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Modeling the Real-Time Use of Reserves in the Joint Energy and Reserve Hourly Scheduling of a Pumped Storage Plant

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Abstract

This paper studies the impact that different approaches of modeling the real-time use of the secondary regulation reserves have in the joint energy and reserve hourly scheduling of a price-taker pumped-storage hydropower plant. The unexpected imbalance costs due to the error between the forecasted real-time use of the reserves and the actual value are also studied and evaluated for the different approaches. The proposed methodology is applied to a daily-cycle and closed-loop pumped-storage hydropower plant. Preliminary results show that the deviations in the water volume at the end of the day are important when the percentage of the real-time use of reserves is unknown in advance, and also that the total income in all approaches after correcting these deviations is significantly lower than the maximum theoretical income.

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Keywords: Pumped-Storage Plant; Secondary Regulation Reserve Market; Real-Time Use of Reserves;

1. Introduction

The secondary regulation service, also called secondary control or load-frequency control service, is defined as a centralised automatic function to restore frequency deviations in a control area and to maintain the interchange power flow with all other control areas, according to the European Network of Transmission System Operators of Electricity (ENTSO-E) [1]. This service generally comprises two payments: one for the available power capacity and one for the real-time use of the said capacity [2]. The former is related to the remuneration of the amount of power that has been reserved for the provision of the service. The latter refers to the remuneration/charge of the real-time use of the upward/downward reserves by the Transmission System Operator (TSO) [3].

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In the context of the co-optimization of the energy and reserve hourly scheduling of a daily-cycle, price-taker and closed-loop pumped-storage hydropower plant (hereinafter referred to as PSHP), a hydropower producer must decide, depending on the water availability, which quantity of power is sold and/or bought in the spot market and which quantity of the power is reserved for the secondary regulation service. Here, closed-loop PSHP refers to a plant without natural inflows. However, as the real-time use of reserves (RTURs) is uncertain when bids are submitted, a deviation from the expected secondary regulation energy and, therefore, from the target volume at the end of the day may be expected. The deviation may have an impact in the real-time management of the PSHP as well as a cost due to the corrective actions that might be necessary to exert in order to meet the power and reserve schedule and to minimize the said deviation.

Nomenclature

Sets

c	hydropower unit, running from 1 to C
t	time period, running from 1 to T

Parameters

cSU_c^d	start-up cost of the turbine, €
cSU_c^p	start-up cost of the pump, €
δ^d	energy coefficient in generating mode, MW/hm^3
fv	target water volume in the last hour, hm^3
$\overline{g}_c^d$	maximum technical power generation, MW
$\underline{g}_c^d$	minimum technical power generation, MW
$\overline{g}_c^p$	maximum technical power consumption, MW
λ_t^{DM}	spot market price, €/MWh
λ_t^{SM}	secondary regulation reserve market price, €/MW
$\lambda_t^{UEM}, \lambda_t^{DEM}$	upward and downward secondary regulation energy market price, respectively, €/MWh
$\lambda_t^{UDES}, \lambda_t^{DDES}$	upward and downward imbalance price, respectively, €/MWh
$\overline{\eta}_c^d, \underline{\eta}_c^d$	turbine efficiency at maximum and minimum flow, respectively, %
$\overline{\eta}_c^p$	pump efficiency at maximum flow, %
$\overline{q}_c^d$	maximum technical water discharged, hm^3
$\underline{q}_c^d$	minimum technical water discharged, hm^3
$\overline{q}_c^p$	maximum technical water pumped, hm^3
ρ_t^{up}, ρ_t^{dw}	percentage of the real-time use of upward and downward secondary regulation reserves, respectively, %
R_t^{SM}	relationship between upward and total secondary regulation reserve, %
$\overline{v}, \underline{v}$	maximum and minimum technical water storage limits of upper reservoir, hm^3

