Proceedings of the 10th World Congress on New Technologies (NewTech'24)
Barcelona, Spain - August 25-27, 2024
Paper No. ICERT 110
DOI: 10.11159/icert24.110

Battery Depth-of-Discharge Optimization for Maximized Return in Electricity Markets

Lamya Al Qahtani[1], Munirah Aldossary[2], Fadia El Hamami[3], Ala A. Hussein[4]
Department of Electrical Engineering
Prince Mohammad bin Fahd University
Khobar, Saudi Arabia
[1]alqahtanilamya20@gmail.com; [2]Munirah_Aldossary@yahoo.com; [3]fadialeena@hotmail.com; [4]ahussein@pmu.edu.sa

***Abstract* -** This paper presents insights on optimizing the operation of batteries used in electricity markets to maximize their economic feasibility. Various depth-of-discharge (DOD) values are considered and evaluated. Besides the cycle life, the calendar life is also considered in the proposed model. Derivation of the model followed by simulation results are presented.

***Keywords*:** Depth-of-discharge (DOD), economic feasibility, electricity markets, energy storage, lithium battery.

1. Introduction

Using large-scale batteries in electricity markets has several benefits. The study in [1] details these advantages which include an enhanced and reliable system, flexibility in the grid, as well as support for the growth of renewable energy sources. Grid-level large-scale electrical energy storage (GLEES) allows for balancing the generation of electricity in terms of supply and demand. According to [2], storage systems should satisfy the needs of GLEES which offer emergency action, peak shaving, and regulation in terms of frequency and voltage. Significant benefits of large-scale battery storage are that it ensures grid stability, enables seamless integration of intermittent renewables, manages peak loads efficiently, and provides ancillary grid services. Moreover, it reduces reliance on fossil fuels and promotes a sustainable energy future while generating cost savings and revenue through participation in energy markets [3].

However, the cost of the battery is yet a major obstacle. Hence, enhancing the battery's performance is key to maximizing its economic value. It is known that batteries age at different rates depending on many factors such as the operating temperature and the charge and discharge rates. As the battery ages, its capacity or state-of-health (SOH) degrades resulting in reduced capacity and hence declining cycle capacity. Often, the battery service life is confused by the cycle life or the calendar life. The cycle-life refers to the number of cycles the battery can achieve before replacement. It is found that cycle life is inversely related to the depth of discharge. In other words, batteries with a higher depth of discharge and more frequent discharges will have fewer cycle lives. For example, a battery that consistently discharges 80% will have fewer cycles compared to one that discharges only 20%. Therefore, it is generally not recommended to fully discharge a battery as it significantly reduces its cycle life [4].

The calendar life refers to the battery's anticipated lifetime before it must be replaced and is independent of the cycle-life. It represents the total lifespan of the battery, regardless of the number of charge and discharge cycles it experiences. Calendar life is particularly relevant for applications with infrequent use or long-term storage, as factors like temperature, humidity, and storage conditions can impact the battery's performance over time. High temperatures can accelerate the aging process and lead to a reduction in overall battery performance [5]. In fact, the $LiFePO_4$ battery has a temperature range of up to 70 degrees Celsius [6]. Due to these environmental factors, the battery will slowly age even if it is not used. Once the calendar life is reached, the battery must be replaced.

In general, batteries can have a wide range of cycle life and a calendar life. For example, $LiFePO_4$ batteries have a cycle life lasting between 1,000 and 3,000 charge and discharge cycles and a calendar life of five to ten years [7]. When comparing $LiFePO_4$ and lead-acid batteries in grid applications, there are notable differences. $LiFePO_4$ batteries have a longer cycle life. Similarly sized lead-acid batteries typically range from 200 to 1,000 cycles, assuming the depth of discharge is within recommended limits for both battery types [7]. In terms of calendar life, $LiFePO_4$ batteries also outperform lead-acid batteries, with lead-acid batteries generally having a shorter lifespan influenced by factors such as temperature, charge and discharge rates, and depth of discharge. If the lead-acid battery is used frequently, it is expected to last for around two years [8]. In general, $LiFePO_4$ batteries, specifically the LFP type, are known for their higher cycle life, energy density, energy efficiency, and lower maintenance compared to lead-acid batteries [9].

This paper focuses on the depth-of-discharge (DOD) as a crucial parameter to consider when using batteries due to its significant impact on service life, performance, cycle life, and overall longevity. DOD refers to the amount of energy drawn from a battery relative to its total capacity, typically expressed as a percentage. The DOD is dictated by the upper and lower state-of-charge (SOC) cutoffs used by a battery management system. Also, it can be calculated as the ratio of the energy drawn from the battery to its total capacity. Practically, high DOD shortens the cycle-life of the battery. That is, the battery reaches its service life earlier than anticipated. The article in [10] examines the effect of DOD on the cycle life of a $LiFePO_4$ battery. The study shows that at the early cycles, there is no relationship between the DOD and the cycle life because the battery capacity changed uniformly at different DOD. However, in later cycles, it was clear that at a larger DOD, the decay of the battery's capacity is greater, and the battery life is reduced at a quicker pace. Batteries subjected to deep discharges may have a shorter cycle life compared to those with shallower discharges.

This paper is an attempt to maximize the battery's economic value by identifying the best DOD value when the battery is used in an electricity market for peak shaving. Different DOD values including 90%, 80%, and 70% are evaluated on a hypothetical $LiFePO_4$ battery used for grid storage. Details on the model followed by simulation results and conclusions are presented.

2. Proposed Model

The SOH curves shown in Fig. 1 are considered where each curve corresponds to a DOD value.

