

Optimal scheduling of a hybrid wind–battery power plant in the day-ahead and reserve markets considering battery degradation cost

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Abstract— This paper deals with the integration of the cost of battery degradation into the short-term self-scheduling problem of a hybrid power plant (HPP) comprising a wind farm and a lithium-ion battery. The HPP participates in the Spanish day-ahead (DA) energy and secondary regulation reserve markets. The model not only takes into account the cost of battery lifetime loss due to cycle aging, which is a function of depth of discharge (DOD) and discharge rate (C-Rate), but also considers the cost of calendar aging that is affected by three factors: time (t), state of charge (SOC), and temperature (T). Numerical simulations demonstrate that taking calendar aging into account significantly impacts the BES charge/discharge strategy and energy market trading.

Keywords— Battery degradation, Hybrid power plant, Calendar aging, Cycle aging.

NOMENCLATURE

Indices

j	BESS degradation cost curves [1,10].
t	Time step.
Parameters	
\bar{P}^B	BESS output/input power capacity [MW].
\bar{E}^B	BESS capacity [MWh].
\bar{P}^W	Installed capacity of wind farm [MW].
\bar{C}^B	maximum battery degradation cost [€].
$\bar{C}_j^B / \underline{C}_j^B$	Maximum/minimum BESS degradation cost corresponding to curve j [€].
$\overline{SOC} / \underline{SOC}$	Maximum/minimum state of charge [MWh].

S_j^B	BESS degradation cost slope corresponding to curve j [€/dch].
α, β	Coefficients of BESS Degradation cost.
η^B	Charging/discharging efficiency factor of BESS.
L_j^B	Minimum initial state of charge of BESS related to curve j [MWh].
Φ_j	Auxiliary parameter for of BESS degradation cost curve j .

Variables

dcr_t	BESS discharge rate in period t [0,1].
$e_t^{SM,up} / e_t^{SM,dw}$	Upward/downward secondary energy schedule in period t [MWh].
$e_t^{B,ch} / e_t^{B,dch}$	BESS energy charge/discharge in DA electricity market in period t [MWh].
$p_t^{SM,up} / p_t^{SM,dw}$	Upward/downward secondary regulation reserve in period t [MW].
soc_t	BESS state of charge in period t [MWh].
AG_t^{cal}	BESS calendar aging [MWh].
$c_t^{AG,cal}$	BESS calendar aging cost [€].
$c_t^{AG,cyc}$	BESS cycle aging cost [€].
p_t^B	BESS discharge/charge output/input power in the day-ahead electricity market in the period t [MWh] (positive discharge: negative charge).
u_t^B	Binary variable corresponding to the charging/discharging status of the

u_t^{dch}	BESS energy scheduled in period t in the DA energy market.
dch_t	Binary variable corresponding to the charging/discharging status of BESS in period t .
$\theta_{t,j}^B$	battery discharge rate in period t $[0,1]$.
	Binary variable used for selecting battery degradation cost curve j in period t .

Random Variables

ρ_t^W	Wind energy generation in period t [MWh].
λ_t^{DA}	DA electricity market price in period t [€/MWh].
λ_t^{SM}	Secondary regulation reserve market price in period t [€/MWh].
ρ_t^{SM}	Relationship between upward secondary reserve and total regulation reserve [pu].
$\rho_t^{SM,up} / \rho_t^{SM,dw}$	Percentage of utilized secondary upward/downward reserve in period t .
$\lambda_t^{ER,up} / \lambda_t^{ER,dw}$	Market price of the secondary upward/downward regulation energy reserve in period t [€/MWh].

I. INTRODUCTION

Nowadays, the adoption of distributed generation (DG) and renewable energy sources (RES), such as wind generation, have experienced rapid growth. This is a constructive step towards improving energy efficiency and transitioning from conventional sources of energy to renewable ones and the decarbonization in the power system [1]. However, the inherent fluctuation of renewable generation poses significant challenges for the power system. Therefore, the coupling of renewable energy sources (RES) such as wind farms with battery energy storage systems (BESSs) to form a hybrid power plant (HPP) has emerged as a highly promising solution [2].