Positive Variables

$g_{c,t}^d, g_{c,t}^p$	power generation and consumption, respectively, MW
$q_{c,t}^d, q_{c,t}^p$	water discharged and pumped, respectively, hm^3
$qs_{c,t}^d$	water discharged above the minimum technical limit, respectively, hm^3
$g_t^{DM,d}, g_t^{DM,p}$	power that is sold and bought in the spot market, respectively, MW
$g_t^{des,up}, g_t^{des,dw}$	upward and downward scheduled imbalance power, respectively, MW
$g_t^{sec,up}, g_t^{sec,dw}$	upward and downward secondary regulation reserve, respectively, MW
$E_t^{\sec,up}, E_t^{\sec,dw}, E_t^{\sec}$	upward, downward and net secondary regulation energy, respectively, MWh
v_t	water volume of the upper reservoir, hm^3

Binary Variables

$u_{c,t}, y_{c,t}$	on/off state in generating and consumption mode, respectively
$SU_{c,t}^d, SU_{c,t}^p$	start-up decision of the turbine and pump in the hydro unit c, respectively
ϕ_t	1 if there is more upward than downward secondary regulation energy, 0 otherwise

The aim of this paper is twofold: 1) to preliminary study the impact that several approaches to model the RTURs have in the joint energy and reserve hourly scheduling of a PSHP; and 2) to preliminary evaluate the economic impact of the RTUR forecasting error when deviations in the committed reserve schedule and in the secondary regulation energy are corrected, following the criteria used in the Spanish electricity market: being charged due to deviations in the committed reserve schedule, receiving an extra payment due to an unexpected upward imbalance (at a price lower or equal to the spot price) and finally, being charged due to an unexpected downward imbalance (at a price greater or equal to the spot price). The conclusions of this study are preliminary as they are obtained from a case study of one day, being expected to carry out a more advanced study in the future.

This paper uses a mixed integer linear programming model to obtain the optimal joint energy and reserve schedules of a PSHP participating in the spot and secondary regulation reserve markets of the Spanish electricity system, and also to obtain the optimal scheduled imbalances. The results of the model change depending on the approach used to model the RTURs. In the literature, modeling the RTURs has not been treated widely, [4]. One of the approaches used in the literature is to neglect the effect of the RTURs, [5] and [6]. Another is to assume that all the committed reserves are used, [7]. Besides, [8] and [9] model the RTURs as an hourly mean value obtained from historical data.

The paper is organized as follows. Section 2 describes the model formulation. Section 3 describes the case study and the methodology. Section 4 presents the results and discussion of the deviations obtained with all approaches and the deterministic one and of the economic impact when correcting the deviations. And, finally, Section 5 shows the conclusions and future work.

2. Model Formulation

The model formulation applies for PSHPs that pump water at a fixed speed. Therefore, they are not able to participate in the secondary regulation reserve market when they are pumping. Besides, for the sake of simplicity and without loss of generality, scheduled and unexpected imbalances are not considered in pumping mode.

2.1. Objective Function

The objective function of the model is presented in (1). It maximizes the income for the upward secondary regulation energy, the scheduled upward imbalance power, the energy sold in the spot market and the upward and downward secondary regulation reserve; and minimizes the cost of the downward secondary regulation energy, the scheduled downward imbalance power, the energy bought in the spot market and, finally, the start-up cost of the turbines and pumps.

$$\begin{aligned} Max \quad z = \sum_t \Big\{ & E_t^{\sec,up} \lambda_t^{UEM} - E_t^{\sec,dw} \lambda_t^{DEM} + g_t^{des,up,d} \lambda_t^{UDES} \\ & - g_t^{des,dw,d} \lambda_t^{DDES} + \sum_c \Big[\left(g_{c,t}^{DM,d} - g_{c,t}^{p} \right) \lambda_t^{DM} \\ & + \left(g_{c,t}^{\sec,up,d} + g_{c,t}^{\sec,dw,d} \right) \lambda_t^{SM} - SU_{c,t}^{d} cSU_c^{d} - SU_{c,t}^{p} cSU_c^{p} \Big] \Big\} \end{aligned} \tag{1}$$

2.2. Constraints

The water balance equation in the upper reservoir appears in (2) whereas limits in the water volume are introduced in (3), and the target water volume is imposed by (4). The target water volume is deemed as input data to the model. The time duration of each period is one hour; hence, it is not included in the model formulation.

