Optimal sizing of battery energy storage systems considering degradation and replacement in microgrids

Nguyen Quoc Minh*, Tran Van Dai, Nguyen The Nam,
Pham Minh Hoang, Nguyen Bich Ngoc, Nguyen Duc Chinh

School of Electrical and Electronic Engineering, Hanoi University of Science and Technology, 1 Dai Co Viet, Hai Ba Trung, Hanoi, Vietnam.

*Corresponding author: minh.nguyenquoc@hust.edu.vn

Received 31 Dec. 2024; Revised 18 Feb. 2025; Accepted 04 Apr. 2025; Published 15 Apr. 2025.

DOI: https://doi.org/10.54939/1859-1043.j.mst.102.2025.41-50

ABSTRACT

In recent years, the integration of Battery Energy Storage Systems (BESS) has played a crucial role in ensuring the reliability and efficiency of microgrids. This paper presents an optimal sizing model for BESS, considering operational degradation and replacement over the system's lifecycle. The proposed model integrates technical, economic, and environmental aspects in the operation of microgrids, while also accounting for the degradation rate of batteries. A Mixed-Integer Nonlinear Programming (MINLP) approach is used to minimize the total system cost, including investment, operation, and replacement costs, while satisfying constraints related to load demand, renewable energy integration, and system reliability. Simulation results demonstrate that the proposed optimal model is highly effective in determining both the capacity and installation cost of the energy storage system. Additionally, the model can support the development of efficient operation scheduling and management strategies for BESS.

Keywords: BESS; Microgrid; MINLP; Renewable resources.

1. INTRODUCTION

Battery Energy Storage Systems (BESS) are vital for advancing the transition to clean energy and incorporating renewable energy sources into power grids. In particular, as microgrids become more common, BESS facilitates energy balance between supply and demand, reduces reliance on fossil fuels, and improves grid reliability. Nonetheless, to maximize BESS capabilities, determining the optimal storage capacity is essential. The battery system's capacity directly impacts the initial investment cost while also being connected to operational effectiveness, lifespan and replacement expenses. Notably, the performance degradation of batteries over time and under various operating conditions is a critical consideration during the design and operation of the energy storage setup. As a result, developing a BESS capacity optimization model that incorporates both the technology and economics involved, and considers both the deterioration and replacement of batteries is necessary to ensure microgrid sustainability and economic viability.

Numerous recent studies have placed an emphasis on improving the capacity and operation of BESS in microgrids. Non-linear optimization techniques and regression analysis have been employed to minimize total expenses, meet energy demand and intergrate incorporating distributed generation sources. Nevertheless, this approach does not thoroughly take into account the degradation of battery performance during actual operation. A number of different studies have started incorporating lithium-ion battery degradation models.

This reveals that declining performance not only impacts operational costs but also increases the need for battery replacements, ultimately leading to higher long-term expenses than initially anticipated. The strategy of battery replacement and lifespan optimization has been integrated into the model in studies [4, 5]. However, these approaches remain limited in that they do not consider the influence of the BESS's state of charge or capacity on overall efficiency.

This research introduces a model designed to find the optimal size for a BESS. The model considers factors that cause performance degradation and includes a plan for replacing batteries at the right time to fully utilize the power from renewable energy sources. The model is tested on a microgrid that uses renewable energy and energy storage, aiming to develop realistic and sustainable energy management solutions for the system.

2. MINLP MODEL

2.1. Objective function

Selecting the appropriate BESS power and storage capacity involves considering both upfront investment and ongoing operational expenses to optimize economic benefits and enhance system reliability [6, 7]. This research develops a Mixed-Integer NonLinear Programming (MINLP) model to minimize investment and operational costs, penalties for load and renewable energy curtailment, and emissions penalties. Equation (1) presents the objective function for this optimized problem.

$$min\, C^I + C^O + C^{LS} + C^{CO_2} + C^{NO_X} + C^{PVcurt} + C^{Wcurt} \tag{1}$$

$$C^I = \sum_{b\in B}\left(C_b{}^P P_b{}^{BESS} + E_b{}^{ins} C^E + \sum_y C_y^{PW}\left[C_{by}^R + C_b{}^{o\&m} P_b{}^{BESS}\right]\right) \tag{2}$$

$$C^O = \sum_y \sum_t C_y^{PW}\left(\sum_{i\in G}\begin{bmatrix} a(P_{iyt}{}^G)^2 + bP_{iyt}^G + u_{iyt}c \\ +SUC_i y_{iyt} + SDC_i z_{iyt} \end{bmatrix} + C_{yt}^{ex} P_{yt}^{ex}\right) \tag{3}$$

