Multi-market optimal scheduling of a power generation portfolio with a price-maker pumped-storage hydro unit

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***Abstract*—The increasing integration of renewables in the energy markets has been raising some challenges to generating companies (GENCOs), in terms of operation and planning of their generation portfolios. A GENCO aiming at maximizing its profits has to deal with offers 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 includes a pumped-storage hydro unit, acting simultaneously in the DAM and SRM. The results were obtained for six different scenarios, where the portfolio may include a thermal generation unit and compares the GENCO behavior in both markets either as a price-taker or as a price-maker. The results put in evidence the portfolio effect when the GENCO takes into account its influence on price, which is seen in the price-maker scenarios, whereas the scheduling remains unchanged under the price-taker behavior.**

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

I. Introduction

Due to its technical and economical characteristics, Pumped-Storage Hydro (PSH) is the most widely used technology to store energy at large scale in power systems [1]. Among the PSH units characteristics, it can be highlighted the amount of potential energy stored, the efficiency of the generation-pumping cycle and the flexibility of operation. For these reasons, PSH units are also increasingly seen as one of the solutions to mitigate wind power curtailment, thus helping with the integration of renewables [2].

One of the impacts of the increasing penetration of renewables in power markets is the decreasing of wholesale market prices [3]. This reduction in wholesale market prices can affect the profitability of the generating companies (GENCOs) and can be partially compensated by additional revenues from providing ancillary system services [1].

In this regard, [4] determines the optimal bidding strategy of a PSH unit participating in the Iberian day-ahead electricity market and in the Portuguese ancillary services market. The authors conclude that for the scenarios analyzed the profit comes almost entirely from the Spinning Reserve Market. The authors also conclude that the profit increases with the growing need of standby power due to the increase in wind energy.

This paper deals with the self-scheduling problem of a price-maker GENCO acting both in the DAM and SRM, where six scenarios were considered. In the first scenario, the GENCO acts in both markets as a price-taker having only a thermal unit in its portfolio. In the second scenario the behavior of the GENCO is also price-taker but now the portfolio includes only a PSH unit. The third scenario is similar to the second one, but the portfolio of the GENCO includes a thermal unit and a PSH unit. The fourth, fifth and sixth scenarios are analogous to the first three ones, but the GENCO behaves in the DAM and in the SRM as a price-maker.

For the scenarios where the GENCO acts as a price-maker, this paper follows the self-scheduling problem formulation of [5], but expanding it in two ways. Firstly, the model presented in this paper expands the model presented in [5] to include not only the case when the GENCO sells energy in the DAM, but also the case when a GENCO buys energy for pumping. Secondly, this paper applies the proposed model in a multi-market setting including the DAM and the SRM.

This paper is organized as follows: section II describes the model for a price-taker and a price-maker behavior of the GENCO in the DAM and SRM, section III presents the scenarios considered, section IV presents the results and section V draws conclusions.

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II. MODEL DESCRIPTION

A. GENCO acting in DAM and SRM as price-taker

When the GENCO acts as a price-taker in both the DAM and the SRM, it does not recognize its influence on market prices. The revenues obtained consist of the sum of the revenue obtained in the DAM and in the SRM. The revenue obtained in each market is given by the quantity traded in that market multiplied by the market price. For the particular case where the GENCO buys energy in the DAM, the energy acquired at market price represents a cost. The total profit of the GENCO is the difference between its revenues and the total costs.

Regarding the output constraints of the generating units, they have to take into account the Secondary Reserve (SR) capacity offered by the GENCO in the SRM. The SR capacity represents a range of power within which the generating unit can change its power output. 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.

If a thermal unit is part of the portfolio of the GENCO, other constraints must be considered, such as ramp-up and down constraints.

In the scenarios where a PSH unit is included in the portfolio of the GENCO, reservoir constraints are also considered, comprising the consideration that the water level in the reservoir in the beginning of the scheduling period is equal to the water level at the end of that period.

B. GENCO acting in DAM and SRM as price-maker

As mentioned before, in the situation where the GENCO is a price-maker in both markets, this paper expands the model presented by [5] considering also situations where the GENCO buys energy in the DAM and the situations where it trades in the SRM. In this sense, Fig. 1 presents an example of a residual demand curve faced by the GENCO. 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 it is only constituted by the steps correspondent to a positive quantity. This has to do with the fact that the 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.

C. Price sensitivity

For the analysis of the scenarios where the GENCO has a price-maker behavior, we have computed a price sensitivity of the residual demand curve. 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).