Recently, employing the lithium-ion battery (LIB) technology has gained widespread usage owing to its potential for power density with high efficiency and a significantly extended lifespan [3]. Nevertheless, the cost of BESSs plays a significant role in determining their performance. Therefore, it is imperative to consider the cost of BES degradation in the BES scheduling problem. Physics-based, semi-empirical and empirical models are the three main types of models used for studying battery degradation. Physics based models [4] are based on mathematical equations that describe the physical and chemical processes that occur within battery aging. The empirical models [5] are based on experimental data and statistical analysis. Since these models can pose a significant computational burden on optimization modeling [3], a semi empirical model is used in this paper. The capacity fade of a BESS is highly influenced by its cycle aging and calendar aging.

Cycle aging refers to the gradual loss of capacity due to the regular charge and discharge cycles of the BES, while calendar aging refers to the aging of the BES over time, even if it is not in use.

In [6] an innovative operational cost function model for BESS is introduced, which takes into account degradation cost by considering depth of discharge and discharge rate. In [7], a semi-empirical model is used to predict Li-ion battery cell life loss through operating profiles and basic theories of battery degradation. The objective is to optimize BESS charge and discharge for frequency regulation market participation. Authors in [8] have developed a methodology that calculates the optimal operational schedule for a BESS while contemplating the efficiency of charging and discharging that varies with the output power levels. The degradation model considers only DoD and SoC factors.

In [9], a short-term optimization model is presented for a virtual power plant consisting of a wind farm and a BESS to participate in the energy and secondary regulation reserve markets. However, in this paper, degradation cost due to calendar aging is neglected. In [3] and [10] a new energy management strategy is presented for an integrated photovoltaic and BESS that incorporates the cost of BESS degradation including cycle and calendar aging into the scheduling problem. Nevertheless, the cycle aging model proposed by this paper only considers the effects of DOD on the cycle aging cost of the BESS.

In contrast to recent research papers concerned with the modeling the BESS degradation cost, which have mostly neglected the calendar aging and discharge rate in the cycle aging modeling, this paper focuses on taking into account the BESS degradation duo to cycle and calendar aging in the short-term self-scheduling problem of a HPP including a wind farm and a lithium-ion battery while considering the effects of various DODs and discharge rates on cycle aging cost of the BESS. In addition, the effects of considering calendar aging on trading strategies in the DA energy and secondary regulation reserve markets have been investigated.

The paper is structured as follows: Section II presents model formulation. The application of the model to a HPP is presented in Section III and finally, Section IV concludes the paper.

II. MODEL FORMULATION

In this section, the short-term self-scheduling problem of the HPP participating in the Spanish DA energy and secondary regulation reserve markets is formulated as a deterministic program. These markets have a scheduling horizon of 24 hours. However, the model has a time horizon of 72 hours so as to consider the opportunity cost of the energy stored in the BESS at the end of the scheduling horizon [9]. Please note that only the decisions corresponding to the markets' scheduling horizon (first 24 hours) will be later used to build the corresponding energy and reserve bids.

A. Objective Function

The proposed model aims to maximize revenue by trading in the DA energy and secondary regulation reserve markets while considering the costs of battery cycle aging and calendar aging (1).

$$\text{Maximize } \sum_{t=1}^{72} \left\{ \begin{array}{l} \lambda_t^{DA} \cdot (p_t^W + p_t^B) \\ + \lambda_t^{SM} \cdot (p_t^{SR,up} + p_t^{SR,dw}) \\ + \lambda_t^{ER,up} \cdot e_t^{SR,up} - \lambda_t^{ER,dw} \cdot e_t^{SR,dw} \\ - c_t^{AG,cyc} - c_t^{AG,cal} \end{array} \right\} \quad (1)$$

$$p_t^W \leq \bar{P}^W \quad \forall t \quad (2)$$

$$-\bar{P}^B \leq p_t^B \leq \bar{P}^B \quad \forall t \quad (3)$$

$$e_t^{B,ch} \leq \bar{P}^B \cdot (1 - u_t^B) \quad \forall t \quad (4)$$

$$e_t^{B,dch} \leq \bar{P}^B \cdot u_t^B \quad \forall t \quad (5)$$

$$e_t^{B,dch} - e_t^{B,ch} = p_t^B \quad \forall t \quad (6)$$

$$p_t^{SM,up} \leq \bar{P}^B - p_t^B \quad \forall t \quad (7)$$

$$p_t^{SM,dw} \leq p_t^B - (-\bar{P}^B) \quad \forall t \quad (8)$$

$$p_t^{SM,up} = \rho_t^{SM} \cdot (p_t^{SM,up} + p_t^{SM,dw}) \quad \forall t \quad (9)$$