P^{BESS} symbolizes the rated power output of the BESS, and E^{ins} indicates its energy storage capacity. The power generated by thermal power units is represented by P^G, P^{ex} signifies the power exchanged with the grid, and P^{LS} represents the load shedding power. The first element (2) of the objective function concerns initial investment costs for the storage system, C^I. This encompasses the cost of power capacity C^P, the cost of energy C^E, the cost of BESS replacement C^R, operation and maintenance expenses $C^{O\&M}$. The second part of the objective function is the operational cost including diesel generator operating expenses, Start-Up Costs (SUC), Shutdown Costs (SDC) for the generator and the cost of purchasing electricity from the grid C^{ex}[4]. The parameters a, b, and c denote the operating cost parameters of the diesel generator unit. Binary variables y and z respectively indicate the shutdown and startup statuses of the power units. This objective function also incorporates other expenses, such as emission costs (calculated as the product of emission quantities or curtailed power and penalization costs) [8, 9].

Since the BESS capacity calculation spans multiple years, future costs have to be brought to their present-day equivalent through the Net Present Value (NPV) discount function, $C^{PW} = (1+e)^{y-1}/(1+r)^{y-1}$, determined by the interest r and inflation rate.

2.2. MG grid constraints

Grid operation constraints include capacity balancing, load reduction limits, and grid exchange capacity limits.

$$\sum_{i\in\{G,W,PV\}} P_{iyt}^R + \sum_{i\in B}\left(P_{iyt}^{ch} - P_{iyt}^{dch}\right) + P_{yt}^{ex} + P_{yt}^{LS} = P^L \tag{4}$$

$$0 \le P_{yt}^{LS} \le P^{NCL} \tag{5}$$

$$0 \le P_{yt}^{ex} \le P_{max}^{ex} w_{yt} \tag{6}$$

$P^R$is the generating power of G diesel, W wind and solar PV power sources. $P^{ch/dch}$is the charge/discharge capacity of the BESS, and P^L is the value of the load. The cutoff load and exchange capacity with the grid are limited by constraints (5) and (6). In operation, non-critical loads P^{NCL} can be cut. The power exchanged with the dependent grid and the line from the main grid to the microgrid (less than the maximum capacity P_{max}^{ex}). w is the binary variable that represents the state of power exchange with the grid.

2.3. Diesel Generator Constraints

Diesel generator constraints include generating capacity constraints, capacity increase, and decrease constraints, operating time constraints, minimum breaks, and constraints between operational states [7].

$$P_{i,min}^{G}u_{iyt} \le P_{iyt}^{G} \le P_{i,max}^{G}u_{iyt} \qquad (7)$$

$$P_{iyt}^{G} - P_{iy(t-1)}^{G} \le r_{i}^{G,\,SU} \qquad (8)$$

$$P_{iy(t-1)}^{G} - P_{iyt}^{G} \le r_{i}^{G,SD} \qquad (9)$$

$$\sum\nolimits_{h=t}^{t+MUT_i-1} u_{iyh} \ge MUT_i y_{iyt} \qquad (10)$$

$$\sum\nolimits_{h=t}^{t+MDT-1}(1 - u_{iyh}) \ge MDT_i z_{iyt} \qquad (11)$$

$$y_{iyt} - z_{iyt} = u_{iyt} - u_{iy(t-1)} \qquad (12)$$

$$y_{iyt} + z_{iyt} \le 1 \qquad (13)$$

The generator output power P^G is limited by the maximum P_{max}^{G} and minimum P_{min}^{G} power values. Equations (8) and (9) limit the power between consecutive time intervals; The increase in generator power must be less than $r^{G,SD}$, and the decrease in generator power must be less than $r^{G,SU}$. The minimum operating/resting time interval is limited by equations (10) and (11). Constraints (12), (13) ensure that operating units can only stop and cannot start. The variable represents the operating state of the generator.