$$v_t = v_{t-1} + \sum_c \left(q_{c,t}^{p} - q_{c,t}^{d} \right) \quad \forall t \tag{2}$$

$$\underline{v} \le v_t \le \overline{v} \quad \forall t \tag{3}$$

$$v_t = fv \quad t = T \tag{4}$$

In this study, hydropower generation and consumption curves are modeled in the same manner as in [10]. It is assumed that the PSHP has a negligible head variation in comparison with the total head between the upper and lower reservoirs. Hence, head dependency can be disregarded in the formulation. Due to this, the hydropower generation and consumption curves of each unit are formed by one linear segment and one point, respectively.

Hydropower generation curve is modeled with (5) and (6), imposing the limit of the discharged flow above the minimum in (7). Hydropower consumption curve is modeled with (8) and (9).

$$g_{c,t}^{d} = u_{c,t} \underline{g}_c^{d} + qs_{c,t}^{d} \delta_c^{d} \quad \forall c,t \tag{5}$$

$$q_{c,t}^{d} = u_{c,t} \underline{q}_c^{d} + qs_{c,t}^{d} \quad \forall c,t \tag{6}$$

$$qs_{c,t}^{d} \le u_{c,t} \left(\overline{q}_c^{d} - \underline{q}_c^{d} \right) \quad \forall c,t \tag{7}$$

$$g_{c,t}^{p} = y_{c,t} \overline{g}_c^{p} \quad \forall c,t \tag{8}$$

$$q_{c,t}^{p} = y_{c,t}\overline{q}_{c}^{p} \quad \forall c,t \tag{9}$$

Start-up decisions of turbines and pumps are modeled according to (10) and (11), respectively. In addition to this, each hydropower unit cannot be operated simultaneously in generating and consumption modes, (12) because reversible Francis turbines are assumed to be used. Besides, as it is assumed that there is only one pipe between the upper reservoir and the power station, when a unit operates in generating mode, the rest cannot operate in pumping or consumption mode and vice versa, (13). Note that *C* refers to the total number of hydro units in the PSHP.

$$SU_{c,t}^{d} \geq u_{c,t} - u_{c,t-1} \quad \forall c,t \tag{10}$$

$$SU_{c,t}^{p} \geq y_{c,t} - y_{c,t-1} \quad \forall c,t \tag{11}$$

$$u_{c,t} + y_{c,t} \leq 1 \quad \forall c,t \tag{12}$$

$$\sum_{c' \neq c} u_{c',t} \leq (C-1) - (C-1) \cdot y_{c,t} \quad \forall c,t \tag{13}$$

Secondary regulation reserves are modeled in (14) and (15). The available reserves depend on the power that is sold in the spot market. Upward and downward reserves must fulfill an hourly ratio imposed by the TSO, (16). The secondary regulation energy is remunerated according to the hourly net energy, i.e. upward minus downward regulation energy, (17)-(19). When the net energy is positive, ϕ_t=1, whereas when the net energy is negative, ϕ_t=0. Here, *M* is a scalar that stands for a large number.

$$g_{c,t}^{\sec,up,d} \leq u_{c,t}\overline{g}_{c}^{d} - g_{c,t}^{DM,d} \quad \forall c,t \tag{14}$$

$$g_{c,t}^{\sec,dw,d} \leq g_{c,t}^{DM,d} - u_{c,t}\underline{g}_{c}^{d} \quad \forall c,t \tag{15}$$

$$\sum_{c} \left(\frac{g_{c,t}^{\sec,up,d}}{g_{c,t}^{\sec,up,d} + g_{c,t}^{\sec,dw,d}} \right) = R_{t}^{SM} \quad \forall t \tag{16}$$

$$E_{t}^{\sec,up} \leq \phi_{t} M \quad \forall t \tag{17}$$

$$E_{t}^{\sec,dw} \leq (1-\phi_{t}) M \quad \forall t \tag{18}$$

$$E_{t}^{\sec,up} - E_{t}^{\sec,dw} = \sum_{c} \left[\rho_{t}^{up} g_{c,t}^{\sec,up,d} - \rho_{t}^{dw} g_{c,t}^{\sec,dw,d} \right] \quad \forall t \tag{19}$$

