated from available data in the technical literature of existing, to be commissioned and projected PSHPs. The pay-back period is estimated with and without considering hydraulic short-circuit operation.

The paper is organised as follows: the MTI is presented in Section 2 whereas the estimated investment costs are described in Section 3. The discussion of the economic viability is shown in Section 4. Finally, conclusions are drawn in Section 5.

## 2. Maximum theoretical income

The scheduling model used to obtain the MTI of the PSHP is based on [6]. The PSHP is assumed to participate in the day-ahead energy market and in the secondary regulation service (SRS) of the Spanish electricity system. The SRS comprises the participation in the day-ahead secondary regulation reserve market and the deployment of the reserves in real-time, i.e. the secondary regulation energy, managed by the Transmission System Operator. Note that both the secondary regulation reserves and energy are remunerated in the Spanish system. The tertiary regulation service is not included as it is outside the scope of the model that is used to obtain the maximum theoretical income of the PSHPs<sup>1</sup>.

In [6], the PSHP is modelled as a price-taker in both, the day-ahead energy and reserve markets. The assumption that the PSHP is a price-taker in the reserve market can significantly overestimate the MTI obtained in the SRS. Due to this, in this paper, the model from [6] is adapted to consider the PSHP as a price-maker only in the secondary regulation reserve market. The formulation used to model the PSHP as a price-maker is based on the one presented in [7], using a linear approximation of the residual demand curves of the secondary regulation reserve market. Note that the PSHP is modelled as a price-taker in the day-ahead energy market because the maximum power of the plant (594.8 MW) represents 1.3% of the maximum demand of the Spanish system.

We use the term MTI to refer to the income that the PSHP would obtain assuming perfect information of the next day hourly energy prices, the residual demand curves of the reserve market, the amount of the committed reserves effectively used in real-time and the regulation energy prices.

The technical data of the PSHP can be seen in Table 1. The data are the same as those used in [6] for the case of PSHP with ternary units. Note that the plant is composed by two hydro units whereas the data in Table 1 is for the entire plant. Efficiencies in generating mode at maximum and minimum water discharge are 90% and 80%, respectively. Efficiency in pumping mode is 90%. Start-up costs in generating and pumping modes are obtained following the guidelines of [8]. As the maximum variation of the water level in the upper reservoir can be negligible in comparison with the available gross head, the head dependency in the mathematical formulation is neglected.

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<sup>1</sup> The required modifications to consider the tertiary service are the following: 1) a new term in the objective function with the income/cost due to the upward/downward tertiary energy, 2) the available upward tertiary energy is the difference between the maximum power minus the committed power in the day-ahead market and the upward secondary reserve and 3) the available downward tertiary energy is the committed power in the day-ahead market minus the downward secondary reserve.

**Table 1.** Technical data of the PSHP.  $g$  refers to power,  $q$  refers to flow and  $cSU$  refers to start-up cost. Superscript  $d$  refers to generating mode whereas  $p$  refers to pumping mode. Flows are expressed in  $\text{m}^3/\text{s}$ , power in MW and start-up cost in €.

| $\bar{g}^d$ | $\bar{q}^d$ | $\underline{g}^d$ | $\underline{q}^d$ | $\bar{g}^p$ | $\bar{q}^p$ | $cSU^d$ | $cSU^p$ |
|-------------|-------------|-------------------|-------------------|-------------|-------------|---------|---------|
| 594.8       | 231.4       | 52.9              | 23.2              | 779.6       | 231.4       | 3301.2  | 2643    |

The MTIs of the PSHP with (HSC) and without (Conv) considering the operation in hydraulic short-circuit mode are presented in Table 2. It shows the net income in the day-ahead energy market (DM Income), i.e. income for selling energy in generating mode minus cost for purchasing energy in pumping mode, the income in the day-ahead secondary regulation reserve market (SM Income), the income for the real-time use of the upward reserves (ER2UP Income), the cost for the real-time use of the downward reserves (ER2DW Cost) and the start-up costs in generating mode (SupT Cost) and in pumping mode (SupP Cost). Note that in the Spanish power system, the upward/downward secondary regulation reserve which is effectively used in real-time is paid/bought at the price of the tertiary regulation reserve.

**Table 2.** Maximum theoretical income of the PSHP and in each market and service considered. All data are expressed in €.

| PSHP | DM Income  | SM Income  | ER2up Income | ER2dw Cost | SupT Cost  | SupP Cost  | Total      |
|------|------------|------------|--------------|------------|------------|------------|------------|
| Conv | 10 636 427 | 25 839 584 | 8 662 665    | -7 552 568 | -3 060 212 | -1 694 163 | 32 831 733 |
| HSC  | 1 178 941  | 37 698 356 | 15 118 981   | -8 149 052 | -2 069 852 | -1 647 910 | 42 129 462 |

The inclusion of the operation in HSC mode increases the total MTI around 28%, especially thanks to the participation in the SRS. Regarding each market and service, it increases the SM Income around 46%, decreases the DM Income around 88%, increases the net income for the secondary regulation energy more than five times and reduces the start-up costs around 22%.

The methodology used to obtain the MTI assumes that the upper reservoir starts and finishes each day with the same amount of stored water (half of the storage capacity). The authors are currently working to include a look-ahead period and relax the end of day target volume in the scheduling model which will hopefully enlarge the MTI.