2.4. Gas emissions

To assess the impact of emissions such as CO_2 and NOx, empirical formulas (14) and (15) are used to calculate the amount of emissions generated from the power output $P_{iyt}^{G}$and the proportion of biofuel in the fuel mixture D_i [9].

$$CO_{2,iyt} = 0.7 + 2.7P_{iyt}^{G} + 0.8D_i + 0.005P_{iyt}^{G}D_i + 2.2 \times 10^{-5}D_i^2 \qquad (14)$$

$$NO_{x,iyt} = -0.25 + 181P_{iyt}^{G} - 2.7D_i - 2.9P_{iyt}^{G} + 0.0561D_i^2 \qquad (15)$$

2.5. Renewable energy curtailment constraints

These reductions are necessary to keep the power grid stable and secure, preventing overloads or significant imbalances. This curtailment is represented by constraints (16)-(17), ensures that the combined power from solar (P^{PV}) and wind (P^{W}), along with the curtailed power, remains below the forecasted power generation for solar (P^{PVfc}) and wind (P^{Wfc}) as described in reference [10].

$$0 \le P_{yt}^{PV} + P_{yt}^{PVcurt} \le P_{yt}^{PVfc} \qquad (16)$$

$$0 \le P_{yt}^{W} + P_{yt}^{Wcurt} \le P_{yt}^{Wfc} \qquad (17)$$

2.6. BESS constraints

BESS operating constraints are expressed by equations (18) – (24).

$$P_{b,min}^{BESS}z_b \le P_{b}^{BESS} \le P_{b,max}^{BESS}z_b \quad \forall b \in B \qquad (18)$$

$$E_{\min} \le E_{by}^{ins} \le E_{\max} \quad \forall b \in B, \forall y \qquad (19)$$

$$0 \le P_{byt}^{dis} \le P_{b}^{BESS}U_{byt}^{dis} \quad \forall b \in B, \forall y, \forall t \qquad (20)$$

$$0 \le P_{byt}^{ch} \le P_{b}^{BESS}\left(1 - U_{byt}^{dis}\right) \ \forall b \in B, \forall y, \forall t \qquad (21)$$

$$SOC_{byt} = SOC_{by(t-1)}\left(1 - \sigma_i\right) - \frac{P_{byt}^{dis}}{\eta_{bdis}} + \eta_{bch}P_{byt}^{ch} \quad \forall b \in B, \forall y, \forall t \qquad (22)$$

$$\left(E_{by}^{BESS} - \sum_{k}\frac{DOD_{bk}}{100}E_{by}^{BESS}\mu_{bk}\right) \le SOC_{byt} \le E_{by}^{BESS} \quad \forall b \in B, \forall y, \forall t \qquad (23)$$

$$\sum_k \mu_{bk} \le z_b \tag{24}$$

The rated power of the battery energy storage system (BESS), denoted as P^{BESS}, is constrained by its minimum power output P^{BESS}_{bmin} and its maximum power output $P^{BESS}_{b,max}$. A binary variable z ensures whether or not the BESS is in operation. Equation (19) restricts the nominal energy of the BESS, E^{ins}, to a range between its maximum capacity, E_{max}, and its minimum capacity, E_{min}. The BESS's charging/discharging power, $P^{ch/dis}$, must not exceed its rated power. With the binary variable U^{dis}_{byt} ensures the BESS's mode at time t, enforcing that it can only be either charging or discharging at any given time. The state of charge (SOC) of the BESS is calculated using equation (22) and must adhere to constraint (23) as detailed in reference [4]. Here, σ represents the self-discharge rate of the BESS, and $\eta_{ch/dch}$ represents its charging/discharging efficiency.

The relationship between maximum Depth of Discharge (DOD) and the number of life cycles is shown in figure 1. Therefore, in this study, a binary variable μ_bk is introduced to determine the maximum DOD k of the BESS b. Throughout the life cycle of the BESS, only one maximum DOD value is selected and shown in constraint (24).

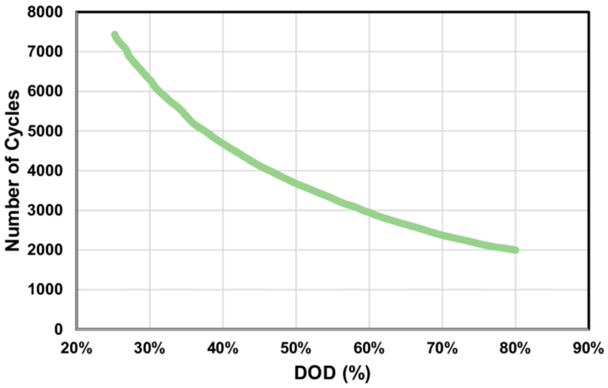

Figure 1. *BESS degradation based on DOD.*

Using the big M method, with M being a very large number, the nonlinear equation (20) is replaced by equations (25), (26) [4, 7].