$$e_t^{SM,up} - e_t^{SM,dw} = \rho_t^{SM,up} \cdot p_t^{SM,up} - \rho_t^{SM,dw} \cdot p_t^{SM,dw} \quad \forall t \quad (10)$$

$$e_t^{SM,up} \leq \bar{P}^B \cdot u_t^B \quad \forall t \quad (11)$$

$$e_t^{SM,dw} \leq \bar{P}^B \cdot (1 - u_t^B) \quad \forall t \quad (12)$$

$$\overline{SOC} \leq soc_t \leq \underline{SOC} \quad \forall t \quad (13)$$

$$soc_t = soc_{t-1} + \eta^B \cdot (e_t^{B,ch} + e_t^{SM,dw}) - (e_t^{B,dch} + e_t^{SM,up}) \quad \forall t \quad (14)$$

$$dch_t \geq \frac{soc_{t-1} - soc_t}{\overline{SOC}} \quad \forall t \quad (15)$$

$$u_t^{dch} \geq dch_t \quad \forall t \quad (16)$$

$$soc_{t-1} \geq L_{j-1}^B \cdot (\theta_{t,j-1}^B - \theta_{t,j}^B) + L_j^B \cdot \theta_{t,j}^B \quad \forall t, j \in [2, J] \quad (17)$$

$$soc_{t-1} \leq \overline{SOC} \cdot \theta_{t,j}^B + L_{j-1}^B \cdot (1 - \theta_{t,j-1}^B) + L_j^B \cdot (\theta_{t,j-1}^B - \theta_{t,j}^B) \quad \forall t, j \in [2, J] \quad (18)$$

$$\theta_{t,j}^B \leq \theta_{t,j-1}^B \quad \forall t, j \in [2, J] \quad (19)$$

$$c_t^{AG,cyc} \leq u_t^{dch} \cdot \underline{C}_j^B + S_j^B \cdot dch_t + \bar{C}_j^B \cdot (\varphi_j \quad \forall t, j \in [2, J] \quad (20)$$

$$- \sum_{n=2}^{j-1} \theta_{t,n}^B + \theta_{t,j}^B)$$

$$c_t^{AG,cyc} \geq u_t^{dch} \cdot \underline{C}_j^B + S_j^B \cdot dch_t \quad \forall t, j=1 \quad (21)$$

$$- \bar{C}_j^B \cdot (\theta_{t,j+1}^B + \theta_{t,j}^B)$$

$$c_t^{AG,cyc} \geq u_t^{dch} \cdot \underline{C}_j^B + S_j^B \cdot dch_t - \bar{C}_j^B \cdot (\varphi_j \quad \forall t, j \in [2, J] \quad (22)$$

$$- \sum_{n=2}^{j-1} \theta_{t,n}^B + \theta_{t,j}^B)$$

$$AG_t^{cal} = \left[\left(\frac{t}{720} \right)^{0.8} - \left(\frac{t-1}{720} \right)^{0.8} \right] \quad \forall t \quad (23)$$

$$\times (0.0028 \cdot soc_t + 0.001939 \cdot \bar{E}^B)$$

$$c_t^{AG,cal} = \alpha \cdot AG_t^{cal} + \beta \quad \forall t \quad (24)$$

In (1), the first term expresses the net revenue in the DA market due to the wind energy generation and the charging/discharging power output of the BESS. The second term presents the revenue in the secondary regulation reserve market. The third and fourth terms correspond to the revenue and cost due to the upward and downward secondary regulation energy, respectively. Finally, the fourth and fifth terms correspond to the BESS degradation cost resulting from the cycle and calendar aging, respectively.