### 3. Investment costs

Investment costs of PSHPs are strongly site-dependent. In the technical literature, to the best of our knowledge, there are no papers where the investment costs of PSHPs with ternary units are analysed. However, several papers can be found regarding investment costs of PSHPs equipped with binary units. [2] proposes a range between 470-2170 €/kW from projects in countries such as Spain, Portugal or Switzerland, among others. [9] proposes a range between 775-1280 €/kW from projects in Germany and Luxemburg. Or [10], which proposes a range between 2000-4300 \$/kW. Note that the latter is expressed in \$ and has been changed to € using the exchange rate of 1.12 \$/€ at 29/07/2016. Therefore, the considered cost ranges between 1786-3839 €/kW.

There is an absolute lack of information about investment costs of HSC-PSHPs. However, hydro industry experts estimate an increase of 30%–40% of the investment costs of a PSHP equipped with binary units [11]. In this paper, an extra cost of 35% is considered for the HSC-PSHP. In addition to this, we assume that the extra investment cost related to permit a PSHP equipped with ternary units to operate in HSC mode is 3%. This extra investment cost is due to both 1) the reinforcement of the pipes in the short-circuit link and 2) the more complex design of the said pipe section in order to, respectively, resist pressure oscillations of a higher amplitude and to reduce the hydraulic losses.

Several ranges of the investment costs have been considered according to the information available in the literature and the above-mentioned hypothesis (Table 3).

**Table 3.** Investment cost ranges considered in the paper according to the information available in the technical literature. All data are expressed in millions of €.

| PSHP | [2]   |        | [9]   |        | [10]   |        |
|------|-------|--------|-------|--------|--------|--------|
|      | Min   | Max    | Min   | Max    | Min    | Max    |
| Conv | 366   | 1690.2 | 603.6 | 996.9  | 1390.9 | 2990.4 |
| HSC  | 377.4 | 1742.5 | 622.3 | 1027.8 | 1433.9 | 3082.9 |

#### 4. Economic viability

The economic viability is analysed using the so-called pay-back period, i.e. the number of years that the investment costs are expected to be recovered according to the expected income of the PSHP. The calculation of the pay-back period assumes that the interest rate and the expected increase of the MTI due to an increase of the demand will be 0% in the whole pay-back period. The estimated pay-back periods corresponding to the proposed investment cost ranges are shown in Table 4.

**Table 4.** Pay-back period with the considered investment cost ranges. All data are expressed in years.

| PSHP | [2]  |      | [9]  |      | [10] |      |
|------|------|------|------|------|------|------|
|      | Min  | Max  | Min  | Max  | Min  | Max  |
| Conv | 11.2 | 51.5 | 18.4 | 30.4 | 42.4 | 91.1 |
| HSC  | 9    | 41.4 | 14.8 | 24.4 | 34   | 73.2 |

According to the investment costs proposed in [2], the mean pay-back period of the Conv PSHP and of the HSC-PSHP would be 31.3 and 25.2 years, respectively. Assuming a lifetime of the plant between 40 years (see for example [2]) and 60 years (see for example [1]), or even 100 years [12], the economic viability is not discarded.

Even better results are obtained when the investment costs proposed in [9] are considered: the mean pay-back period of the Conv PSHP and of the HSC-PSHP would be 24.4 and 19.6 years, respectively.

By contrast, with the investment costs proposed in [10] the PSHP is not economically viable, as the mean pay-back period of the Conv PSHP and of the HSC-PSHP would be 66.7 and 53.6 years, respectively.

A promising result of the paper is that the inclusion of the HSC operation substantially reduces the pay-back periods in all cases as the increase in the MTI is significantly larger than the increase in the investment costs.

Despite the foregoing, further research must be carried out because, in this paper, perfect information is assumed in all uncertain data and therefore the income is expected to be reduced due to the effects of imperfect information. To give an idea, the value of perfect information of the price in the day-ahead energy market can be around 25% of the MTI according to the results presented in [7].

#### 5. Conclusions

The economic viability of a closed-loop and daily-cycle PSHP equipped with ternary units with and without considering the operation in hydraulic short-circuit mode has been preliminarily evaluated in this paper. The PSHP is assumed to participate in the day-ahead energy market as a price-taker and in the day-ahead secondary regulation reserve market as a price-maker. In addition, the net income from

the real-time use of the committed reserves has been also taken into account. The pay-back period of the PSHP has been estimated considering different ranges of investment costs proposed in the technical literature. Results show that the pay-back periods of the PSHP are in most cases lower than the lifetime of the PSHP and, therefore, the economic viability is not discarded. Besides, the inclusion of the hydraulic short-circuit operation reduces the pay-back periods in all cases. Nonetheless, these results have been obtained assuming perfect information of all the uncertain data in the day-ahead energy and reserve scheduling. Further work is necessary to estimate the economic viability of the PSHP taking into account uncertainty. In addition, the evaluation of the economic viability of PSHPs equipped with variable speed binary units is also deemed as promising future work. Finally, it should be taken into account that the consideration of other markets, such as the intraday markets and the tertiary regulation service, would contribute to increase the revenues of PSHPs in the short-term whereas the dissemination of other storage technologies and the penetration of the electric vehicle might cause in the long-term a reduction in the price spread and, therefore, the revenues.

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