Techno-economy study of battery energy storage system for electricity grid peak generation

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Abstract. Indonesia’s new and renewable energy mix in 2025 is objective at least 23%, and 31% in 2050 requires PLN to look for alternative sources of power supply as a substitute for fuel generation besides increasing new and renewable energy power plants. Advances in technology provide choices of power resources for PLN, one of Battery Energy Storage System (BESS) technology, where this technology can be used as a substitute for diesel power plant with a comparable level of services. Therefore, a study of the Levelized Cost of Electricity (LCOE) calculation is needed to determine the economic feasibility obtained by calculating the Net Present Value (NPV) of investment, maintenance, and operating costs during the plant’s lifetime. The simulation resulted in the Levelized Cost of Electricity for Battery Energy Storage System that substitutes diesel engine generating with 5MW power capacity to supply grid electricity. During peak-load is 13,996.77 for Li-Ion Battery and 27,321.38 IDR/kWh for Redox Flow Battery, which is higher than diesel engine generating set as the impact of high investment cost.

1. Introduction

Energy is a basic human need today to support various activities. Today, electrical energy is increasingly being used and is more widely used than other energy forms. Data from the Indonesian government shows an increase in electricity consumption from year to year in the industrial and household sectors [1]. The increase in electricity consumption by the community demands that PLN as the sole business owner in Indonesia, be able to meet the community’s electricity needs, which is useful for supporting economic, social, and cultural activities [2].

Electrical energy is channeled through the network from power plants to distribution channels. In the distribution process, electrical energy is supplied through the network that connects the electric energy generator with the load. One of these connected systems’ characteristics is that supply and demand must be balanced to maintain reliability, stability, and electrical energy [3]. If there is an increase in demand, then the supply must be added and vice versa. Therefore, we recognize that there are baseload generation plants and peak load generation plants for system operational flexibility. Peak load generators are generally supplied by the plant to supply instant energy, such as gas and fuel-based power plant.

One of the problems that arise from generating electrical energy is the emission of exhaust gases resulting from the combustion of primary energy, even though the government has set an emission threshold that is safe for the environment. In the future, the world will move towards zero-emission by using renewable energy generators to sign the Paris Agreement.
The signing of the Paris Agreement by several countries has changed the paradigm towards the use of more environmentally friendly energy, in the case of Indonesia. The target of Indonesia's new and renewable energy mix in 2025 is at least 23% and 31% in 2050 [1][2] as the implementation of the agreement requires PLN which is engaged in electricity services to look for alternative sources of electricity as a substitute for diesel-fuel based generation. The IEA research data mention that Petroleum Oil releases 0.75 ~ 0.8 kg CO$_2$ per kWh [4].

The development of research in Battery energy storage (BESS) technology rapidly grows and significantly increases the maturity level. Battery energy storage systems can store excess power when the load is low and supply energy during peak load [5]. Also, it improves the quality and reliability of electric power systems with its ability to produce electrical energy output instantaneously [5]. Including a backup of renewable energy generation that is intermittent [3]. Capital costs of BESS construction is projected to fall by 21-67% in 2030 and 31-80% in 2050 [6], so that in long-term electricity planning, the use of BESS needs to be considered an alternative. However, the environment’s impact should evaluate the possibility and technical-economic factors [7].

Piece of research on Battery Energy storage rapidly grow and become a mature technology. The biggest problem of implementing BESS is economically expensive compared to other technologies with similar technical capability, but with some advantages described by Lawder. In their research, BESS should consider one of the alternatives like Fast and flexible construction because it can be built anywhere that requires little land improvement, does not cause pollution during operation, has a high response capability with high energy density and high efficiency [8]. Research by Christian Joubert [9] found that BESS’s use in Europe provides an advantage by optimizing BESS’s location and capacity could yield higher capacity factors by simulation. Previous research by Manasseh Obi [10] has provided a formula for calculating LCOE for several types of energy storage by including incentives and taxes imposed by the government. Research by Marvin Killer [11] found that Li-Ion battery’s implementation for energy storage is minimal rather than its potential due to an uneconomical price. For the technical capability of BESS, inverter base connection allows reactive supply power in addition to active power to the power grid.[5]

This work presents the measurement feasibility of BESS implementation in the Electricity Grid System from the economic side by calculates the minimum selling price of electricity produced. The electricity tariff is obtained by simulating the Levelized Cost of Electricity (LCOE). LCOE is defined as the net present value (NPV) of all costs that may occur, starting from project construction (investment) and operation (operation and maintenance cost). Simulate during the equipment lifetime with a financial parameter divided by the amount of electrical energy that can be sold, resulting in a minimum electricity tariff so that all projected costs can be returned.

