Sizing Li-ion BESS for Participation in Ancillary Services With Consideration of Degradation Cost

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***Abstract*—For BESSs participating at the grid-level, lithium-ion (Li-ion) batteries are a promising technology for grid-scale applications due to their high energy and power density, flexible installation, and long life cycles. The main obstacle facing the expansion of BESSs is related to their high capital costs. Therefore, despite their technological advantages, there are still concerns about the economic feasibility of BESSs. This paper proposes a MILP optimization model to optimally size and schedule Li-ion batteries for grid-scale applications. This model's goal is to estimate long-term revenue accurately, by considering life cycles, degradation costs, and discharge rates when sizing and managing a BESS for grid applications. These factors are crucial to giving investors a longer-term comprehensive economic assessment. Frequency regulation and energy arbitrage are considered in this model for the generation of revenue. Additionally, the proposed model technique takes into account economic and technological factors, such as degradation costs and battery lifespan. PJM historical data is used in this simulation.**

***Index Terms*—battery size, frequency regulation market, ancillary services, arbitrage, reserved capacity.**

NOMENCLATURE

Indices

d Index for day.
h Index for hour.

Parameters

R_{dh}^{rmccp} Regulation market capability clearing price.
R_{dh}^{rmpcp} Regulation market performance clearing price.
S_{dh} BESS actual performance.
β_{dh} Mileage ratio.
$R\text{egD}_{dh}^{down}$ Normalized signal for frequency regulation down.
$R\text{egD}_{dh}^{up}$ Normalized signal for frequency regulation up.
E^{RC} Battery annualized energy rating capital cost.
P^{RC} Battery annualized power rating capital cost.
E_{max} Maximum energy rating for BESS.
E_{min} Minimum energy rating for BESS.
$C_{100\%}$ Cycle life at 100% depth of discharge.
P_{max} Maximum power rating for BESS.
P_{min} Minimum power rating for BESS.
L_{dh} Load.
M BESS maintenance capital cost.
lmp_{dh} Historical electricity price.
$I\text{n}$ BESS installation capital cost.
$D\text{OD}$ Depth of discharge of BESS.
$a_1 - a_4$ Coefficients of Li-ion battery degradation cost.
B_{cost} The total cost of a battery.
B_{size} The size of a battery.
$D\text{IR}_{max}$ Maximum discharging rate of BESS.
$D\text{IR}_{min}$ Minimum discharging rate of BESS.
k A coefficient from the slope of cycles vs. depth of discharge.
$S\text{oC}_{max}$ Maximum state of charge of BESS.
$S\text{oC}_{min}$ Minimum state of charge of BESS.

Variables

$P_{reg,dh}$ The actual power integrated into the frequency regulation market.
$P_{arb,dh}$ The sum of BESS's power.
B_{deg} BESS degradation cost.
B_{invs} BESS investment cost.
C Discharging cycles of BESS.
C_{DOD} Number of cycles at a specific depth of discharge.
$C\text{OD}$ Cost of degradation to a particular depth of discharge.
$D\text{IR}_{dh}$ Discharging rate of BESS.
E^R BESS optimal energy rating.
E_{dh} Energy stored in the BESS at each time interval in MWh.
P^R BESS optimal power rating.
$P_{arb,dh}^{ch}$ BESS charging capacity (bought) from the energy market.
$P_{arb,dh}^{dis}$ BESS discharging capacity (sold) into the energy market.
$P_{reg,dh}^{ch}$ Actual power charged into BESS from frequency regulation market.
$P_{reg,dh}^{dis}$ Actual power discharged from BESS into frequency regulation market.
$P_{res,dh}$ Power reserved for frequency regulation market.
$P_{sub,dh}$ Power exchange with the main grid.
R_{arb} Revenue from energy market when positive and cost of energy when negative.
R_{reg} Revenue from frequency regulation market.
$S\text{oC}_{dh}$ State of charge of the battery.
$S\text{oC}_{dis,dh}$ The state of charge at the end of a discharging operation.
u_{dh}^1 A binary variable associated with charging and discharging for energy arbitrage.
u_{dh}^2 A binary variable associated with participating in

frequency regulation market.

u_{dh}^{3} Binary variable associated with discharging process.

z_{dh}^{down} Binaries for ramp-down frequency regulation.

z_{dh}^{up} Binaries for ramp-up frequency regulation.