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.

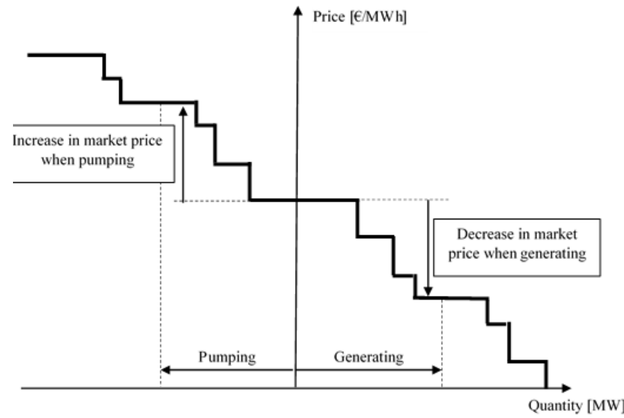

Figure 1 – GENCO's Residual Demand Curve

For the SRM, we have also computed a price sensitivity of the residual demand curve. In this, we have only one price sensitivity (SRM Price Sensitivity) describing linearly the influence in market price of each unit of power sold in the SRM.

III. SCENARIOS

In this work six scenarios were analyzed:

Scenario A: The GENCO acts in DAM and SRM as a price-taker having in its portfolio only a thermal unit.

Scenario B: The GENCO acts in DAM and SRM as a price-taker having in its portfolio only a PSH unit.

Scenario C: The GENCO acts in DAM and SRM as a price-taker having in its portfolio a thermal unit and a PSH unit.

Scenario D: The GENCO acts in DAM and SRM as a price-maker having in its portfolio only a thermal unit.

Scenario E: The GENCO acts in DAM and SRM as a price-maker having in its portfolio only a PSH unit.

Scenario F: The GENCO acts in DAM and SRM as a price-maker having in its portfolio a thermal unit and a PSH unit.

Data for the analysis, namely prices, selling and demand curves of the DAM were obtained from the Iberian Market Operator-Spanish pole (OMIE) [6]. Regarding SRM, data were obtained from the Portuguese TSO and SRM operator, Redes Energéticas Nacionais (REN) [7].

Also worth mention the fact that, in this work, 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 to the Portuguese SRM.

The results were obtained for 168 hours (one week period) and the characteristics of the PSH and thermal units are represented in Table I and Table II, respectively.

TABLE I. 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]**	η_g **[%]**	η_p **[%]**
0	**19**	**90**	**80**

The model here presented was programmed in General Algebraic Modeling System (GAMS) and solved by the CPLEX solver.

TABLE II. CHARACTERISTICS OF THE THERMAL UNIT

P_g^{min} [MW]	P_g^{max} [MW]	*Ramp down* [MW]	*Ramp Up* [MW]
180	**425**	**200**	**300**
***Fixed Cost* [€]**	***Var. Cost* [€/MWh]**	***Start-up Cost* [€]**	***Shut-down cost* [€]**
5	**10**	**5**	**0.1**

IV. RESULTS

The results of the six scenarios are presented in Table III, where scenarios A, B and C represent price-taker behavior of the GENCO, whilst scenarios D, E and F represent price-maker behavior.

TABLE III. DAM AND SRM RESULTS FOR THE SIX SCENARIOS

	DAM							**SRM**						
	Energy				***Profit***[b]			***SR Capacity***			***Profit***[b]			
	PSH													***Total Profit***
Scenarios[a]	***Pump. [GWh]***	***Gen. [GWh]***	***Thermal [GWh]***	***Total [GWh]***	***PSH [k€]***	***Thermal [k€]***	***Total [k€]***	***PSH [GW]***	***Thermal [GW]***	***Total [GW]***	***PSH [k€]***	***Thermal [k€]***	***Total [k€]***	***DAM + SRM [k€]***
A	-	-	47.4	47.4	-	2171.4	2171.4	-	36.0	36.0	-	385.6	385.6	2557.0
B	-31.3	22.5	-	-8.8	56.3	-	56.3	16.1	-	16.1	537.2	-	537.2	593.6
C	-31.3	22.5	47.4	38.6	80.6	2221.9	2302.5	16.1	36.0	52.1	55.8	25.2	81.0	2383.5
D	-	-	53.6	53.6	-	2463.7	2463.7	-	25.8	25.8	-	868.6	868.6	3332.3
E	-31.3	22.5	-	-8.8	58.9	-	58.9	15.6	-	15.6	578.7	-	578.7	637.5
F	-29.2	21.0	62.0	53.8	134.0	2947.2	3081.1	13.8	12.4	26.3	508.2	404.2	912.4	3993.5

