# Scheduling of a Pumped-storage Hydro in the Day-ahead Market and in the Secondary Reserve Market

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***Abstract* — The increasing integration of renewables in the energy markets has been raising some challenges to generation companies (GENCO), in terms of operation and planning of their generation portfolios. A GENCO aiming at maximizing its profits has to deal with bids to several available markets, among which are the Day-ahead Market (DAM) and the Secondary Reserve Market (SRM). This paper presents a scheduling solution of a price-maker GENCO whose portfolio comprises a pumped-storage hydro (PSH) unit with variable pumping capacity, acting simultaneously in the DAM and SRM. The results were obtained for four different scenarios, where the PSH may or may not possess variable pumping capacity and compares the PSH behavior in one or both markets simultaneously. The results put in evidence the advantages of having a PSH unit with variable pumping capacity in a generation portfolio, the advantages of acting in both markets simultaneously and the PSH bidding strategy taking into account its influence on price.**

***Index Terms* — Bidding strategy, Day-ahead market, Pumped-storage hydro, Renewable integration, Secondary reserve market**

## I. Introduction

The current situation of the energy system, in particular in terms of the evolution of the energy mix, with the increase in renewable production (especially, the technologies included in Special Regime Production, SRP) has raised some challenges both in network management and in the management of liberalized energy markets. In this regard, it has been verified that the incorporation of SRP introduced some variability in production and, in the market, causing a reduction of the average spot price in the short and medium term, thus affecting the revenues of generation companies.

In this perspective, reversible pumped-storage hydro (PSH) plants have an increased role in the integration of renewable generation, in particular wind energy (the one that, in Portugal, has undergone a greater increase in installed power), storing surplus energy and, thereby minimizing the need for curtailment. In a liberalized market environment, given that PSHs are price takers, the low price of electricity resulting from periods of low consumption and high wind availability will give the incentive for PSHs to pump, promoting the proper integration of wind energy. However, if a PSH has the capacity to influence the market price, its strategy of maximizing revenues can lead to a different pumping and generation profile, shifting away from the goal of maximizing the integration of wind power.

In a strategic perspective, in order to maximize revenue, in addition to the day-ahead market (DAM), the ancillary system services market (in particular, the secondary reserve market, SRM) can provide a source of additional revenue for electricity producers. On the other hand, with the installation in the PSHs of pumps that allow variable pumping capacity (a relatively recent technology that, in Portugal, is only installed in Venda Nova III/Frades II hydro plant), companies that have these plants in their generation portfolios can also bid in the SRM when they are pumping, further boosting this market as a source of revenue for the portfolio.

This paper developed a model, restrictions and evaluation parameters in order to study, from the point of view of the producer, the dispatch of a PSH plant that sells its energy in the DAM and in the SRM, through numerical simulation using the Matrix Laboratory (MATLAB) and the General Algebraic Modeling System (GAMS) optimization package.

## II. Model Description

In the context of this paper, it is assumed that we are in an energy market subject to a bidding mechanism to define the market price (as is the case of MIBEL) and that we want to optimize the operational profit of a generation company (GENCO) with a portfolio of power plants which allows it, in each hour, to have the capacity to affect that same market price.

The optimization problem considered for this paper is based on the method proposed by S. Torre, J. M. Arroyo, A. J. Conejo and J. Contreras [1] and the representation the residual demand curve has been adapted and extended for cases in which the total energy marketed by the generation company is negative, therefore, this now includes the cases in which the energy consumed by the hydroelectric power stations when they are in pumping is higher than the energy generated by the other plants in the company's portfolio. In this regard, Fig. 1 presents an example of a residual demand curve faced by the GENCO.

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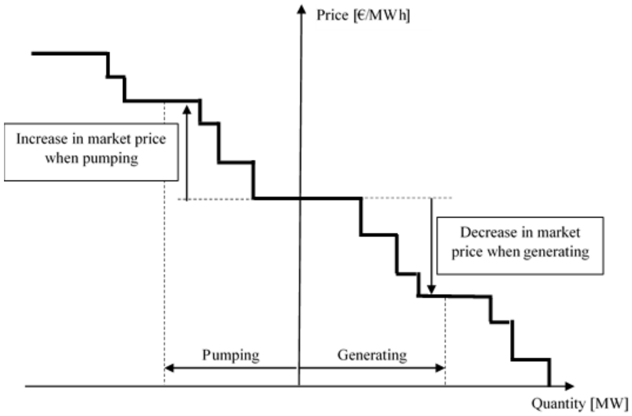

Figure 1 – GENCO's Residual Demand Curve [2].