$$0 \le P^{dis}_{byt} \le P^{BESS}_{b} \quad \forall b \in B, \forall y, \forall t \tag{25}$$

$$0 \le P^{dis}_{byt} \le U^{dis}_{byt} M \quad \forall b \in B, \forall y, \forall t \tag{26}$$

Similar to equation (20), the discharge power in equation (21) can also be linearized using the big M method. Therefore, the equation can be replaced by

$$0 \le P^{ch}_{byt} \le P^{BESS}_{b} \quad \forall b \in B, \forall y, \forall t \tag{27}$$

$$0 \le P^{ch}_{byt} \le \left(1 - U^{dis}_{byt}\right) M \ \forall b \in B, \forall y, \forall t \tag{28}$$

In the nonlinear equation (23), the multiplication $E^{BESS}_{by}\mu_{bk}$ is replaced by the variable N^{BESS}_{bky}, $N^{BESS}_{bky} = E^{BESS}_{by}\mu_{bk}$, the variable N^{BESS}_{bky} is bounded by the following equation:

$$0 \le N^{BESS}_{bky} \le M \mu_{bk} \quad \forall b \in B, \forall m, \forall y \tag{29}$$

$$\begin{aligned} & E^{BESS}_{by} - M\left(1 - \mu_{bk}\right) \le N^{BESS}_{bky} \\ & \le E^{BESS}_{by} + M\left(1 - \mu_{bk}\right) \quad \forall b \in B, \forall m, \forall y \end{aligned} \tag{30}$$

2.7. BESS replacement constraints

Due to its complexity, the lifespan of a BESS cannot be accurately predicted; However, the replaceable time can be determined based on the total discharge capacity.

$$SP_{by}^{dis} = SP_{b(y-1)}^{dis} + \sum\nolimits_t \frac{P_{byt}^{dis}}{\eta_{dis}} - SP_{b(y-1)}^{dis}\beta_{by} \;\; \forall b \in B, \forall y \tag{31}$$

$$SP_{by}^{dis} \le \sum_k CL_{bk} N_{bky}^{BESS} \;\; \forall b \in B, \forall y \tag{32}$$

$$RY_{by} = \beta_{by} y \;\; \forall b \in B, \forall y \tag{33}$$

The energy supplied to the grid from the time of SP^{dis} installation is calculated via equation (31) and this value must be less than the total available energy based on the maximum DOD calculated from the number of charge/discharge cycles CL (32). The replacement year RY is calculated via equation (33). The binary variable β_{by} represents the BESS replacement in year y. BESS will also be replaced when the operating years OP exceed its lifespan [11]. In this case, the replacement year is represented by constraints (34) – (36).

$$OP_{by} = OP_{b(y-1)} + \lambda_{by} - OP_{b(y-1)}\beta_{by} \; \forall b \in B, \forall y \tag{34}$$

$$OP_{by} \le FL_b \; \forall b \in B, \forall y \tag{35}$$

$$\lambda_{by} \le \sum_t \frac{P_{byt}^{dis}}{\eta_b} \le M\lambda_{by} \tag{36}$$

Equation (34) represents the number of years the BESS operates, with the binary variable λ_{by} taking a value of 1 for each operating year and 0 for non-operating years. This number of years must be less than the lifespan of the BESS, FL_b, as shown in equation (35). The operating years of the BESS are determined by its discharge power; if this power is non-zero, the binary variable λ_{by} will be 1, indicating that the BESS is operating.

2.8. BESS degradation

2.8.1. Calendar aging

Equation (37) defines the capacity fade over time, which helps predict remaining lifespan and plan maintenance, optimizing charge/discharge cycles to extend the lifespan and performance of the BESS [10].

$$Age_{byt}^{cal} = \left[\left(\frac{t}{720} \right)^{0.8} - \left(\frac{t-1}{720} \right)^{0.8} \right] \times \left(\alpha_1 SOC_{byt} + \alpha_2 E_{by}^{BESS} \right) \tag{37}$$

The capacity degradation, Age_{byt}^{cal}, for BESS unit 'b' at time 't' in year 'y' is calculated. This calculation is based on the degradation factors α_1 and α_2, as well as the SOC and capacity of the BESS in that particular year, represented by E^{BESS}.