a. Price-taker scenarios: A, B and C. Price-maker scenarios: D, E and F

b. In price-taker scenarios the profit is computed considering ex-post prices

Regarding the GENCO's profit presented in Table III for scenarios A, B and C, it has been considered the ex-post market prices, to compute those figures. This means that we have distinguished what is the belief of the GENCO (behaving as price-taker does not impact market price) from what is the actual impact that the GENCO has on market price by behaving that way. Thus, the GENCO's profit for scenarios A, B and C, where computed considered the market prices that would occur with the production made by the generating units.

Fig. 2 depicts the operation of the thermal unit in scenario A, where the brown color represents for each hour the amount of SR capacity that the thermal unit can increase from the DAM operation point, and the orange color the SR capacity that it can decrease. This means that the separation between the brown and orange area is the operational set point in the DAM. The blue line represents the hours where the thermal unit operates in the SRM. The hours where the line is interrupted means that the thermal unit did not operate in the SRM. The scheduling of the thermal unit is fairly understandable if one keeps in mind that in this scenario the thermal unit makes arbitrage between the two markets.

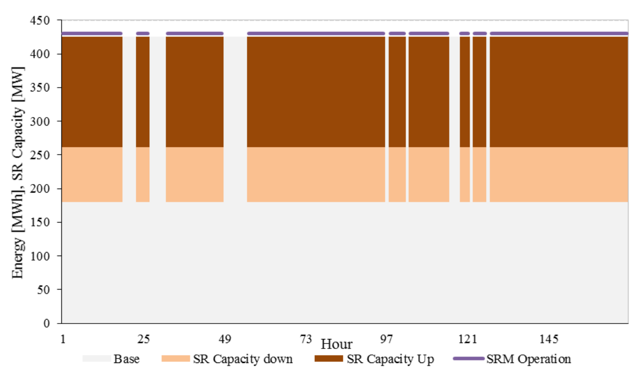

Figure 2 – Scheduling of thermal unit in scenario A

In Fig. 3, the prices of the DAM and SRM are presented. Moreover, the ratio between the margin of the thermal unit in the DAM (difference between DAM price and variable production cost of the thermal unit here denoted by DAM margin) is also represented.

The dashed blue line represents the value of 1.5. As it can be seen, by the thicker blue line that represents the SRM operation (the same blue line of Fig. 2) the thermal unit only operates in the SRM if the ratio between the DAM margin and SRM price is lower than 1.5. The reason for this value stems from the rules put in place in the Portuguese SRM, which state that the generating units must be able to increase its power output by 2/3 of the SR capacity bided in the SRM. That is why, for each MW that the generating unit gives up in the DAM, it can increase the SR capacity sold in the SRM by 1.5 MW.

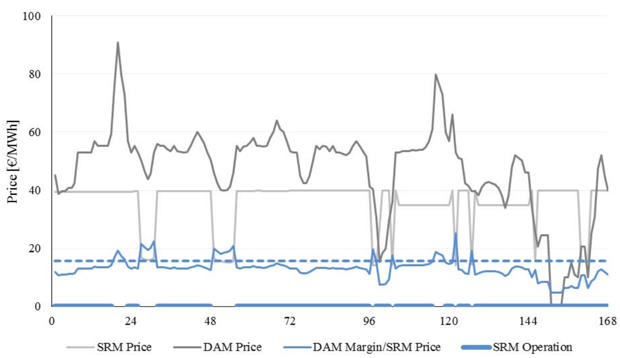

Figure 3 – SRM and DAM prices and the ratio between DAM margin and SRM prices

For scenario B, where only a PSH unit is available to the GENCO, the results are different and are presented in Fig. 4.

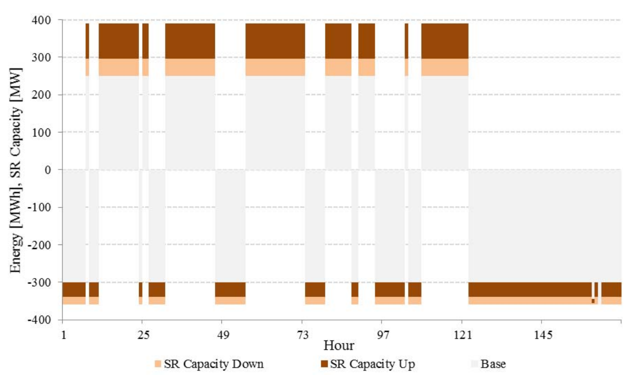

Figure 4 – Scheduling of the PSH unit in scenario A

The main reason for the different scheduling of the PSH unit when compared with the thermal unit is that fact that the PSH unit besides the arbitrage that it makes between the DAM and the SRM, it also makes arbitrage between different hours. Since the PSH unit has a reservoir to store water and thus energy, it has the ability to decide in which hour to generate in order to maximize profits.