The price-maker behavior of the GENCO can be understood in the sense that if the GENCO sells energy in the DAM (positive quantity) the market price may decrease and if the GENCO buys energy in the DAM (negative quantity), it might push market prices up.

Regarding the application of this methodology to the SRM, it must be taken into account that the residual demand curve faced by the GENCO in the SRM only comprises the steps corresponding to a positive quantity. This has to do with the fact that the Secondary Reserve (SR) capacity traded in the SRM is always a positive value.

It should also be noticed that, in the case the PSH unit is pumping, the output of the PSH unit is negative corresponding to energy consumed.

## III. Mathematical formulation

### A. Equations

Equations (1) through (16) represent the mathematical formulation of the model when the GENCO acts in both the DAM and SRM.

$$\max_{\substack{p_{t,i},pres_{t,i},bv_{t,v},\\ uv_{t,v},bc_{t,c},uc_{t,c},\\ bvb_{t,vb},uvb_{t,vb}}} \pi = \sum_{t=1}^{T}\left[\begin{array}{l}\sum_{v=1}^{V}\lambda v_{t,v}\left(bv_{t,v}+uv_{t,v}q_{t,v}^{\min}\right)+\sum_{c=1}^{C}\lambda c_{t,c}\left(bc_{t,c}+uc_{t,c}q_{t,c}^{\min}\right)+\\ \sum_{vb=1}^{Vb}\lambda vb_{t,vb}\left(bvb_{t,vb}+uvb_{t,vb}q_{t,vb}^{\min}\right)-\sum_{i=1}^{I}c_{t,i}\end{array}\right] \quad (1)$$

s.t.

$$p_{t,i}^{\min} \le p_{t,i} - \frac{1}{3}pres_{t,i} \quad (2)$$

$$p_{t,i} + \frac{2}{3}pres_{t,i} \le p_{t,i}^{\max} \quad (3)$$

$$q_t = \sum_{i=1}^{I} p_{t,i} \quad (4)$$

$$q_t = \sum_{v=1}^{V}\left(bv_{t,v}+uv_{t,v}q_{t,v}^{\min}\right)+\sum_{c=1}^{C}\left(bc_{t,c}+uc_{t,c}q_{t,c}^{\min}\right) \quad (5)$$

$$qres_t = \sum_{i=1}^{I} pres_{t,i} \quad (6)$$

$$qres_t = \sum_{vb=1}^{Vb}\left(bvb_{t,vb}+uvb_{t,vb}q_{t,vb}^{\min}\right) \quad (7)$$

$$\sum_{v=1}^{V} uv_{t,v} + \sum_{c=1}^{C} uc_{t,c} = 1 \quad (8)$$

$$\sum_{vb=1}^{Vb} uvb_{t,vb} = 1 \quad (9)$$

$$0 \le bv_{t,v} \le uv_{t,v} bv_{t,v}^{\max} \quad (10)$$

$$-uc_{t,c} bc_{t,c}^{\max} \le bc_{t,c} \le 0 \quad (11)$$

$$0 \le bvb_{t,vb} \le uvb_{t,vb} bvb_{t,vb}^{\max} \quad (12)$$

$$W_t = \begin{cases} W_{t-1} - \eta_p p_{t,'H'} & if \;\; p_{t,'H'} < 0 \\ W_{t-1} - \dfrac{p_{t,'H'}}{\eta_g} & if \;\; p_{t,'H'} \ge 0 \end{cases} \quad (13)$$

$$W^{\min} \le W_t \quad (14)$$

$$W_t \le W^{\max} \quad (15)$$

$$W_{t=1} = W_{t=T} \quad (16)$$

### B. Variables and units

The variables and units in Eq. (1) are represented in Table I.