In each hour, the total generated power by the plant must be the same as the power committed in all markets and the net regulation energy according to the modeled RTURs, (20). Finally, the scheduled downward imbalance in generating mode is limited to the power that is reserved for the downward secondary regulation, (21).

$$\sum_{c} g_{c,t}^{d} = \sum_{c} \left(g_{c,t}^{DM,d} + \rho_{t}^{up} g_{c,t}^{\sec,up,d} - \rho_{t}^{dw} g_{c,t}^{\sec,dw,d} \right) + g_{t}^{des,up,d} - g_{t}^{des,dw,d} \quad \forall t \tag{20}$$

$$g_{t}^{des,dw,d} \leq \sum_{c} g_{c,t}^{\sec,dw,d} \quad \forall t \tag{21}$$

3. Case Study

This study deems uncertainty in the percentage of the RTURs and assumes perfect knowledge in the rest of the data: spot prices, secondary regulation reserve prices, upward and downward secondary regulation energy prices and upward and downward imbalance prices. The reason for this is to obtain preliminary results with just the impact of the uncertainty of the RTURs in the joint energy and reserve scheduling of the PSHP. Four approaches to model the RTURs are considered, Table 1. In addition to this, the results of the case study refers to 27/01/2013, chosen arbitrarily from a group of days that are representative enough to preliminary analyze and compare to each other the impact of the different approaches to model the RTURs. The electric power system data used in this case study correspond to hourly values of the Spanish electricity system, and the RTURs of Fig. 1.

Table 1. Approaches to model the upward and downward RTURs and the mean errors comparing to the historical value

Approach	Upward RTURs	Downward RTURs	Mean Error of the Upward RTURs	Mean Error of the Downward RTURs
A	0% in all hours, [5] and [6]	0% in all hours, [5] and [6]	56.72%	13.97%
B	100% in all hours, [7]	100% in all hours, [7]	43.28%	86.03%.
C	Hourly mean value in 2012, [8] and [9]	Hourly mean value in 2012, [8] and [9]	40.43%	24.85%.
D	ARMA(12,8) model	ARMA(24,22) model	46.16%	26.44%
E	Perfect knowledge of the RTURs	Perfect knowledge of the RTURs	No error	No error

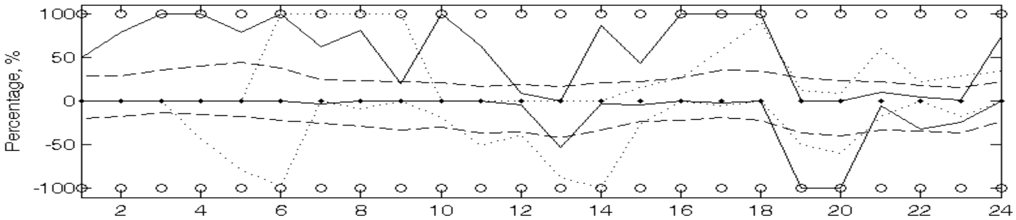

Fig. 1. Percentage of the upward (positive) and the downward (negative) RTURs considered in each Approach for 27/01/2013. RTURs of Approach A in dots, Approach B in circles, Approach C in dashed line, Approach D in dot line and Approach E in solid line

This study considers a PSHP with a single unit in order to ease the interpretation of the results. Technical data of the unit is presented in Table 2, obtained from guidelines in [11] and considering a gross head of 400 m, 3% of hydraulic losses due to friction in the pipes and a total storage capacity of 2 Mm^3. Technical data has been chosen in such a way for the use of a price-taker approach in the secondary regulation reserve market to be reasonable. Start-up costs of the turbine and pump are obtained according to guidelines in [12].