B. Constraints

The objective function is subject to constraints (2)-(24). In (2), the wind energy schedule in the DA electricity market is restricted to be lower than or equal to the maximum available wind power. The maximum charging or discharging charge power output of the BESS is given by (3). Constraint (4)-(5) limits the energy scheduled of the BESS in the DA electricity market and ensure that the BESS energy schedule is only set to either discharge or charge mode. The net "position" in the DA energy market is calculated in (6). In (7)-(8), the available upward and downward secondary regulation reserve in reserve market are restricted, respectively. Constraint (9) ensures the fulfilment of the predefined ratio ρ_t^{SM} set by the transmission system operator (TSO) between the upward and the total secondary regulation reserve. In (10), the expected upward and downward secondary regulation energy are indicated as a function of the expected percentage required in real-time of the committed reserves. Constraints (11) and (12) ensure that for each period the secondary regulation energy is either upward or downward. Constraints (9)-(12) correspond to particular rules determined in the secondary regulation market of the Spanish power system. In constraint (13) the SOC of the BESS is limited. In (14) the SOC of the BESS in the period t is calculated. Constraint (15) and (16) indicate the BESS discharge rate.

Using the methodology provided in [6], the BESS degradation cost is computed as a function of the discharge rate and the initial SOC. Several BESS degradation cost curves have been used to establish the relationship between the discharge rate and degradation cost, which are presented in [9] and each curve is related to a distinct level of the initial battery SOC. Constraints (17)-(19) are presented for choosing the BESS

degradation cost curve that corresponds to its the initial SOC according to the method that is described in [11], whereas constraints (20)-(22) are used to determine the cycle aging cost according to the selected degradation cost curve

Constraint (24) and (25) calculate the calendar aging and the cost of the calendar aging based on a semi-empirical model proposed in [3] and [12]. The calendar aging is a function of time and SOC of the BESS. It is assumed that the BESS's temperature is constant by utilizing a suitable cooling system.

III. CASE STUDY

The proposed scheduling model in this section is implemented to the HPP and an analysis and comparison of numerical results of scheduling are presented according to various cases.

A. Data

A set of 32 scenarios are used as input to the short-term scheduling model so as to get representative enough results about the model's performance. Each scenario comprises the following data series (each spanning 72 hours): (i) DA electricity market price, (ii) secondary regulation reserve market price, (iii) secondary upward/downward regulation reserve energy prices, (iv) utilized secondary upward regulation energy and (v) the ratio between secondary upward regulation and total reserve market. The HPP includes a Li-ion battery of 2 MW power output/input capacity and a storage capacity of 8 MWh and a wind farm with a total installed capacity of 33 MW.

B. Results

In this subsection we analyze the effects of considering the BESS calendar aging on the SOC profile resulting from the energy and reserve schedule, and on the revenue the BESS can make in the DA energy and reserve market. For this purpose, we have run the model with and without considering the cost of calendar aging. The latter case is referred hereinafter as base case.

We investigate the impact of considering the calendar aging on charging and discharging strategies of the BESS in different hours. Secondly, we demonstrate the correlation between the cost of calendar aging of the BESS and its SOC and time range. Finally, the effect of considering the calendar aging on the profit of the HPP in energy markets is investigated.

Fig. 1 demonstrates the effects of considering calendar aging on charging and discharging scheduling of the BESS. By taking calendar aging into account, the SOC of the BESS in some hours experiences a noticeable decrease compared to the base case to minimize the calendar aging cost.

In Fig. 2, the cost of cycle and calendar aging and SOC of the BESS are shown within 24 hours of the scheduling day. The cost of calendar aging reduces over time in which, it decreases by 55.2% at hour 24 in comparison to hour 1. This demonstrates that the effect of time on calendar aging is significant at the beginning of the scheduling horizon. However, the calendar

aging is also affected by the SOC and whenever the BESS is charged, the SOC rises and as a result, the calendar aging increases.

In Table I, the daily average revenue or cost of the HPP over 32 scenarios in the DA energy market, the secondary regulation reserve (SRR) market, and for the secondary regulation energy (SRE) are compared for both cases where the BESS's calendar aging is considered and neglected. According to the Table, taking into account the cost of calendar aging, the revenue in the DA and SRR markets decreases by 0.63% and 13.87% respectively. On the other hand, neglecting the calendar aging cost leads to a 24.43% increase in the cost corresponding to the SER compared to considering the calendar aging cost. Therefore, it is imperative to underscore the significance of taking such expenses into account in the short-term scheduling of an HPP.