TABLE I
VARIABLES AND UNITS – OPTIMIZATION EQUATION

| Symbol | Designation | Unit |
|---|---|---|
| $\pi$ | Operational profit | Euro (€) |
| $T$ | Scheduling period | Hour (h) |
| $\lambda v_{t,v}$ / $\lambda c_{t,c}$ | Price in the DAM | Euro (€) |
| $\lambda vb_{t,vb}$ | Price in the SRM | Euro (€) |
| $bv_{t,v}$ / $bc_{t,c}$ | Quantity in the active step of the DAM | Megawatt (MW) |
| $bvb_{t,vb}$ | Quantity in the active step of the SRM | Megawatt (MW) |
| $uv_{t,v}$ / $uc_{t,c}$ | Binary variable of the active step in the DAM | ------------- |
| $uvb_{t,vb}$ | Binary variable of the active step in the SRM | ------------- |
| $q_{t,v}^{\min}$ / $q_{t,c}^{\min}$ | Quantity up to the active step in the DAM | Megawatt (MW) |
| $q_{t,vb}^{\min}$ | Quantity up to the active step in the SRM | Megawatt (MW) |
| $c_{t,i}$ | Operational Costs | Euro (€) |

The variables and units in Eq. (2) through (16) are represented in Table II.

TABLE II
VARIABLES AND UNITS – RESTRICTIONS

| Symbol | Designation | Unit |
|---|---|---|
| $p_{t,i}$ | Power in the DAM | Megawatt (MW) |
| $p_{t,i}^{\min}$ | Minimum power | Megawatt (MW) |
| $p_{t,i}^{\max}$ | Maximum power | Megawatt (MW) |
| $pres_{t,i}$ | Power in the SRM | Megawatt (MW) |
| $q_t$ | Quantity in the DAM | Megawatt (MW) |
| $qres_t$ | Quantity in the SRM | Megawatt (MW) |
| $W_t$ | Energy in the upper reservoir | Megawatt hour (MWh) |
| $W^{\min}$ | Minimum energy in the upper reservoir | Megawatt hour (MWh) |
| $W^{\max}$ | Maximum energy in the upper reservoir | Megawatt hour (MWh) |
| $\eta_g$ | Generation efficiency | ------------- |
| $\eta_p$ | Pumping efficiency | ------------- |

## C. Description

Equation (1) represents the operational profit of the GENCO over the scheduling period *T*. The GENCO's profit is the difference between total revenues and total costs. The first and third term within brackets represent the revenue obtained by selling the generated energy in the DAM and in the SRM, respectively. The second term represents the cost of buying in the DAM the consumed energy for pumping and the forth term represents the total generation cost. In Fig. 2 and Fig. 3, it can be observed how revenues are calculated for the situations where the GENCO has a positive net energy traded in the DAM (energy generated higher than energy pumped), and when it has a negative net energy traded in the DAM, respectively.

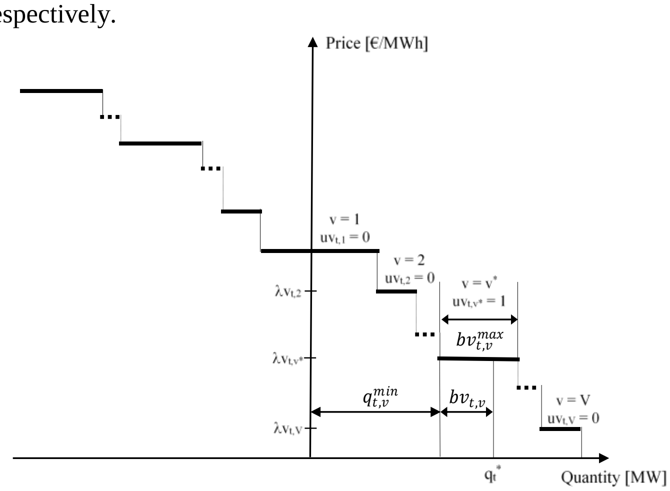


Figure 2 – GENCO's residual demand curve. Representation of the variables and constants when the GENCO has a positive net energy traded in the DAM [3].