I. Introduction

The deployment of grid-scale BESSs in various grid applications increased after the Federal Energy Regulatory Commission issued FERC Orders 755 and 784. Investment in BESSs capable of performing grid applications then became more appealing to new investors and utilities because such systems could provide reliability and security to the power grid as well as generate high revenue to investors/operators. Since BESSs can function as both a power supply and a load at the same time, they are an excellent choice for grid support. Therefore, BESSs have been utilized for different grid applications due to their flexibility and fast response capability. More specifically, BESSs have been used in several grid-supporting applications, such as renewable resource integration, deferral of infrastructure upgrades, peak shaving, and ancillary services (i.e., frequency and voltage regulation). Various battery types can be used for BESSs being employed for grid-scale applications, including lead-acid, vanadium-redox flow (VRB), molten-salt, and lithium-ion. Moreover, each electrochemical combination possesses unique technical characteristics that make it particularly suited to fit a specific application. Costs of the different battery types vary [1].

The majority of installed U.S. BESS capacity comprises Li-ion, according to a report by the U.S. Energy Information Agency (EIA) [2]. The average cost of a BESS decreased by 72%, to around $589/kWh, between 2015 to 2019 [2]. Nevertheless, installing a Li-ion BESS is an expensive investment due to the high capital costs involved, especially in the case of a BESS sized for the grid. However, when a BESS is an essential part of a project – such as a data center or university campus – participating in the ancillary services markets can generate extra revenue for investors, which allows for the recovery of the initial high capital cost over a short period of time. When a BESS participates in the ancillary services markets, it can generate considerable revenue for stakeholders if sized and operated optimally. Sizing a BESS for stacked applications is a complicated process, since each application requires specific configurations. For example, high energy capacity is required for bulk energy applications, such as energy arbitrage. On the other hand, ancillary service applications – such as frequency regulation and voltage support – require high power capacity. Applications that require deep charging and discharging cycles, such as frequency regulation, can significantly affect BESS lifespan and increase BESS degradation rate. Thus, it is crucial to consider these unique factors when sizing, managing, and bidding BESSs for ancillary services. Even though the frequency regulation market is the most profitable application among grid applications, a 2020 market report by PJM illustrated that frequency regulation market-clearing prices fell by 15% compared to the previous year, due to the increase in competition. This emphasizes how important it is that investment in BESSs includes an optimal-sizing methodology and profitable management approaches that guarantee the highest possible revenue to cover initial costs/investment while also prolonging the lifespan of the BESS.

Much research has been conducted on optimal grid-scale BESS sizing where the impact on BESS lifespan is generally ignored. In [3], the BESS is scaled to provide spinning reserve for an isolated power system by modifying the state of charge restrictions but disregarding all other parameters. A similar approach is proposed in [4] to size a BESS for primary frequency control by optimizing the state of charge. This is problematic as such methodologies ignore the ramifications to BESS operating costs and lifespan. In [5], BESS control is introduced to manage the energy exchange between a wind farm with the MISO energy market for both Day-Ahead-Market (DAM) and real-time markets. The size of the BESS in this study is dependent upon the energy produced from wind, meaning the revenue generated is subject to weather conditions. In [6], an optimal location and sizing of a BESS with wind and solar distributed generation is proposed that considers several factors that affect BESS lifespan, such as degradation cost and temperature. However, in this study the BESS is primarily used for voltage regulation, which generates less revenue compared to that obtained by other grid applications. Recent studies conducted by [7] and [8] use MILP to size a BESS participating in the frequency regulation market, where [7] involves a grid-sized BESS while [8] involved a BESS for the microgrid. Both studies neglect critical considerations for calculating the size of a BESS, most significantly the degradation cost.