Fig 3. illustrates the prices of the DA energy market and the charging/discharging energy scheduled in the DA market. As shown in this figure, during low-price periods in the DA market energy is stored, while during high-price periods BESS sells energy into the DA market to maximize the revenue of the HPP.

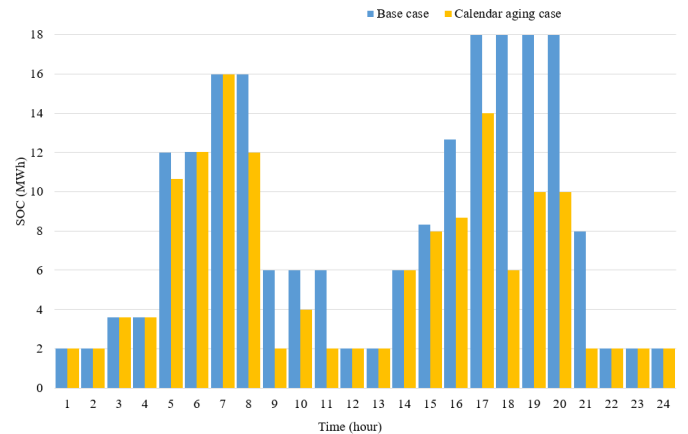


Fig. 1. SoC of the BESS in the base case and with considering calendar aging

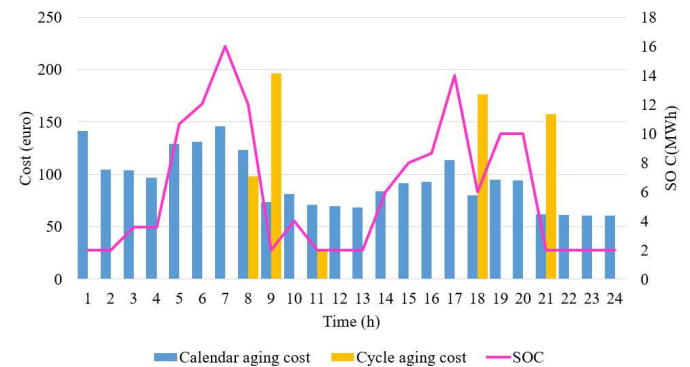


Fig. 2. Cost of calendar and cycle aging of the BESS and SOC of the BESS

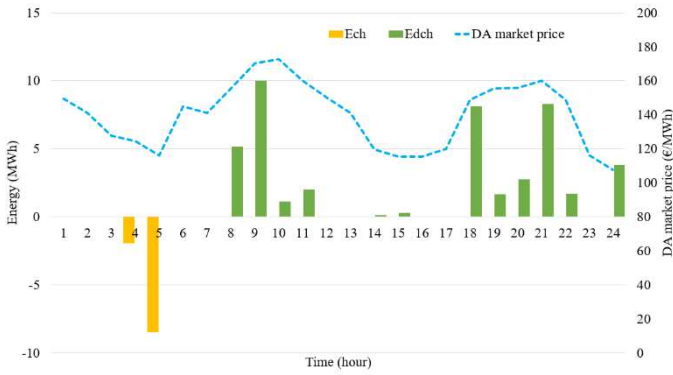


Fig. 3. Charging and discharging energy of BESS in DA market

Table I. DAILY AVERAGE REVENUE/COST of the HPP for EACH ELECTRICITY MARKET

Average Revenue or Cost (€)	Electricity Markets		
	DA	SRR	SRE
Base case	84140	2747.98	-887.349
Calendar aging cost	83602.38	2366.577	-670.569

C. Sensitivity Analysis

There are several factors that impact the amount of BESS degradation. The investment cost of the BESS has a major impact on the cost associated to its degradation as the expressions used to model the cost of both cycle and calendar aging depend on the investment cost, consistently with the sources [6], [9], [3], from which we have taken such expressions. Therefore, in this section, several numerical experiments are conducted to investigate the effect of various BESS investment cost scaling factors (λ) on the degradation cost and profit in the considered markets. The experiments will be based on various values of λ , which are presented in [3].