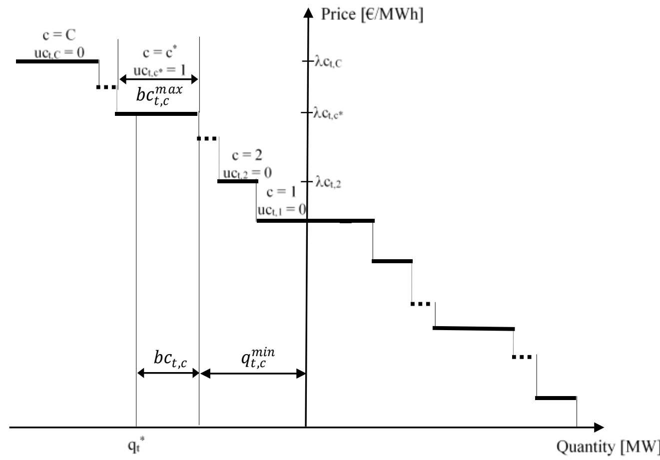


Figure 3 – Representation of the residual demand curve with variables and constants when the GENCO has a negative net energy traded in the DAM [3].

The representation of the residual demand curve for the SRM is shown in Fig. 4 and resembles the portion of the residual demand curve when the GENCO trades a positive net energy in the DAM (the portion represented in Fig. 2). This is due to the fact that the SR capacity traded in the SRM is always a positive value.

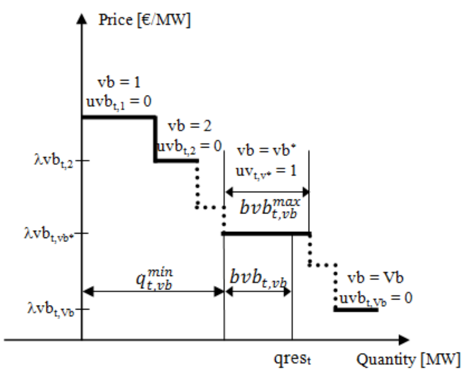


Figure 4 – Representation of the residual demand curve with variables and constants when the GENCO trades in the SRM.

The GENCOs bid in the SRM a SR capacity for each of their generating units. This SR capacity represents a range of power that the generating unit can change its power output. As mentioned before, in the Portuguese power system, the generating units participating in the SRM must be able to decrease its power output by 1/3 of the SR capacity or to increase its power output by 2/3 of the SR capacity. In that sense, Eq. (2) and (3) represent the minimum and maximum output constraints of the generating units. For instance, Eq. (2) states that the generating unit must be able to decrease the power output that it is selling in the DAM, $p_{t,i}$, by 1/3 of the SR capacity traded in the SRM, $pres_{t,i}$, without generating below its minimum output capacity, $p_{t,i}^{\min}$.

Equation (4) shows that the net energy traded in the DAM by the GENCO is the sum of the output of all its generating units. In the case the PSH unit is pumping, the output of the

PSH unit is negative corresponding to energy consumed.

Equation (5) states the net energy traded in the DAM by the GENCO as a function of the variables, $bv_{t,v}$, $uv_{t,v}$, $bc_{t,c}$, $uc_{t,c}$.

Equations (6) and (7) are the equivalent for the SRM of Eq. (4) and (5).

Equation (8) imposes that only one of the variables $uv_{t,v}$ and $uc_{t,c}$ is different from zero, thus imposing that only one step of the residual demand curve of the DAM is the marginal step. Equation (9) has the same purpose of Eq. (8) but for the SRM.

Equations (10) and (12) impose that $bv_{t,v}$ and $bvb_{t,vb}$ are positive values, while Eq. (11) imposes that $bc_{t,c}$ is a negative value.

Equations (13) through (16) are related with the energy stored in the PSH unit reservoir. Thus, Eq. (13) represents the energy stored in period *t*, which is equal to the energy stored in period *t-1*, plus the energy pumped by the PSH unit ($p_{t,'H'}$ lower than zero means the PSH unit is pumping) or minus the energy generated by the PSH unit ($p_{t,'H'}$ higher than zero means the PSH unit is generating).

Equations (14) and (15) refer to the lower and higher limits of the stored energy and Eq. (16) imposes that the energy stored in the beginning of the simulation period must be equal to the energy stored in the end of the period.