2. Method

The building model of LCOE conducted this simulation. These are a general method to evaluate the economic feasibility of the project. Technical parameters cannot be separated from this economic simulation that illustrates the operation and defines the electricity that can be produced. The calculation of LCOE used is to calculate Net Present Value (NPV) evaluation of investment costs, operating, and maintenance costs, that simulated during the power plant lifetime. NPV is used to get the value of an investment in the future, calculated at present. [10]. The calculation results are the basic cost of providing electrical energy in IDR / kWh units. The basic Principle of LCOE is given in the figure below.
The basic concept of LCOE adapted from “The Economics of Wind Energy” [12].

LCOE obtains by calculating Net Present Value (NPV) over the lifetime of the BESS operation, considering investment costs, operating costs, and maintenance costs as well as charging costs. The Investment cost is spent on Battery Capital Expenditure from preparation to completion of construction. The amount of construction cost depends on the capacity of the storage system being built. Bigger capacity means that there is more battery should be bought to build the BESS System. Cost as an impact of financing term also added to this cost component. Some of the most influencing aspects are project funding methods such as loan portion, loan interest, and the repayment period.

The operation and maintenance cost calculation is divided into 2 (two), fixed costs and Maintenance Variable costs. Maintenance Fixed cost can be defined as fixed costs such as expenses for operators, expenses for scheduled maintenance, and routine spare parts purchases. Whereas variable costs such as spending on equipment spare parts that run out quickly depending on the amount of production energy. Operation cost that may vary depending on technology and operating pattern.

Charging costs is closely related to the efficiency of using the battery itself. As we know, the battery will store energy obtained from the grid and will release it stored energy when needed. However, not all the grid’s energy charges can be discharged again because of the battery losses. The measure of the number of losses in battery operation we call a function of efficiency is the electricity ratio that supplies electricity input to the battery. Since the battery cannot generate energy, the charging cost is also affected by electricity prices that charge the battery. Therefore, we can formulate the LCOE model into the following [13]:

$$LCOE = \sum_{t=1}^{n} \left( \frac{I_t + M_t + C_t}{1 + r} \right)^t$$

$$I_t = Investment \ Cost \ at \ year-t \ (include \ cost \ of \ capital),$$

$$M_t = Operation \ and \ maintenance \ cost \ at \ year-t,$$
\( C_t \) = Charging cost at year-\( t \),  
\( E_t \) = Net Electricity Production/sealable electricity at year-\( t \),  
\( r \) = Discount rate,  
\( n \) = Life time

Equation (1) can be split into each component. One of the components is Investment cost.

\[
I_t = C_{p,E} \times Cap_{nom,E} + C_{p,P} \times Cap_{nom,P} \tag{2}
\]

Where,

\( I_t \) = Investment Cost at year-\( t \) (include the cost of capital),  
\( C_{p,E} \) = Specific Energy Cost (IDR/kWh)  
\( C_{p,P} \) = Specific Power Cost (IDR/kW)  
\( Cap_{nom,E} \) = Nominal Energy Capacity, state the energy storage capacity (kWh)  
\( Cap_{nom,P} \) = Nominal Power Capacity, state the Power output capacity (kW)

for the maintenance fixed and variable cost, defined as follows

\[
\sum_{t=1}^{n} \frac{M_t}{(1+r)^t} = \sum_{t=1}^{n} \frac{(FOM_t \times Cap_{nom,P}) + (VOM_t \times CyC_{pa} \times DOD \times Cap_{nom,E} \times (1-CyC_{Deg})) \times CyC_{pa} \times (1-T_{Deg})}{(1+r)^t + T_c} \tag{3}
\]

\( M_t \) = Operation & Maintenance Cost at year-\( t \) (IDR)  
\( FOM_t \) = Fixed maintenance Cost at year-\( t \) (IDR/kW)  
\( VOM_t \) = Variable maintenance cost at year-\( t \) (IDR/kWh)  
\( CyC_{pa} \) = Cycle per annum, state the charge-discharge activity count per year (cycle/year)  
\( Cap_{nom,E} \) = Nominal Energy Capacity, state the energy storage capacity (kWh)  
\( Cap_{nom,P} \) = Nominal Power Capacity, state the Power output capacity (kW)  
\( DOD \) = Deep of Discharge represents the amount of energy discharged (% capacity)  
\( CyC_{Deg} \) = Degradation cause by Cycle (% capacity / cycle)  
\( T_{Deg} \) = Degradation cause by time (% capacity / year)  
\( T_c \) = Construction Time (year)