As demonstrated in fig. 4, by reducing λ from 0.9 to 0.5, the total profit in the considered markets experiences only a marginal increase of 0.3%, while the cost of degradation of the BESS declines rapidly by 37.8%.

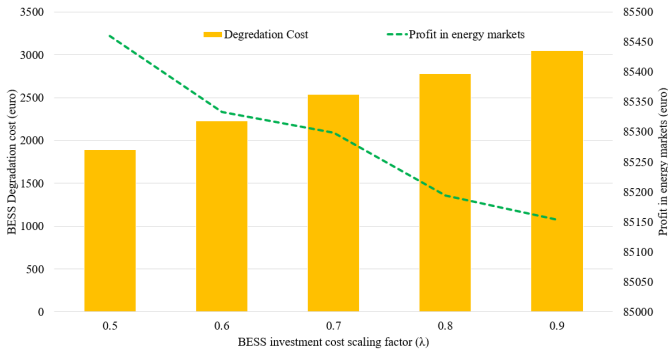


Fig. 4. Average BESS degradation cost and average total profit in the considered markets based on the investment cost scaling factor.

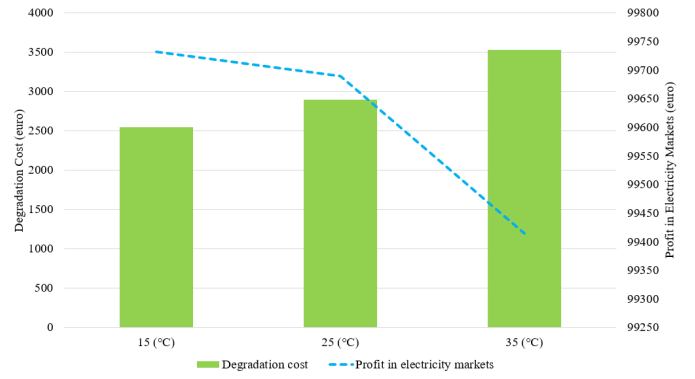


Fig. 5. BESS degradation cost and profit of the HPP in the considered markets for different values of temperature.

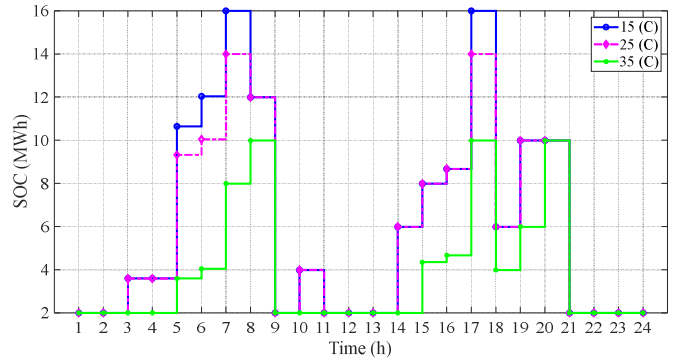


Fig. 6. SOC of the BESS for different values of temperature.

This highlights the significance of reducing the investment cost of BESS, as it enables the HPP to engage more actively in energy markets and maximize its profit.

Temperature is also an important factor that has a significant impact on calendar aging. A number of numerical experiments have been conducted to analyze the effects of different temperature values on the cost of degradation, the state of charge of the BESS, and the total profit of the HPP in the considered markets.

Fig 5. and Fig 6. compare the average degradation cost of the BESS, the profit in considered markets and the SOC of the BESS for different temperature values over 32 scenarios, respectively. As a result of increasing the value of temperature, the average degradation cost is experiencing an upward trend in contrast to the SOC of the BESS and the profit in markets.

For example, by increasing the value of temperature from 15 to 35, degradation cost increases by 38.54%, while the profit in the considered markets declined by 0.317%. This highlights that by decreasing the value of temperature, the SOC increases, and this allows the BESS to deliver more energy during discharge in the considered markets to achieve a higher profit. In addition, this emphasizes the importance of installing an efficient air conditioning system to prevent the BESS from overheating.

It is worth noting that as shown in Fig. 6, when the value of temperature rises, the SOC of the BESS declines to minimize the calendar aging.