Table 2. Unit Technical Data, water flows in m^3/s, power in MW and start-up costs in €

$\overline{g}_c^d$	$\overline{q}_c^d$	$\underline{g}_c^d$	$\underline{q}_c^d$	$\overline{g}_c^p$	$\overline{q}_c^p$	cSU_c^d	cSU_c^p
190.31	55.56	69.11	23.89	190.31	42.38	735.47	603.84

3.1. Water Volume Deviation

The water volume deviation due to errors in modeling the RTURs is calculated as the difference between the target water volume, fv, and the water volume at the end of the day with the solution of the scheduling model in each Approach and the secondary regulation energy obtained with the actual RTURs. The problem of each Approach is solved with a branch and cut algorithm in Cplex 12.2 in a 2.4 GHz i5-450M Intel Core CPU, with 4 GB of RAM memory. Less than 5 seconds of CPU time were necessary for each Approach.

3.2. Economic Impact of Water Volume Deviation

In this study, reneging on the committed reserves and on the deviation of the expected regulation energy is proposed as a corrective action to avoid water volume deviations during the time horizon. This strategy seems to be allowed by the Spanish TSO, according to [13]. The reason to finish the day at the target water volume is to follow the guidelines from a long-term model. The difference between the total income after the actual RTURs and with the proposed corrective action is the economic impact of the water volume deviation. In addition to this, the difference between the total income of Approach E and each Approach, after correcting the water volume deviations can be seen as the value of perfect information (VPI) of the RTURs plus the value of the quality of the proposed strategy to correct the water volume deviations (VQS) in each Approach.

The rules of the secondary regulation service in the Spanish electricity system do not explicitly specify penalizations when the provision of the said service is reneged on. Therefore, and according to our interpretation, the following penalties are assumed:

- There is a penalty associated to renege on the committed secondary regulation reserves. This deviation is penalized by the reserve price in the respective hour and multiplied by a factor of 1.5, Section 10.2 of [14]. The committed reserves that are penalised are obtained by comparison between the real E_t^{sec} and the E_t^{sec} obtained from the model. The former refers to the E_t^{sec} that is obtained in the post-optimal simulation process, when the reserves are deployed whereas the latter is the E_t^{sec} that is obtained directly from the model with the assumed RTURs of Approaches A-D.
  - For hours with positive real E_t^{sec}: 1) if there is negative E_t^{sec} from the model, all the upward committed reserve is reneged and 2) if there is positive E_t^{sec} from the model: 2.1) the upward committed reserve minus the E_t^{sec} from the model is reneged if the E_t^{sec} from the model is lower than the real E_t^{sec} and 2.2) No committed reserve is reneged if the E_t^{sec} from the model is higher than the real E_t^{sec}.
  - For hours with negative real E_t^{sec}: 1) if there is positive E_t^{sec} from the model, all the downward committed reserve is reneged and 2) if there is negative E_t^{sec} from the model: 2.1) the absolute value of the real E_t^{sec} and the E_t^{sec} from the model is reneged if the E_t^{sec} from the model is higher than the real E_t^{sec}, i.e. the E_t^{sec} from the model is closer to zero and 2.2) no committed reserve is reneged if the E_t^{sec} from the model is lower than the real E_t^{sec}.
- There is a penalty associated to renege on the actual RTURs. This deviation is penalized by the upward or downward imbalance price, depending on the direction of the unexpected imbalance, Section 13.4.1 of [13].

4. Results and Discussion

4.1. Water Volume Deviation

The results of the operation of the PSHP for the Approach C are shown in Fig. 3. It is split into 8 subfigures with the following results:

1) The water volume of the upper reservoir in solid line and total water through the turbines (positive) or pumps (negative) in bars, before the actual RTURs. In addition to this, the water volume according to the actual RTURs in dashed line.
2) The water volume of the upper reservoir in dashed line and the total water through the turbines (positive) or pumps (negative) in bars, after the actual RTURs.
3) The energy schedule in the spot market in bars, the price of the spot market in blue solid line and the prices of the secondary upward and downward regulation energy in black solid and dashed line, respectively.
4) The reserve schedule in bars and the reserve price in solid line
5) The upward and downward expected regulation energy in bars and the upward and downward RTURs (expressed in percentage) in solid and in dashed lines, respectively, assumed in Approach C.
6) The actual upward and downward regulation energy in bars and the actual upward and downward RTURs (expressed in percentage) in solid and in dashed lines, respectively.
7) The scheduled imbalances in bars, the price of the spot market in blue solid line and the prices of the upward and downward imbalances in black solid line and in dashed line, respectively. Note that the spot price and the downward imbalance price overlap, i.e. blue solid line and dashed line overlap.
8) The unexpected imbalances of the upward and downward regulation energy in order to correct water volume deviations. Prices are the same as the previous subfigure.