## IV. PRICE SENSITIVITY

For the analysis of the scenarios presented in this paper, we have computed a price sensitivity of the residual demand curve (both before and after the GENCO acts in the market). For the DAM residual demand curve, two price sensitivities were computed: a price sensitivity for energy sold in the DAM (DAM Price Sensitivity Down) and one price sensitivity for energy bought in the DAM (DAM Price Sensitivity Up), according to what is shown in Fig. 5.

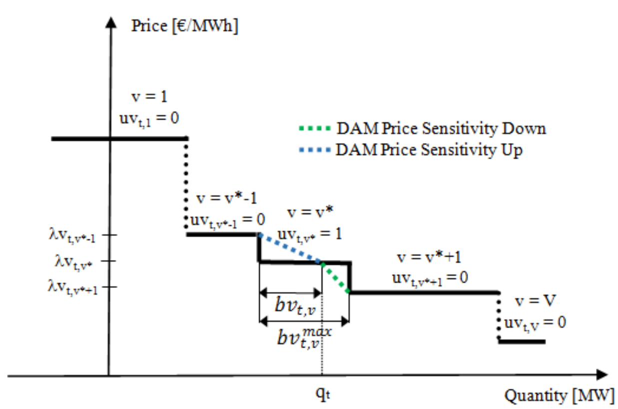


Figure 5 – Price sensitivity down and price sensitivity up in the DAM.

These price sensitivities describe linearly what is the influence in market price for each unit of energy sold (DAM Price Sensitivity Down) or for each unit of energy bought (DAM Price Sensitivity Up) in the DAM.

For the SRM, we have also computed a price sensitivity of the residual demand curve. Considering that in the SRM the GENCO can only sell a power band, we only have one price sensitivity (SRM Price Sensitivity Down), describing linearly the influence in market price of each unit of power sold in the SRM, nevertheless, a SRM Price Sensitivity Up was also computed for analysis purposes. These price sensitivities are represented in Fig. 6.

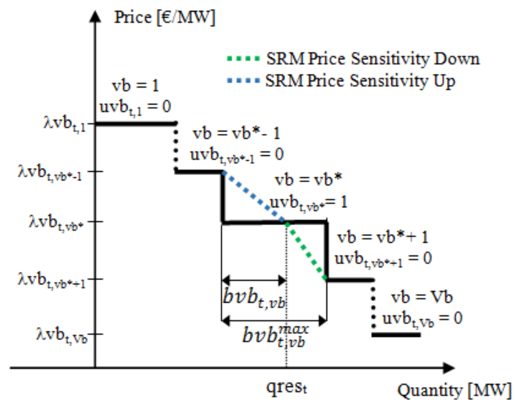


Figure 6 – Price sensitivity down and price sensitivity up in the SRM.

## V. SCENARIOS

In order to evaluate the behavior of the PSH and the impact in the DAM and in the SRM, 4 case studies were considered, with different technologies for the PSH and different combinations of markets in which the PSH acts:

Scenario A: The GENCO acts in the DAM with a PSH without variable pumping capacity.

Scenario B: The GENCO acts in the DAM and SRM with a PSH without variable pumping capacity.

Scenario C: The GENCO acts in the DAM with a PSH with variable pumping capacity.

Scenario D: The GENCO acts in the DAM and SRM with a PSH with variable pumping capacity.

Data for the analysis, namely prices, selling and demand curves of the DAM were obtained from the Iberian Market Operator-Spanish pole (OMIE) [4]. Regarding the SRM, data were obtained from the Portuguese TSO and SRM operator, Redes Energéticas Nacionais (REN) [5].

Also worth mention the fact that, in this paper, it is considered that the GENCO has its units located in Portugal, once the SRM of Portugal and Spain are not integrated. Thus, the residual demand curve obtained for the SRM concerns only the Portuguese SRM.

According to Kanakasabapathy and Swarup [6], it is economically more advantageous to plan the operation of a PSH within a one-week horizon than for just one day as it allows better exploitation of the storage capacity of its upper reservoir. In this way, portfolio optimization for the case studies considered is carried out for one week, with the weekly operation starting at midnight on Monday and ending at midnight on the Monday of the following week.