The amount of energy for charge the storage must meet adequate supply for discharge required both power and energy amount after considering losses, where there is a function of Round-Trip Efficiency (RTE). For the charging cost formula, we obtain by.

\[
\sum_{t=1}^{n} \frac{C_t}{(1+r)^t} = \sum_{t=1}^{n} \frac{1}{\eta_{RT}} \times \sum_{t=1}^{n} P_{el,t} \times \frac{E_t}{(1+r)^t} \tag{4}
\]

\( C_t \) = Charging cost (IDR)  
\( P_{el} \) = Electricity Price (IDR/ kWh)  
\( \eta_{RT} \) = Round-Trip Efficiency (%)  
\( E_t \) = Net electricity generation at year-\( t \), (kWh)  
\( r \) = Discount rate, (%)  
\( n \) = Life time (year)

For the discounted sealable electricity, use the formula as follow.

\[
\sum_{t=1}^{n} \frac{E_t}{(1+r)^t} = CyC_{pa} \times DOD \times Cap_{nom,E} \times \eta_{RT} \times (1 - \eta_{self}) \times \sum_{t=1}^{n} \frac{(1-CyC_{Deg})(1-CyC_{pa})(1-T_{Deg})}{(1+r)^t + T_c} \tag{5}
\]
\[ E_t = \text{Energy Produced at year } - t \text{ (kWh)} \]
\[ Cy_{pa} = \text{Cycle per annum} \text{ (cycle/year)} \]
\[ Cap_{nom,E} = \text{Nominal Energy Capacity (kWh)} \]
\[ DOD = \text{Deep of Discharge} \text{ (% capacity)} \]
\[ \eta_{RT} = \text{Round Trip Efficiency} \text{ (%)} \]
\[ \eta_{self} = \text{Self Discharge} \text{ (% capacity)} \]
\[ Cy_{Deg} = \text{Degradation cause by Cycle} \text{ (% capacity / cycle)} \]
\[ T_{Deg} = \text{Degradation cause by time} \text{ (% capacity / year)} \]
\[ T_c = \text{Construction Time} \text{ (year)} \]

The sizing of the nominal Capacity of BESS, not only power capability but also storage capability. BESS energy capacity as a function of RTE and Deep of Discharge obtained by the following formula [14]:

\[
\text{BESS Capacity} = \frac{\text{Power Required}[MW] \cdot \text{Duration Required}[h]}{\text{Deep of Discharge} [\%] \cdot \text{Round Trip Efficiency} [\%]}
\] (6)

2.1 Grid Opportunity and Service Requirement

This simulation’s case study is the South Sulawesi Grid System that covered 3 Province, including South Sulawesi, Central Sulawesi, and South-East Sulawesi, with several conditions below [2][15].

| Parameter                  | Unit | 2019  | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 |
|---------------------------|------|-------|------|------|------|------|------|------|------|------|------|
| Electricity Production    | GW h | 8458  | 1028 | 1153 | 1267 | 1431 | 1556 | 1687 | 1815 | 1953 | 2112 |
| Peak Load                 | MW   | 1411  | 1757 | 2027 | 2234 | 2550 | 2778 | 3013 | 3187 | 3382 | 3611 |
| Load Factor               | %    | 68    | 67   | 65   | 65   | 64   | 64   | 64   | 65   | 66   | 67   |

*adjusted to updated data

Table 2. South Sulawesi electricity production based on primary energy 2019.

| Primary Energy | Energy (GWh) |
|----------------|--------------|
| Coal           | 4381         |
| Natural Gas    | 1332         |
| Hydro          | 1586         |
| Wind Turbine   | 480          |
| Diesel Fuel    | 476          |


Figure 2. Average 2019 Daily Load Curve South Sulawesi Grid.

The demand for electricity in Sulawesi is projected to grow, as shown in Table 1. Diesel-fuel generators partly supply during the current condition, the supply of electricity. Therefore, an alternative supply of electricity is needed to support emission reduction. The data gave in Table 1 also shows the load factor, which is the ratio of power during peak load to average power is below 70%, which in electricity term indicates that a power supply with fast response and high operating flexibility is needed to supply peak load. The differences between Peak Load and average load is illustrated in Figure 2.