Regarding scenario C, where the GENCO acts in both markets as a price-taker, the scheduling of the generating units does not change. This fact can be observed in the figures presented in Table III, which show that both the energy and the SR capacity of the PSH and thermal unit are the same in scenarios A, B and C, regardless of the fact that the units are in standalone mode or included in a portfolio. This has to do with the fact that when the GENCO behaves as a price-taker the composition of the portfolio does not have impact on the scheduling of the generating units that compose the portfolio. Due to the fact that, as mentioned previously, the profits are computed with the ex-post market prices, the GENCO's profit in scenario C is lower than the sum of the scenario B and scenario C profits'.

For the scenario where the GENCO acts as a price-maker in both markets, the scheduling of the thermal unit in scenario D is presented in Fig 5.

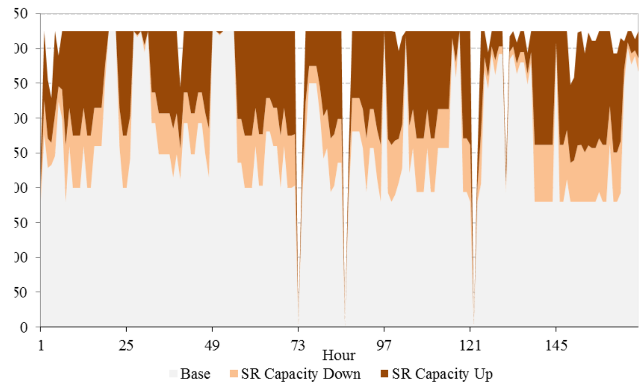

Figure 5 – Scheduling of the thermal unit in scenario D

The different scheduling of the thermal unit between scenarios A and D, stems from the fact that now the GENCO recognizes its impact on market prices, thus generating less energy in the DAM and bidding less SR capacity in the SRM. The impact that the GENCO has on market prices can be observed in Fig. 6 and Fig. 7, which represent the price sensitivities of the DAM and SRM, respectively. A note to the fact that for the thermal unit the only price sensitivity that matters is the price sensitivity down.

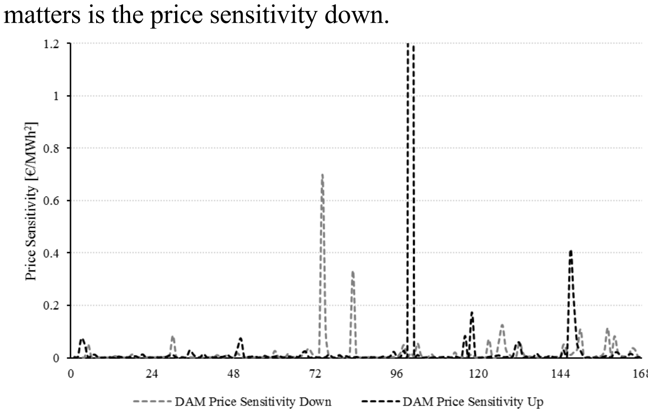

Figure 6 – Price sensitivities in the DAM

In Fig. 5, it can be seen that in hours 73, 86 and 122, the scheduling in the DAM of the thermal unit is zero. In Fig. 6, it can be also seen that for those hours the price sensitivity down has higher values, thus the thermal unit has a higher impact on DAM price.

In what concerns scenario E, the scheduling of the PSH unit is presented in Fig. 8.