The characteristics of the PSH are represented in Table III.

TABLE III
CHARACTERISTICS OF THE PSH UNIT

| $P_g^{min}$ [MW] | $P_g^{max}$ [MW] | $P_p^{min}$ [MW] | $P_p^{max}$ [MW] |
|---|---|---|---|
| **250** | **390** | **300** | **360** |
| $W^{min}$ **[GWh]** | $W^{max}$ **[GWh]** | $\eta_g$ **[%]** | $\eta_p$ **[%]** |
| **0** | **19** | **90** | **80** |

The results of the four scenarios in terms of operational profit and scenario comparison are presented in Table IV.

TABLE IV
OPERATIONAL PROFIT AND SCENARIO COMPARISON

| Scenario | Operational Profit (€) | | |
|---|---|---|---|
| | DAM | SRM | Total |
| A | 252.643 | --------- | 252.643 |
| B | 158.591 | 337.831 | 496.422 |
| C | 254.936 | --------- | 254.936 |
| D | 59.113 | 578.415 | 637.528 |

| Scenarios | Scenario Comparison (€/%) | | |
|---|---|---|---|
| | DAM | SRM | Total |
| B-A | -94.052 (-37%) | 337.831 (NA) | 243.779 (+96%) |
| D-C | -195.823 (-77%) | 578.415 (NA) | 382.592 (+150%) |
| C-A | 2.293 (+0,9%) | --------- | 2.293 (+0,9%) |
| D-B | -99.478 (-63%) | 240.584 (+71%) | 141.106 (+28%) |

When comparing scenarios A and C, there is an increase of only 2.293€ (+0,9%) in the operational profit and a global energy differential of -50MWh (+1,5%). Despite the extra flexibility that the variable pumping capacity allows, the restrictions of considering only one market, one week of simulation and, at the end of that period we having to have the same amount of water in the upper reservoir, doesn't allow the PSH to take advantage of this increased capacity. In this scenario, although the pumping power is variable, the PSH will still tend to pump at maximum power or near that value, as shown in Fig. 7.

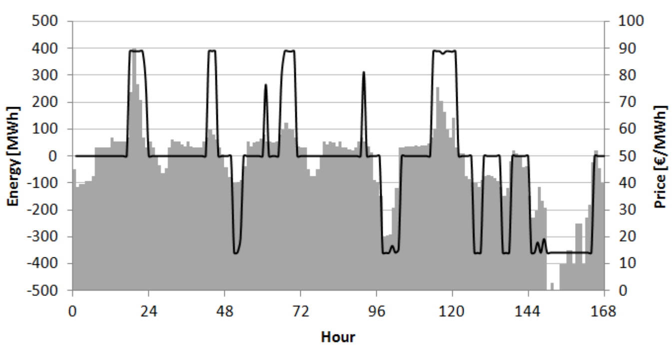

Figure 7 – DAM energy/power of the PSH and market price for scenario C.

When comparing scenarios B and D, there was an increase of 141.106€ (+28%) in the operational profit, a global energy differential of -1.605MWh (+22%) in the DAM and an overall power differential of 6.906MW (+ 80%) in the SRM. It should be noted that, in the case of the DAM, due to the efficiency of the pumping cycle and the condition of having the same initial and final energy in the upper reservoir, the energy differential will become more negative with the increased production/consumption of the PSH and, in percentage, the increase in generated energy is equal to the increase in pumped energy (these considerations are also valid for any comparing where increases in production/consumption of PSH occur). In this scenario, the ability to vary the power in the pumps allowed a better fit of the pumping profile to the residual demand curve (in the DAM and in the SRM) and allowed the PSH to operate 92 hours in the SRM with a total of 4.946MW (something that is not possible with fixed power), as shown in Fig. 8.