To our knowledge, no recent research or work has comprehensively sized Li-ion battery energy storage for stacked services that also considers degradation and discharging rate cost effects. In this work, we attempt to address this gap by developing a MILP-sizing methodology that includes the crucial factors ignored by the previous literature.

This paper discusses an economic study and proposes an optimization to determine the optimal size and schedule of a BESS for stacked services. The paper aims to solve the problem associated with BESS high capital costs, which are associated with the physical size of BESSs. The model takes into consideration essential factors, including degradation costs, life cycles, and depth of discharge. The remainder of the paper is organized as follows. Section II describes and explains the degradation cost approach and the model. Next, Section III describes the BESS case study presented in this paper and the results. Then, Section IV presents the conclusion and describes future work.

II. Outline of Model for BESS Sizing

This section discusses an economic study and proposes an optimization method for determining the optimal size and schedule of a BESS for stacked services. Our proposal aims to solve the problems associated with the high capital costs of BESSs, which are associated with their required physical size.

The model takes into consideration essential factors, including degradation cost, life cycles, and depth of discharge.

A. Degradation Cost Modeling

The degradation cost has a significant impact on BESS operation and scheduling. Considering degradation cost when sizing a BESS for ancillary services, especially frequency regulation, is essential to predicting overall revenue for investors. The cost of degradation calculation in this model depends on the depth of discharge and the discharging rate [9]. For the depth of discharge, it is essential to identify from which level exactly the BESS will start to discharge and at what level it will stop discharging. When the state of charge of the BESS is 100% of the rated energy capacity and the BESS is set to discharge to 70% of that, it is equal to a discharging rate of from 80% to 50%, but the second case (from 80%) is going to have a more negative effect on the BESS than will the first case (from 100% of the rated energy capacity) [10]. The depth of discharge and the number of cycles for a Li-ion battery at a specific discharging rate have almost a linear relationship to one another . Battery manufacturers estimate this relationship using several factors, which can be found at [9]. To express the number of cycles as a function of the depth of discharge and to estimate the degradation cost of a Li-ion battery as a specific discharging rate, the proposed methods in [11], [12] are used in this research. The degradation cost is expressed as a function of the state of charge and the discharging rate. The battery life cycles at a specific depth of discharge can be calculated using the following [12]:

$$C_{DOD} = (C_{100\%})e^{\alpha(1-DOD)} \tag{1}$$

The cost of degradation for a specific discharging rate *DIR* starting from full SOC:

$$COD(DIR) = \frac{B_{cost}\ DoD\ K}{B_{size} * 100} \tag{2}$$

k can be determined using the linearized slope of cycles life:

B. BESS Sizing Model

Equation (3) represents the primary objective function of this work, which is to minimize the capital investment and degradation costs and maximize the revenue from the energy arbitrage and frequency regulation markets. The income is subtracted from the objective function (3) because it is a minimization function.

$$min[B_{invs} + B_{deg} + R_{arb} - R_{reg}] \tag{3}$$

The annualized investment cost of the BESS is represented by (4). The cost is composed of the energy rating capital cost, the power rating capital cost, and the installation and maintenance costs. The maintenance and installation costs are presented regarding the power and energy rates, respectively.

$$B_{inv} = \left[P^R(P^{RC} + M) + E^R(E^{RC} + In)\right] \tag{4}$$

The BESS degradation cost function in (5) is dependent on the state of charge after discharging and the charging rate. The coefficients a_1 and a_2 represent the effect of the depth of discharge of the BESS's lifecycle, a_3 accounts for the impact of the battery discharging rate on lifecycle, and a_4 is the linearization offset, which is dependent on the BESS's size [10].