In the results of Fig. 3, when the reserves are deployed, differences between expected and real secondary regulation energy occur, subfigure 8 of Fig. 3. Without correcting the deviations, the upper reservoir finishes at a water volume of 0.26 Mm^3 lower than the desired value (here 1 Mm^3) but earning 113598.51 €, Table 3.

The economic results after the actual RTURs are shown in Table 3. The economic results are composed by the income in the spot market, DM, in the reserve market, SM, due to the upward regulation energy, ER2UP, cost due to the downward regulation energy, ER2DW, income for the scheduled upward imbalance energy, DESUP, cost due to the scheduled downward imbalance energy, DESDW and start-up costs in turbine mode, cSUPt and pump mode, cSUPp.

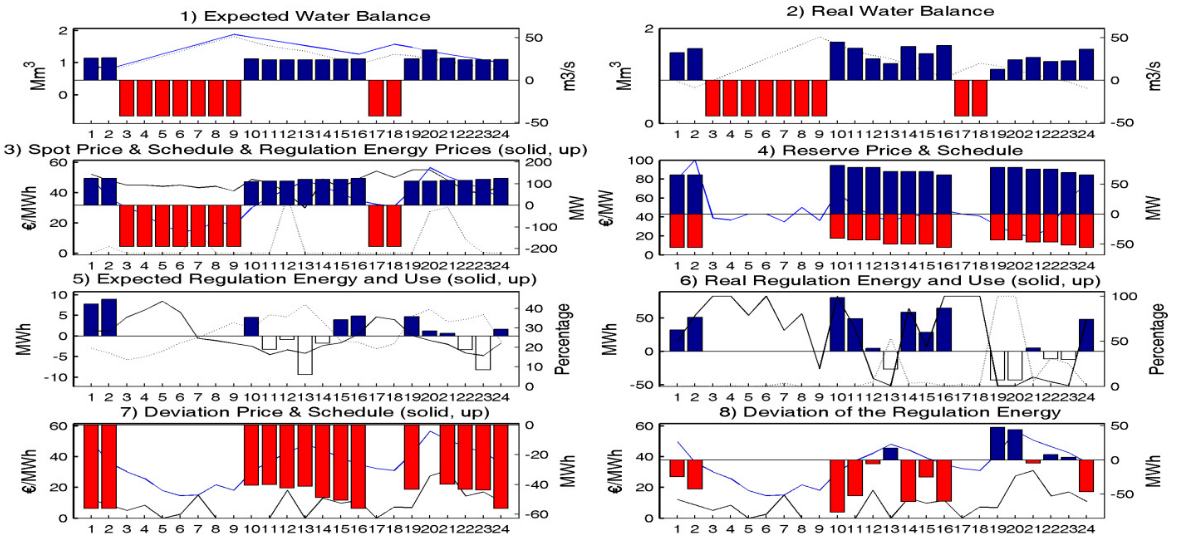

Fig. 2. Results of the Approach C before and after the actual RTURs

Table 3. Income in each market (in €), total income (in €) and water volume deviations (in Mm3) after the actual RTURs

Approach	Total	DM	SM	ER2UP	ER2DW	DESUP	DESDW	cSUPt	cSUPp	dVol
A	114352.52	35741.63	89358.33	20320.98	-1284.25	0	-26370.07	-2206.41	-1207.68	-0.27
B	96488.24	22997.54	85650.83	20320.98	-1284.26	0	-27782.76	-2206.41	-1207.68	-0.02
C	113598.51	35741.63	89358.34	20320.98	-1284.26	0	-27124.09	-2206.41	-1207.68	-0.26
D	116345.80	34772.69	88403.57	20220.37	-1284.26	0	-22352.48	-2206.41	-1207.68	-0.35
E	95894.33	24070.68	82207.73	16278.13	-1284.26	0	-21963.86	-2206.41	-1207.68	0

As can be seen in Table 3, the final volume of the upper reservoir may change significantly depending on the way the RTURs are modeled. The deviations in the final water volume in Approaches A, C and D are large enough to carry out further research in this topic (13.6%, 13% and 17.5%, respectively, of the total storage capacity of the upper reservoir). It is important to bear in mind that said Approaches assume very different values of RTURs. Approach B finishes the day closer to the target volume, with just an error of 1% of the total storage capacity.