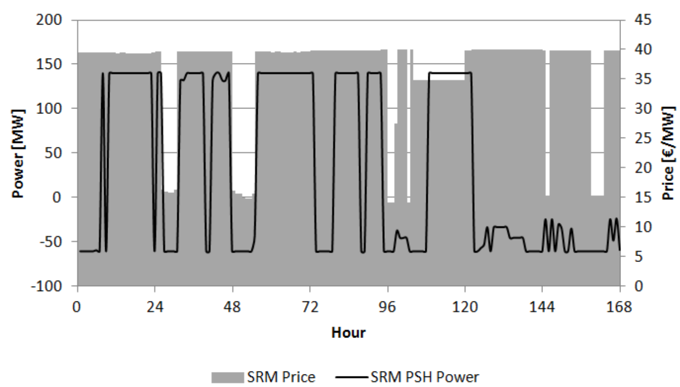

Figure 8 – SRM power of the PSH and market price for scenario D.

In scenarios A/B and C/D, comparing the cases in which the PSH acts only in the DAM with the cases in which it acts in both markets, there is an increase in operational profit of 243.779€ (+96%) in the scenario B and 82.592€ (+150%) in scenario D, despite the fact that, in both scenarios, the PSH "sacrifices" the operational profit in the SRM since, this way, it obtains a higher total operational profit (through the SRM operational profit). In any of the scenarios, given the profitability of operating in both markets, the plants increase their participation (the number of hours and the energy put into play) in the DAM to be able to also act in the MBS and, in each hour, tend to limit their power in the DAM so that they can also operate in the SRM (so that they can increase 2/3 and decrease 1/3 of the power band in this market), as seen in Fig. 9 (where it's clear that the PSH tends to operate bellow it's maximum power in the DAM).

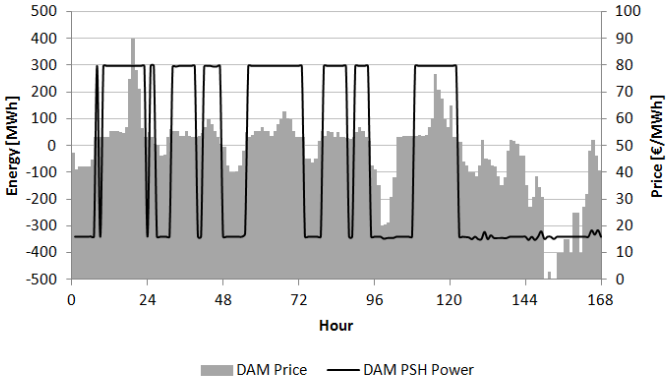

Figure 9 – DAM energy/power of the PSH and market price for scenario D.

In terms of sensitivity analysis, Fig. 10 and Fig. 11 represent the price sensitivity in scenario C before and after the GENCO acts in the market, respectively.

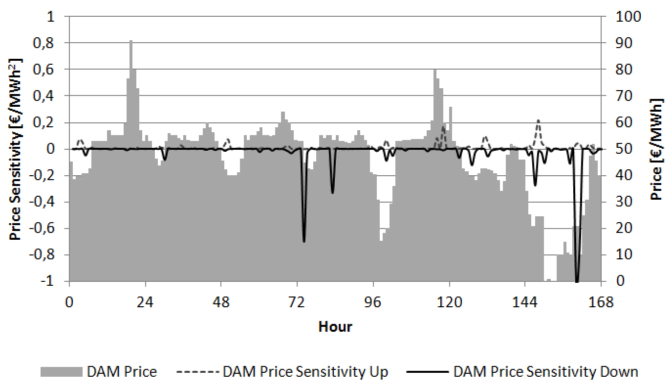

Figure 10 – DAM Price sensitivity before the GENCO acts in the market for scenario C.

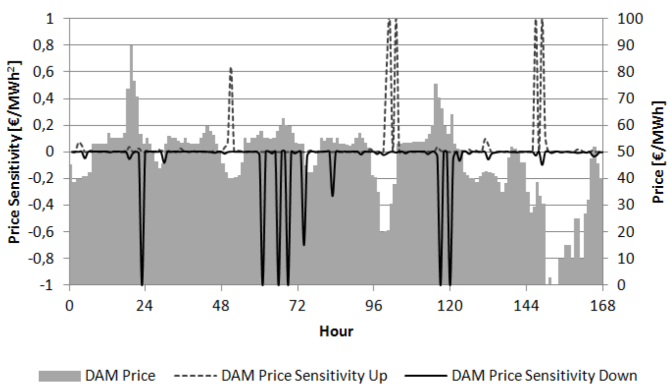

Figure 11 – DAM Price sensitivity after the GENCO acts in the market for scenario C.