2.8.2. Cycle aging

The performance degradation of a BESS, Age^{cyc}, can be approximated using equation (38). Within that equation, the parameters represented by n_0, n_1, n_0 and are factors used to adjust the lifespan curve.

$$Age_b^{cyc} = \frac{0.2 \times E_b^{ins}}{n_0 \times DOD^{n_1} \times e^{n_2 \times (1-DOD)}} \tag{38}$$

Equation (38), however, is a nonlinear equation, potentially complicating the problem and making it challenging to discover the optimal global solution. To address this, the state of charge (SOC) is redefined as SOC[%]=1-DOD[%], which allows equation (38) to be linearized by dividing SOC into N_s segments.

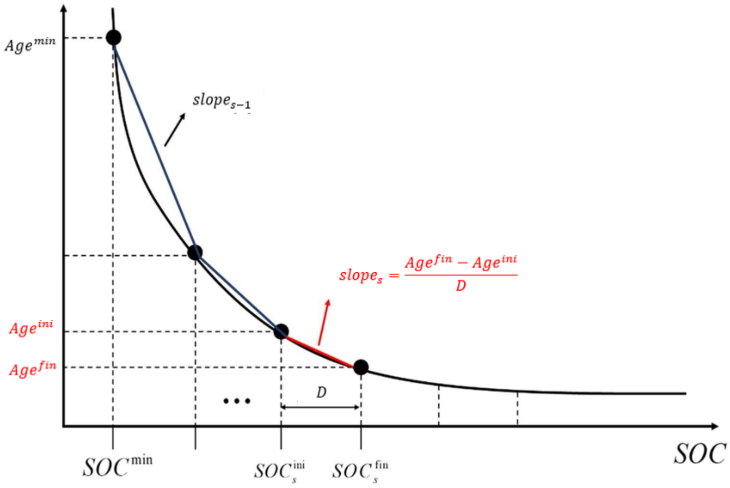

Figure 2. *Piecewise linearization of operational aging.*

$$SOC_b^{min}(\%) + \sum_{s=1}^{N_s} \begin{bmatrix} SOC_{byts}(\%) \\ +(s-1) \times D_b \times v_{byts} \end{bmatrix} = \frac{SOC_{byt}}{E_b^{ins}} \tag{39}$$

$$Age_{byt}^{cyc} = \sum_{s=1}^{N_s} \begin{bmatrix} v_{byts} \times Age_{bs}^{ini}(\%) \\ +slope_{bs} \times SOC_{byts}(\%) \end{bmatrix} \tag{40}$$

The BESS lifespan curve is divided into equal SOC segments, with the start and end points of each segment corresponding to the values Age^{ini}, Age^{fin} calculated via equation (38). Additionally, a binary variable v_{byts} is introduced to ensure the SOC value always remains within the permissible range for each segment. Equation (39) requires that the sum of SOC values across all segments equals the SOC value calculated through the charging/discharging process. Finally, the nonlinear equation (38) will be replaced by (40). However, the BESS charging/discharging process is an incomplete cycle charging/discharging process, therefore, the rainfall counting algorithm and the big M method are applied to calculate the degradation of the BESS during operation via equations (41) – (43).

$$y_{byt}^{BESS} - z_{byt}^{BESS} = u_{by,t+1}^{BESS} - u_{byt}^{BESS} \tag{41}$$

$$Age_{byt}^{cyc} \le \left(Age_{byt} - Age_{by,t-1}\right) + bigM \times \left(1 - u_{byt}^{BESS}\right) \tag{42}$$

$$Age_{byt}^{cyc} \ge \left(Age_{byt} - Age_{by,t-1}\right) - bigM \times \left(1 - u_{byt}^{BESS}\right) \tag{43}$$

2.8.3. BESS capacity

The BESS capacity is determined using equation (44) considering both calendar and cycle aging:

$$E_{by}^{BESS} = E_{b(y-1)}^{BESS} - \sum_t \left(Age_{byt}^{cyc} + Age_{byt}^{cal}\right) - \beta_{by}\left(E_{b(y-1)}^{BESS} - E_b^{ins}\right) \tag{44}$$