4.2. Economic Impact of the Unexpected Imbalances

In order to fairly compare the economic results of the Approaches, it is necessary either to value the final volume deviation by using a sort of future water value, or to correct the water volume deviations according to a suitable strategy, assuming whenever necessary the corresponding penalties, as suggested in this paper (see section 3.2). Table 4 shows the economic results corresponding to each Approach after correcting the volume deviations according to the strategy described in section 3.2.

Table 4. Income in each market (in €) and total income (in €) after correcting water volume deviations

Approach	Total	DM	SM	ER2UP	ER2DW	DESUP	DESDW	cSUPt	cSUPp
A	15728	35741.63	23856.73	1845.79	-15931.98	0	-26370.08	-2206.41	-1207.68
B	36827.85	22997.54	36064.56	18779.50	-9816.90	0	-27782.76	-2206.41	-1207.68
C	19810.11	35741.63	25958.35	3619.87	-14971.57	0	-27124.09	-2206.41	-1207.68
D	18879.07	34772.69	23990.38	6222.70	-20340.13	0	-22352.48	-2206.41	-1207.68
E	95894.33	24070.68	82207.73	16278.13	-1284.26	0	-21963.86	-2206.41	-1207.68

The cost of correcting the water volume deviation in Approach A is 98624.52 € and 86.25% of the total income of Table 3, in Approach B 59660.39 € and 61.83%, in Approach C 93788.4 € and 82.56% and in Approach D

97466.73 € and 83.77%. This cost is obtained as the difference between total income of Table 3 and Table 4. Comparing this result with the economic result in the following day, assuming that deviations are not corrected, i.e. beginning the following day at the deviated water volume, is established as a promising future work. In addition to this, the VPI of the RTURs plus the VQS in the Approach A is 80166.33 €, in the Approach B is 59066.48 €, in the Approach C is 76084.22 € and in the Approach D is 77015.25 €. In all Approaches, the VPI of the RTURs plus the VQS is significant. Note that the VPI of the RTURs plus the VQS in Approach B is the lowest, with a 61.59% of the maximum theoretical income, Approach E and that Approach B does not have the lowest mean error of the RTURs, Table 1. Not only is the mean error of the RTURs important but also if the error provokes unexpected upward or unexpected downward imbalances. As downward imbalances are typically more penalized than upward imbalances, Approach B obtains a better economic result because it deviates more for unexpected downward than for unexpected upward imbalances in this day, comparing to Approaches A, C and D. However, the results of this study only correspond to a specific day, being necessary to carry out a further study for more days, for instance, two years.

5. Conclusion and Future Work

This study has analyzed the impact that different approaches of modeling the RTURs have in the joint energy and reserve hourly scheduling of a daily-cycle and price-taker PSHP. The results show that the water volume deviations with respect the target value can be significant and, therefore, corrective actions could be taken to correct the deviations and follow the guidelines of a long-term model. Besides, this study has proposed to correct the deviations by means of reneging on the committed reserve schedule and the actual RTURs. Under this strategy, the cost of correcting the water volume deviations (at least 61.83% of the expected total income in the day under study) and the VPI of the RTURs plus the VQS (at least 61.59% of the maximum theoretical income in the day under study) are high enough to justify further research. However, we propose to enlarge the study for enough days to extract more general conclusions. In addition to this, replicate this study participating in intraday markets as a corrective action and/or for PSHP that are able to provide load-frequency control in pumping or consumption mode can be deemed as a promising future work. Finally, considering the PSHP as a price-maker in the secondary regulation reserve market can be also established as an interesting future work.

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