When comparing the price sensitivities before and after the GENCO acts in the market, as expected, there is an increase in the amount of sensitivity peaks up and down after the GENCO acts. In a few operation hours (both generating and pumping), the PSH occupied the maximum available capacity at the price level (of the residual demand curve) in which it was operating but limited its power to avoid lowering the market price (in the cases where it was generating) or not raising the market price (in the cases where it was pumping), examples of this behavior being hours 61 and 147.

At hour 61, the PSH is generating with a power of 265,6MW and an infinite price sensitivity down, showing that the PSH used only part of its power (the total power being 390MW) in order to occupy the whole price level in which it was operating (hence the infinite sensitivity down) and, at the same time, not moving to the lower level of market price.

At hour 147, the PSH is pumping with a power of -321.5MW and an infinite price sensitivity up, that is, the PSH used only part of its pumping capacity (the total capacity being -360MW) in order to occupy the whole price level in which it was operating (hence the infinite price sensitivity up) and, at the same time, not moving to the upper level of market price.

## VI. Conclusion

Regarding the analysis of the technology of the PSH, namely the variable pumping capacity, the comparison between scenarios A and C, with an increase in operational profit of only 0.9%, allows us to conclude that acting only in the DAM does not take advantage of the full potential of this new technology. However, the scenario changes completely when the PSH acts simultaneously in the DAM and in the SRM, with a significant increase of 28% in the overall operational profit of the PSH when we compare scenarios B and D. It was verified that, in this scenario of operation in both markets, the variable pumping capacity allowed a better fit of the pumping profile to the residual demand curve and allowed to pump in the SRM (something that is not possible fixed power), which caused the PSH to operate more and with more total energy in the DAM (decreasing by 63% its operational profit in this market), limiting the power that it made available every hour, to also be able to operate more in the SRM (where it obtained a 71% higher operational profit), thus taking advantage of this increased capacity to vary the pumping power.

With respect to the analysis of the markets in which the PSH operates, through the comparisons between scenarios A/B and C/D, it can be concluded that the simultaneous operation in the DAM and in the SRM is quite attractive, with increases in operational profit of 96% for the scenarios A/B comparison and 150% for the scenarios C/D comparison. In any of the comparisons, the PSH tends to sacrifice the operational profit it would get in the DAM (with decreases of 37% and 77%) in order to be able to operate more in the SRM, thus obtaining a higher overall operational profit. In addition, as it was also verified in the technology analysis, given the profitability of operating in the SRM, the PSH tends to limit the power it makes available in the DAM so that it has enough margin to increase 2/3 and to go down 1/3 of the power with which it operates in the SRM.

## REFERENCES


**[1]** S. Torre, J. M. Arroyo, A. J. Conejo, and J. Contreras, "Price Maker Self-Scheduling in a Pool-Based Electricity Market: A Mixed-Integer LP Approach," *IEEE Trans. Power Systems*, vol. 17, pp. 1037-1042, Nov. 2002.

**[2]** J. Lagarto, F. Fernandes, J. A. M. Sousa and J. Santana, "Multi-market optimal scheduling of a power generation portfolio with a price-maker pumped-storage hydro unit" in *13th International Conference on the European Energy Market*, Porto, 2016.

**[3]** J. Lagarto, J. A. M. Sousa e F. Fernandes, "Optimal scheduling of a price-maker pumped-storage hydro unit in the day-ahead and secondary reserve electricity market," in *10th Conference on Sustainable Development of Energy, Water and Environment Systems*, Dubrovnik, 2015.

**[4]** Iberian Electricity Market operator – OMIE, [Online]. Available: www.omie.es.

**[5]** "Sistema de Informação de Mercados de Energia," REN, [Online]. Available: www.mercado.ren.pt.

**[6]** P. Kanakasabapathy e K. S. Swarup, "Pumped storage bidding and its impacts in combined pool-bilateral market," em *International Conference on Power Systems*, Kharagpur, 2009.