$$B_{deg} = \sum_d \sum_h \Big[a_1 SOC_{dis,dh} + a_2 SOC_{dis,d(h-1)} + a_3 DIR_{dh} + a_4\Big] \tag{5}$$

The revenue from the frequency regulation market is calculated using the PJM pay-for-performance payment method in equation (6). The total payment is made up of two payments: the regulation market capability clearing price (R^{rmccp}) and the regulation market performance-price (R^{rmpcp}). Both include performance scores but only the R^{rmpcp} includes a mileage ratio. The calculation of market ratio score and performance score depends on the regulation market signal. More details on this can be found in [13].

$$R_{reg} = \sum_d \sum_h \Big[S_{dh}(R^{\text{rmccp}}_{dh} + \beta_{dh} R^{\text{rmpcp}}_{dh})P_{res,dh}\Big] \tag{6}$$

Energy market costs is calculated using (7) and depends on the locational marginal price (LMP).

$$R_{arb} = \sum_d \sum_h \Big[lmp_{dh}\ P_{sub,dh}\Big] \tag{7}$$

Equations (8) and (9) limit the optimal size of the rated energy and power of the BESS, and this depends on the project budget.

$$P_{min} \leq P^R \leq P_{max} \tag{8}$$

$$E_{min} \leq E^R \leq E_{max} \tag{9}$$

The power for energy arbitrage may be obtained through charging (buying power from the grid when prices are low or charging from the frequency regulation market when the signal is negative) or discharging (selling to the grid when prices are higher). A binary variable u^1 is applied to ensure that the BESS is only charging or discharging. The energy arbitrage charging and discharging status and limits are represented in Equations (10) - (12).

$$P_{arb,dh} = P^{dis}_{arb,dh} + P^{ch}_{arb,dh} \qquad \forall d, \forall h \tag{10}$$

$$0 \leq P^{dis}_{arb,dh} \leq P^R u^1_{dh} \qquad \forall d, \forall h \tag{11}$$

$$-P^R(1-u^1_{dh}) \leq P^{ch}_{arb,dh} \leq 0 \qquad \forall d, \forall h \tag{12}$$

When participating in the frequency regulation market, a capacity is reserved P_{res}, and the BESS gets paid for the reserved capacity. The actual capacity is determined after receiving the signal from the market. The signal determines exactly how much from the reserved capacity will be charged or discharged from the BESS. Equation (13) limits and controls the reserved capacity for frequency regulation. The actual power for frequency regulation is calculated using equations (14) - (16). The frequency regulation signal $RegD$ in this model is divided into two parts in order to optimally calculate the cost of degradation, which, as mentioned previously, depends on the discharging capacity. The binary variables z^{down} and z^{up} determine when the BESS is charged and discharged during frequency regulation market participation. The following equations, (17) and (18), are the constraints of the regulation signal.

$$-u^2_{dh}P^R \leq P_{res,dh} \leq u^2_{dh}P^R \quad \forall d, \forall h \tag{13}$$

$$P_{reg,dh} = P^{dis}_{reg,dh} + P^{ch}_{reg,dh} \quad \forall d, \forall h \tag{14}$$

$$P^{dis}_{reg,dh} = RegD_d \; P_{res,dh} \; z^{down}_{dh} \quad \forall d, \forall h \tag{15}$$

$$P^{ch}_{reg,dh} = RegD_{up} \; P_{res,dh} \; z^{up}_{dh} \quad \forall d, \forall h \tag{16}$$

$$u^2_{dh} \; RegD_{up} \leq \; z^{up}_{dh} \leq 1 \quad \forall d, \forall h \tag{17}$$

$$u^2_{dh} \; RegD_d \leq \; z^d_{dh} \leq 1 \quad \forall d, \forall h \tag{18}$$