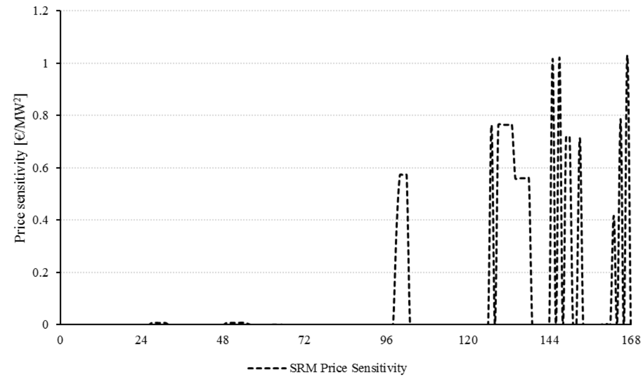

Figure 7 – Price sensitivity in the SRM

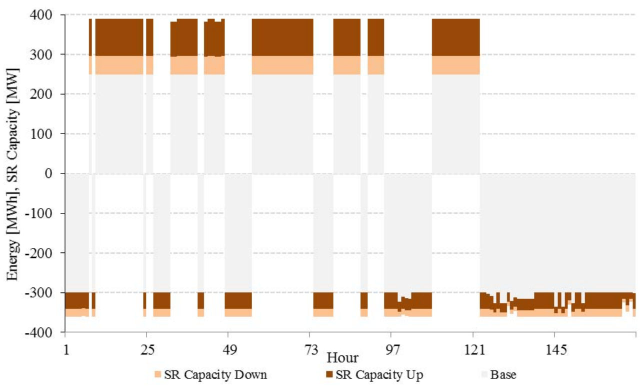

Figure 8 – Scheduling of the PSH unit in Scenario E

Likewise the scheduling of the thermal unit in scenario D, the scheduling of the PSH unit in this scenario is influenced by the price sensitivities in both markets.

For scenario F, Fig. 9 and 10 present the scheduling of the thermal unit and PSH unit, respectively.

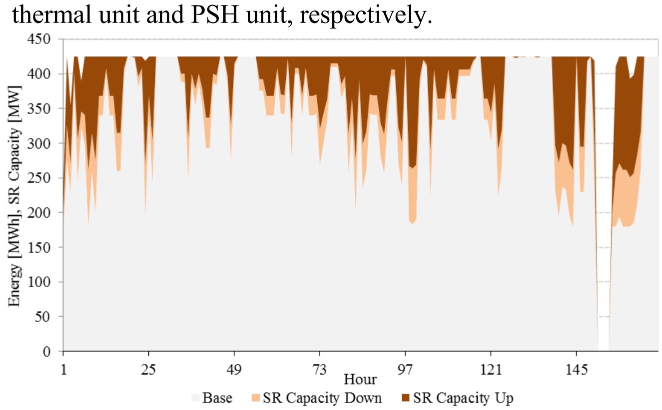

Figure 9 – Scheduling of the thermal unit in scenario F

As can be seen by Fig. 9 and 10, the scheduling of both units changes considerably when compared with scenarios D and E. In particular, the amount of SR capacity bided by the two units decreases and the energy traded in the DAM increases. This can also be verified in Table III. However, the GENCO's profit increases in both markets, being higher than the sum of the scenario D's profit and scenario E's profit. This happens because, unlike scenario C, when the GENCO has a price-maker the composition of the portfolio plays a major role in maximizing the GENCO's profits.

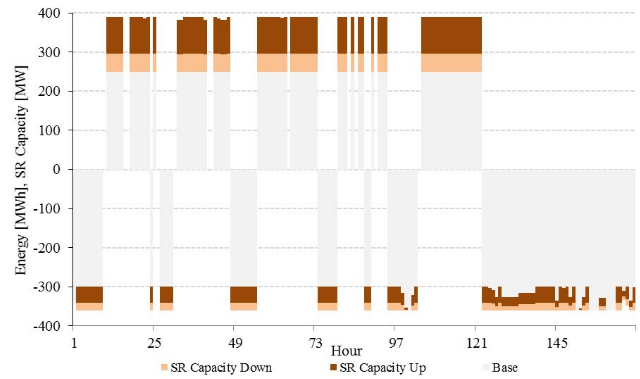

Figure 10 – Scheduling of the PSH unit in scenario F

V. Conclusions

This papers deals with the self-scheduling problem of a GENCO acting in the DAM and SRM. For this study, six scenarios were considered for different price behavior of the GENCO and portfolio composition.

Results showed that the thermal unit only makes arbitrage between markets, whereas the PSH unit makes arbitrage between markets and between scheduling hours. Moreover, in the price-taker scenarios, results showed that the composition of the portfolio does not impact the scheduling of the generating units, whereas in price-maker scenarios the portfolio plays a major role in maximizing GENCOS's profit. Future work will be devoted to study the integration of intermittent generation from renewable sources for different market behaviors of the GENCO and portfolio compositions.

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