2.2. LCOE Calculation assumption

Handbook of Battery Energy Storage that published by Asian Development Bank (ADB) differentiate BESS technology-based of energy density, charge and discharge efficiency (Round Trip Efficiency) and life span[14], the cost of Battery Energy Storage for each technology obtain from report by Pasific Northwest National Laboratory [16]. Base on this work, we can use the data from this reference, as shown in Table 3.

| Parameter                              | Li-Ion Battery | Redox Battery | Flow |
|----------------------------------------|----------------|---------------|------|
| Project Capital Cost                   |                |               |      |
| - Powerbase (USD/kW)                   | 1,876          | 3,430         |      |
| - Energy base (USD/kWh)                | 469            | 858           |      |
| O&M Fixed (USD/kW-year)                | 10             | 10            |      |
| O&M Variable (cents/kWh)               | 0.03           | 0.03          |      |
| Round Trip Efficiency (RTE)            | 0.86           | 0.67          |      |
| Annual RTE Degradation Factor          | 0.50%          | 0.40%         |      |
| Life Span (years)                      | 10             | 15            |      |
| Cycle at 80% Deep of Discharge (DoD)   | 3,500          | 10,000        |      |

The currency used in this simulation stated in IDR, the exchange rate is cost-sensitive because the electricity price quote in IDR; it easy for us to compare the result with the existing electricity tariff. LCOE calculation uses the technical parameter at Table 3 for Li-Ion Battery and Redox Flow Battery. A Financial parameter that is commonly used by PLN to evaluate project feasibility is shown in Table 4.
Table 4. Financial assumption.

|                        |                  |
|------------------------|------------------|
| Loan Portion           | 70%              |
| Equity Portion         | 30%              |
| Interest Rate          | 8% p.a.          |
| Repayment Period       | 10 year          |
| Exchange Rate          | IDR 14,500 /USD  |
| Discount Factor        | 9.8%             |
| O&M Price Escalation   | 1% p.a.          |
| Electricity Price for charging | IDR 810.76*   |
| O&M Price Escalation   | 1% p.a.          |

* Production Cost from Must Run Hydro Power Plant

This simulation assumed a diesel generating set with 5 MW capacity and 4-hour duration replaced by BESS to supply electricity to the grid.

3. Results and discussion

Table 5. BESS sizing and Discounted Energy Production.

|                          | Li-Ion Battery | Redox Flow Battery |
|--------------------------|----------------|-------------------|
| BESS Power Capacity (MW) | 5              | 5                 |
| Required BESS Energy Capacity (MWh) | 29.4 | 37.3 |
| Discounted Total Energy Production (MWh) | 27,062 | 27,062 |

Table 6. Result of Simulation.

| Parameters                          | Li-Ion Battery | Redox Flow Battery |
|-------------------------------------|----------------|--------------------|
| Levelized Investment Cost (IDR/kWh) | 11,877.73      | 25,199.13          |
| Levelized Operation & Maintenance Cost (IDR/kWh) | 761.64 | 762.80 |
| Levelized Charging Cost (IDR/kWh) | 1,357.4        | 1,359.45           |
| LCOE (IDR/kWh)                      | 13,996.77      | 27,321.38          |

The LCOE resulting in BESS’s electricity tariff is 13,996.77 IDR/kWh for Li-Ion Battery and 27,321.38 IDR/kWh for Redox Flow Battery. The most significant part of LCOE is Investment cost, where takes account 85% for Li-Ion Battery up to 92% for Redox Flow Battery. Maintenance cost becomes the biggest also cause by the NPV factor is 1. The investment cost should be pay in advance of the project.
The operation and maintenance cost slightly different between these two kinds of Batteries. Also, it applies to charge costs because the two types of batteries’ energy are the same. The result of LCOE simulation is costly compared to The necessary production costs of diesel engine generating sets in the range of 3200 – 3400 IDR/kWh depending on the location [15].

4. Conclusion
The result of LCOE calculation both for Lithium-Ion Battery or Redox Flow Battery is not visible when applied. From the simulation obtained, the use of BESS will increase the operating burden for PLN. However, the Battery Energy Storage System’s use to substitute Diesel Engine Generator will decrease CO₂ emission by 20.2 tons up to 21.64 tons if we used the assumption given by [3].

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