A new binary variable is introduced in the constraints for the state of charge after discharging. This binary variable determines the status when the BESS is discharging. The BESS is discharged in two cases: (a) when discharging its capacity (when u^1 = 1), and (b) when the grid frequency is down and the BESS discharges its reserved capacity to the grid (when z^{down} = 1). Thus, the new binary variable is the sum of the two discharging binary variables as follows:

$$u^1_{dh} + z^{down}_{dh} = u^3_{dh} \tag{19}$$

Equation (20) limits the state of charge at the end of the discharging operation. The calculation of its value is obtained by equation (21):

$$SOC_{min}E^R u^3_{dh} \leq SOC_{dis,dh} \leq SOC_{max}E^R u^3_{dh} \quad \forall d, \forall h \tag{20}$$

$$SOC_{dh}E^R - (u^3_{dh} - 1)SOC_{max} \leq SOC_{dis,dh} \leq SOC_{dh}E^R - (u^3_{dh} - 1)SOC_{min} \quad \forall d, \forall h \tag{21}$$

The discharging rate is limited by Equation (22) and obtained from Equation (23):

$$DIR_{min} \; u^3_{dh} \leq DIR_{dh} \leq DIR_{max} \; u^3_{dh} \quad \forall d, \forall h \tag{22}$$

$$(SOC_{d(h-1)} - SOC_{dh}) - (1 - u^3_{dh})DIR_{max} \leq DIR_{dh} \leq (SOC_{d(h-1)} - SOC_{dh}) + (1 - u^3_{dh})DIR_{min} \quad \forall d, \forall h \tag{23}$$

To ensure that the BESS is operating correctly (not charging and discharging at the same time or participating in both markets simultaneously), equations (24) and (25) are applied. The state of charge of the BESS is calculated using equation (26):

$$u^1_{dh} + u^2_{dh} \leq 1 \tag{24}$$

$$z^{up}_{dh} + z^{down}_{dh} \leq 1 \tag{25}$$

$$E_{dh} = E_{d(h-1)} + P_{arb,dh}\tau + P_{reg,dh}\tau \quad \forall t > 1 \tag{26}$$

$$E_{dh} = E^R + P_{arb,dh}\tau + P_{reg,dh}\tau \quad \forall t = 1 \tag{27}$$

The state of charge of the BESS is represented using power (28) and (29):

$$SOC_{min}u^3_{dh} \leq SOC_{dh} \leq SOC_{max}u^3_{dh} \; \forall d, \forall h \tag{28}$$

$$SOC_{dh} = SOC_{d(h-1)} + P_{arb,dh} + P_{reg,dh} \; \forall t > 1 \tag{29}$$

$$SOC_{dh} = P^R + P_{arb,dh} + P_{reg,dh} \; \forall t = 1 \tag{30}$$

To calculate the discharging cycles C, the following equations are applied:

$$C_{dh} = (u^3_{dh} - u^3_{(h-1)d})u^3_{dh} \quad \forall d, \forall h \tag{31}$$

$$\sum_d \sum_h C_{dh} \leq C_{max} \quad \forall d, \forall h \tag{32}$$

The balance equation for our model is represented as follows:

$$P_{sub,dh} + P_{arb,dh} + P_{deg,dh} = L_{dh} \tag{33}$$

III. Simulation and Results

In this section, the proposed model is tested using PJM historical data to determine the optimal BESS size for participation in the energy and regulatory markets. The model's objective is to determine the optimal power and energy ratings, as well as the appropriate maximum depth of discharge, to minimize degradation costs while maximizing overall income. Three cases are run so as to provide investors with a high-level perspective of each grid application as follows:

- **Case 1:** Sizing BESS for energy arbitrage only, frequency regulation only, and both markets, each without consideration of cost degradation.
- **Case 2:** Sizing BESS for frequency market only with consideration of cost degradation.
- **Case 3:** Sizing BESS for both markets with consideration of cost degradation.