3. RESULTS

Table 1. *Source parameters.*

Power supply	Power (MW)	Power Ramp Limit	Minimum Up/Down Time Operation
Diesel	0.5-5	1	1
PV	0-0.5	-	-
Wind	0-13	-	-

Table 2. *Load parameters.*

	Peak (MW)	Important Load (%)	VOLL($/MWh)
Load	**9.24**	**30**	**50000**

The microgrid used in this study comprises one diesel generator, a PV system and a wind turbine system with parameters as shown in table 1. Load data and hourly power output of the components are taken from [12] and presented in table 2. The lifespan of the BESS depends on the DOD, as shown in table 3. The optimization model used is a MINLP model. The model calculates the project time for 10 and 15 years with total costs of $21.291 million and $29.775 million, respectively. Due to the significant wind energy resource, the BESS mostly charges/discharges according to the power output of the RES and the diesel generator only operates when both RES sources are insufficient and there is no reserve in the BESS.

Table 3. *BESS lifetime depending on DOD.*

DOD (%)	Charge/Discharge Cycle	DOD (%)	Charge/Discharge Cycle
20	3000	70	900
30	2075	75	825
40	1500	80	775
50	1175	85	700
60	1000	90	675
65	940	95	600

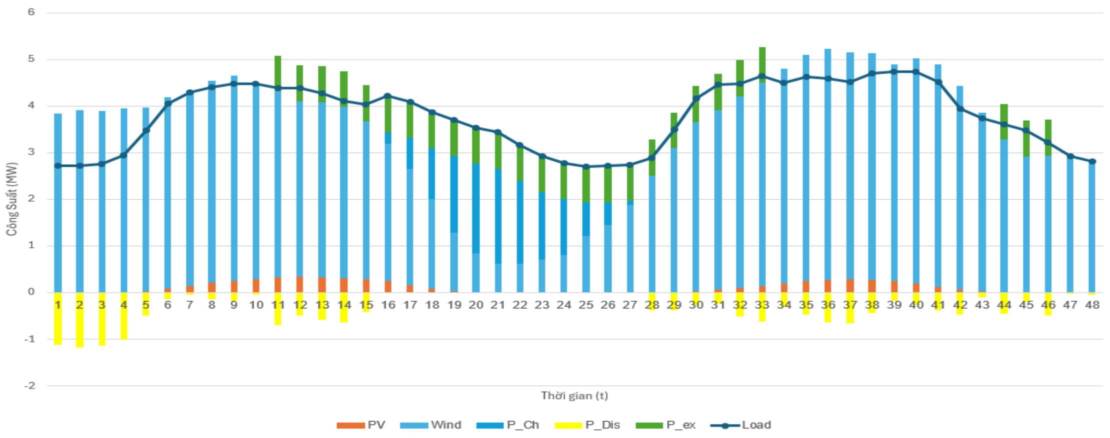

Figure 3. *Source power and load during surplus RES.*

The primary reason for this is that the model considers both the operational expenses of the generators and the costs associated with CO_2 and NO_x emissions, resulting in the microgrid minimizing the power drawn from diesel generators. This reduced reliance on diesel aligns with the increasing demand for greener energy options that lower emissions. Power flow from sources and loads within the grid are illustrated in figure 3 (surplus RES) and figure 4 (deficit RES). Figures 5 and 6 demonstrate the decline in source capacity over the years of operation. Due to equipment replacement, the capacity of the BESS system in the 15-year project will be restored to its initial level at the start of year 10. All projects fully utilize the storage capacity of the BESS.