IV. CONCLUSION

This paper proposes a deterministic model for maximizing the profit of a HPP by trading in the spot market, reserve, and energy in the secondary regulation reserve markets in the framework of the Spanish electricity market while considering the costs of battery cycle aging and calendar aging.

The numerical results demonstrate that considering calendar aging affects BESS charging and discharging strategies, resulting in a decrease in the state of charge of BESS to minimize the cost of calendar aging. Besides, by considering calendar aging, the total profit in the considered markets reduces.

In addition, the results of several sensitivity analysis show that the more the BESS' investment cost rises, the more the average of the degradation cost increases and the total profit of the HPP in markets will decrease. This underscores the significance of minimizing the investment expenses to increase the total profit of the HPP in the markets.

Finally, the experiments illustrated that if the value of temperature increases, the degradation cost of the BESS rises. As a result, the total profit of the HPP in markets will decline in the considered markets.

ACKNOWLEDGMENT

This work has been financed by the Spanish Ministry of Science, Innovation and Universities under the grant TED2021-132794B-C21.

REFERENCES

- [1] K. Das, A. L. T. P. Grapperon, P. E. Sørensen, A. D. Hansen, "Optimal battery operation for revenue maximization of wind-storage hybrid power plant," *Electric Power Systems Research*, vol. 189, 106631, 2020.
- [2] Q. Li, J. Wang, Y. Zhang, Q. Wu, C. Gu and Q. Yang, "Hierarchical market-based optimal planning of transmission network and wind-storage hybrid power plant," *International Journal of Electrical Power & Energy Systems*, vol. 153, 109328, 2023.
- [3] M. Amini, M. H. Nazari, and S. H. Hosseini, "Predictive energy management strategy for battery energy storage considering battery degradation cost," *IET Renewable Power Generation*, vol. 17, no. 5, pp. 1119-1138, 2023.
- [4] N. Gang, and B. N. Popov, "Cycle life modeling of lithium-ion batteries," *Journal of The Electrochemical Society*, vol. 151, no. 10, 2004.
- [5] D. Oliveira, L. Glória and R. Kraemer, "Mixed-Integer Linear Programming Model to Assess Lithium-Ion Battery Degradation Cost," *Energies*, vol. 15, 2002.
- [6] N. Padmanabhan, M. Ahmed and K. Bhattacharya, "Battery energy storage systems in energy and reserve markets," *IEEE Trans. Power Syst.*, vol. 35, no. 1, pp. 215-226, Jan. 2020.
- [7] B. Xu, A. Oudalov, A. Ulbig, G. Andersson, and D. S. Kirschen, "Modeling of lithium-ion battery degradation for cell life assessment," *IEEE Transactions on Smart Grid*, pp. 1131-1140, 2016.
- [8] C. Liu, H. Ma, H. Zhang, X. Shi and F. Shi, "A MILP-based battery degradation model for economic scheduling of power system", *IEEE Trans. Sustain. Energy*, vol. 14, no. 2, pp. 1000-1009, Apr. 2023.
- [9] D. Fernández-Muñoz, J. I. Pérez-Díaz. "Optimisation models for the day-ahead energy and reserve self-scheduling of a hybrid wind-battery virtual power plant," *Journal of Energy Storage*, vol. 57, p. 106296, 2023.
- [10] M. Amini, M. H. Nazari, and S. H. Hosseini, "Optimal energy management of battery with high wind energy penetration: A comprehensive linear battery degradation cost model," *Sustainable Cities and Society*, vol. 93, p.104492, 2023.
- [11] A. J. Conejo, J. M. Arroyo, J. Contreras and F. A. Villamor, "Self-scheduling of a hydro producer in a pool-based electricity market", *IEEE Trans. on Power Syst.*, vol. 17, no. 4, pp. 1265-1272, Nov. 2002.
- [12] M. Swierczynski, D.-I. Stroe, A.-I. Stan, R. Teodorescu and S. K. Kær, "Lifetime estimation of the nanophosphate LiFePO4/C battery chemistry used in fully electric vehicles", *IEEE Transactions on Industry Applications*, vol. 51, no. 4, pp. 3453-3461, July/August 2015.