The data for the BESS configuration used to determine the coefficients of Li-ion battery degradation cost are chosen based on the discussions in [10]. The cost of the BESS and the maximum/minimum power and energy ratings are chosen based on [7] and [8] to approximate the effect of the degradation cost as related to the size of the BESS as configured in this model. The regulation signal RegD is divided into two signals to calculate the discharging status when the BESS is performing frequency regulation down. This also allows us to accurately calculate the state of charge after discharging. The equations are implemented into GAMS and linearized using linearization of bilinear terms, as presented in Appendix A of [14]. The proposed model is solved in GAMS using CPLEX solver. The maximum and minimum state of charge of the BESS are set to be (90%-10%). The simulation is run for 12 days and uses 1 day from each month to represent a whole year of 2019. For the purposes of testing the model, for each case the loads from the 2019 PJM data are increased by 25%, to justify the incorporation of the BESS to support the load; the amount of power exchanged with the grid is limited to 2MW which is a real–world scenario where only 2 MW can be drawn from or sold to grid. The results are then converted to an annual figure, since the cost of the BESS also is determined as an annual figure.

Table (2) shows the detailed results of Case 1, where it can be seen that adding the BESS while only considering participation in the energy market is not optimal due to the high cost of investment, which must be a factor of consideration. For Case 2, see Table (3), the degradation cost is taken into consideration along with participation in the frequency regulation market only, meaning amounts of charging/discharging are reduced through optimized participation in frequency regulation, which results reducing energy rate size. Also presented on Table (3) are the findings of Case 3, which incorporated participation in both the energy arbitrage and frequency regulation markets to maximize revenue earning while also accounting for degradation costs, which again must be considered for real-world application by investors/operators. For Case 3, the total revenue by the end of this simulated year based on the 2019 PJM data would be $841,072. Although the numbers in Case 1 indicate a greater profit, Case 1 does not consider degradation costs, which must be integrated into any model in order for the model to have real-world application for investors/operators.

The reality is that degradation costs are a real-world factor that has simply been ignored in previous simulations. In addition, operating a BESS at maximum power is not feasible in the real-world context nor is failing to consider size limitations due to their impact on initial capital investment. Adding the degradation cost appropriately depicts the true cost of BESS operation, which provides investors with a more comprehensive understanding of the potential return-on-investment of BESSs. Furthermore, considering stacked application increases the BESS size as in Cases 1 (all) and 3 but resulted in annual profits of $1,069,670 and $841,072, respectively. These simulations (Cases 2 3) represent the true cost of degradation, which cannot be ignored because BESS efficiency declines over time, especially when participating in the profitable frequency regulation market where the signal must be followed. Finally, it is important to note that the optimal depth of discharge that results in the highest profits across all cases is the minimum, which is 10%.

IV. Conclusion

A grid-scale BESS-sizing optimization model is proposed that includes exhaustive and enumerative approaches that evaluate BESS configurations, including degradation cost, charging and discharging rates, cycles, stackable services, depth of discharge, and daily scheduling. The results show the revenue generated by participation in the frequency regulation market exceeds that of participating in the energy arbitrage market but also increases the degradation cost and effect on BESS lifespan. Future work could explore adding more applications and investigating other types of BESSs.

TABLE I
BESS Configurations

Max Power Rating (MW)	Max Energy Rating (MWh)	Power Rating Capital Cost ($/MW/yr)	Energy Rating Capital Cost ($/MWh/yr)	M ($/MW)	In ($/MWh)
10	20	18000	22000	50000	14000

TABLE II
Detailed Results of Case 1

Market	PR^R	E^R	c	R_{arb}($)	R_{reg}($)	B_{inv}($)
Arb	10	7.39	-	41,535	-	852,080
FR	10	13.643	7,110	-	2,016,258	1,302,285
All	10	16.5	6,960	631,871	1,945,799	1,508,000

TABLE III
Detailed Results of Cases 2 and 3

Case	PR^R	E^R	c	R_{arb}($)	R_{reg}($)	B_{deg}	B_{inv}($)
2	10	12.22	7,200	-	1,940,420	157,159	1,200,457
3	10	16.686	6,990	600,990	1,977,965	216,422	1,521,371

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