Figure 4. *Source power and load during deficit RES.*

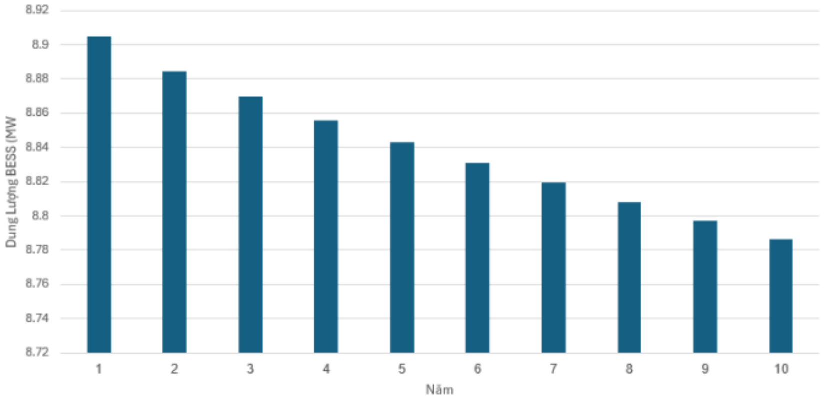

Figure 5. *Capacity degradation over a 10-year project.*

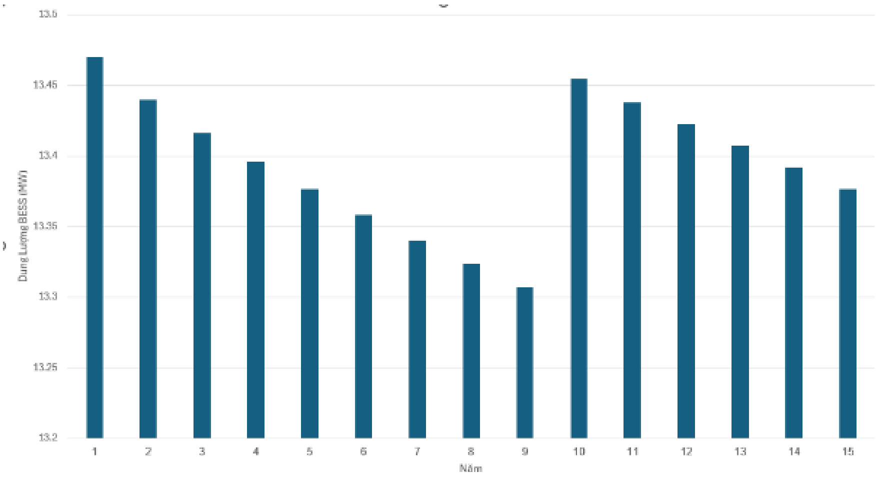

Figure 6. *Capacity degradation over a 15-year project.*

Table 4. *Comparison of project costs for 10-year and 15-year periods.*

Time (year)	IC (10^6 \$)	C^{LS} (10^6 \$)	OC (10^6 \$)	CO_2 (10^6 \$)	NO_x (10^6 \$)	Total cost (10^6 \$)	P (MW)	E (MWh)	DOD (%)	Replaced year
15	7.443	0	20.3	1.017	1.014	29.775	5.4	13.47	100	10
10	5.068	0	14.72	0.752	0.75	21.291	3.57	8.905	100	-

4. CONCLUSIONS

This study introduces a model for determining the optimal size of a BESS within a microgrid. The model considers the BESS's degradation based on the DOD and the environmental pollution caused by diesel generators. This model facilitates the calculation of the BESS size required to minimize overall system costs while significantly curtailing the use of environmentally harmful thermal power sources, opting instead for increased utilization of renewable energy resources. The results demonstrate a 35% reduction in diesel generator output compared to conventional models. The optimization problem is formulated as a MINLP which enables the incorporation of various influencing factors, leading to more realistic results than prior studies. In future work, the nonlinear model will be linearized to reduce computational burden and time. In addition, the load and renewable energy source uncertainties will be considered for actual conditions.

REFERENCES

[1]. P. V. Subbotin, Y. P. Gusev, and D. V. Dvorkin, *"Optimal BESS Sizing & Allocation for Transfer Capacity Increase in Distribution Grids"*, in 2020 3rd International Colloquium on Intelligent Grid Metrology (SMAGRIMET), Cavtat, Dubrovnik, Croatia: IEEE, pp. 1–6, (2020). doi: 10.23919/SMAGRIMET48809.2020.9263996

[2]. S. Jayashree and K. Malarvizhi, *"Methodologies for Optimal Sizing of Battery Energy Storage in Microgrids : A Comprehensive Review"*, in 2020 International Conference on Computer Communication and Informatics (ICCCI), Coimbatore, India: IEEE, pp. 1–5, (2020). doi: 10.1109/ICCCI48352.2020.9104131

[3]. M. Amini, M. H. Nazari, and S. H. Hosseinian, *"Optimal Scheduling and Cost-Benefit Analysis of Lithium-Ion Batteries Based on Battery State of Health"*, IEEE Access, vol. 11, pp. 1359–1371, (2023), doi: 10.1109/ACCESS.2022.3232282

[4]. M. Amini, A. Khorsandi, B. Vahidi, S. H. Hosseinian, and A. Malakmahmoudi, *"Optimal sizing of battery energy storage in a microgrid considering capacity degradation and replacement year"*, Electr. Power Syst. Res., vol. 195, p. 107170, (2021), doi: 10.1016/j.epsr.2021.107170

[5]. A. M. Alharbi, I. Alsaidan, and W. Gao, *"Sizing Li-ion BESS for Participation in Ancillary Services With Consideration of Degradation Cost"*, in 2022 IEEE Kansas Power and Energy Conference (KPEC), Manhattan, KS, USA: IEEE, pp. 1–6, (2022). doi: 10.1109/KPEC54747.2022.9814738

[6]. S.-M. Chen, M.-W. Yang, and L.-W. Lee, *"A new method for fuzzy multiple attributes group decision making based on ranking interval type-2 fuzzy sets"*, in 2011 International Conference on Machine Learning and Cybernetics, Guilin, China: IEEE, pp. 142–147, (2011). doi: 10.1109/ICMLC.2011.6016692

[7]. H. Xie, X. Teng, Y. Xu, and Y. Wang, *"Optimal Energy Storage Sizing for Networked Microgrids Considering Reliability and Resilience"*, IEEE Access, vol. 7, pp. 86336–86348, (2019), doi: 10.1109/ACCESS.2019.2922994

[8]. A. Khodaei, and M. Shahidehpour, *"Microgrid-based co-optimization of generation and transmission planning in power systems,"* IEEE Trans. Power Syst., vol. 28, no. 2, pp.1582-1590, (2013).

[9]. F. F. Nicolosi, J. C. Alberizzi, C. Caligiuri, and M. Renzi, *"Unit Commitment Optimization of A Micro-Grid With A MILP Algorithm: Role Of The Emissions, Bio-Fuels And Power Generation Technology,"* Energy Rep., vol. 7, pp. 8639–8651, (2021), doi: 10.1016/j.egyr.2021.04.020

[10]. Nguyen Quoc Minh, Nguyen Duy Linh, Nguyen Trong Khiem, *"A mixed-integer linear programming model for microgrid optimal scheduling considering BESS degradation and RES uncertainty,"* Journal of Energy Storage, Vol. 104, Part B, pp. 114663, (2024).

[11]. Y. Yang, H. Li, A. Aichhorn, J. Zheng, and M. Greenleaf, *"Sizing Strategy of Distributed Battery Storage System with High Penetration of Photovoltaic for Voltage Regulation and Peak Load Shaving"*, IEEE Trans. Smart Grid, vol. 5, no. 2, pp. 982–991, (2014), doi: 10.1109/TSG.2013.2282504

[12]. J. Muehlenpfordt, *"Time series"*. Open Power System Data, (2019). doi: 10.25832/TIME_SERIES/2019-06-05

TÓM TẮT

Mô hình tối ưu dung lượng hệ thống pin lưu trữ năng lượng xét đến sự suy giảm vận hành và thay thế trong lưới điện siêu nhỏ

Trong những năm gần đây, việc tích hợp hệ thống pin lưu trữ năng lượng (BESS) đóng vai trò quan trọng trong việc đảm bảo độ tin cậy và hiệu quả của lưới điện siêu nhỏ. Bài báo này trình bày một mô hình tối ưu dung lượng BESS xét đến sự suy giảm vận hành và thay thế trong suốt vòng đời của hệ thống. Mô hình đề xuất tích hợp các khía cạnh kỹ thuật, kinh tế và môi trường trong vận hành lưới điện siêu nhỏ, đồng thời xem xét tốc độ suy giảm của pin. Phương pháp quy hoạch phi tuyến nguyên thực hỗn hợp (MINLP) được sử dụng để tối thiểu hóa tổng chi phí của hệ thống, bao gồm chi phí đầu tư, vận hành và thay thế, trong khi vẫn đáp ứng các ràng buộc về nhu cầu tải, tích hợp năng lượng tái tạo và độ tin cậy của hệ thống. Kết quả mô phỏng cho thấy mô hình tối ưu đề xuất mang lại hiệu quả cao trong việc xác định dung lượng và chi phí lắp đặt hệ thống lưu trữ năng lượng bằng pin (BESS). Đồng thời, mô hình có thể hỗ trợ xây dựng kế hoạch lập lịch vận hành và quản lý BESS một cách hiệu quả.

Từ khóa: BESS; Microgrid; MINLP; Năng lượng tái tạo.