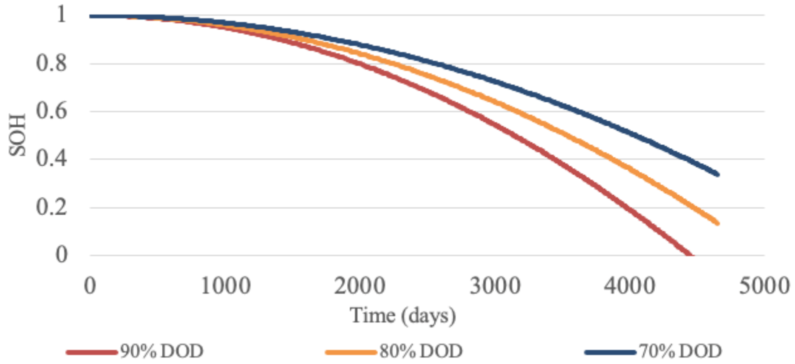

Fig. 1: SOH curves used to assess the economic feasibility of the battery.

The graph in Fig. 1 shows the nature of the SOH curves based on different DOD values. Assuming all scenarios begin with a 100% SOH, it is clear that at a higher DOD, the SOH degrades more quickly. For example, at 90% DOD, the SOH reached 0% after about 4,500 days whereas at 80% DOD, the state of health reaches 0% after around 5000 days. This pattern can be observed across all the different DOD values. The curves were created using the following equation:

$$SOH = 1 - \alpha N^2 \tag{1}$$

Where α is a coefficient, typically between 0.5 and 0.95, that may be determined experimentally and varies in each DOD scenario, and N is a number that gradualluy varies bewteen 0 (brand new battery) to 1 (completely dead battery) and may also be determined experimentally,

Table 1 shows the assumption made to validate the proposed model.

Table 1: Assumptions made for model validation.

Battery cost	$ 300,000.00
Battery initial capacity	1000 kWh
Calendar life	8 years
SOH cutoff	60%
Average spot market electricity price during demand peak	0.5 $/kWh

The energy that can be discharged by the battery (E_{out}) can be expressed using equation 2 (in kWh):

$$E_{out} = (E_0) \cdot (DOD) \cdot (\mathrm{SOH}) \tag{2}$$

Where E_0 is the initial capacity for a brand-new battery in kWh.

Assuming the initial capacity is 1000 kWh and that the battery calendar life is 8 years, the energy discharged by the battery at a specific DOD and SOH value can be easily found. Taking the sum of all the Eout values for each DOD scenario over 8 years (2920 days) will provide the total energy delivered by the battery (Etotal). Using equation 3, it is now possible to find the battery cost per kWh

$$\text{Battery Cost Per KWh} = \frac{\text{Battery Cost}}{E_{total}} \tag{3}$$

This parameter can provide insights into the efficiency and cost-effectiveness of the battery. It provides insights into the battery performance, reliability, and other relevant factors to support and help in the decision-making about its suitability for a particular application.

3. Results

Plotting the battery cost per kWh based on the DOD scenario gives the graph shown in figure 2.

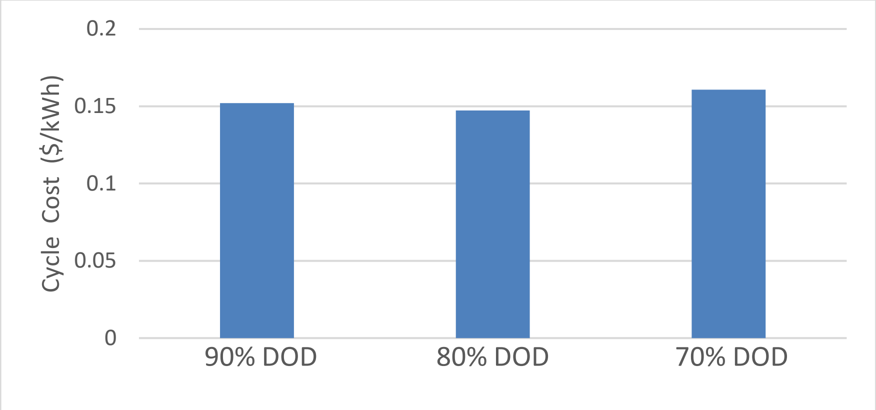

Fig. 2: Battery cost per kWh values based on DOD.

When looking at the data used in this study, it can be seen that in the first case, the battery reaches its service life when its SOH hits the predetermined 60% cutoff. This means in the case of 90% DOD, after being discharged to 90% of its capacity multiple times, the battery's health deteriorates to a point where it is no longer considered useful, even though it might still have some remaining capacity. It is noticed that the SOH reaches 60% before the eight-year calendar life ends. The SOH becomes 60% after 2529 days, which corresponds to an estimated duration of around 7.2 years.

In the other cases with DOD levels including 80% and 70, the battery's lifespan concludes after 8 years. This duration represents the battery's calendar life, serving as a clear indication of the need for replacement. For instance, in the case of an 80% DOD, the state of health declines to 60% after approximately 3164 days, translating to an estimated operational period of around 8.6 years. As established in figure 1, it is clear that as the depth of discharge is reduced, it takes more time for the SOH to reach 60%.

To optimize the return and profit, a comprehensive analysis was conducted. For each DOD case, the total kWh discharged from the battery (Etotal) was calculated. Additionally, the cost per kWh of the battery was determined by equation 2 above. To find the return value, equation 4 can be used.

$$\text{Return} = (\text{Average Spot Market price} - \text{Battery Cost per kWh}) \times E_{total} \tag{4}$$

Finally, the profit was determined using equation 5:

$$\text{Profit} = \text{Return} - \text{Battery Cost per kWh} \tag{5}$$

Based on the calculations, the cost per kilowatt-hour (kWh) was determined. The values can be summarized as shown in Table 2:

Table 2: Values for each DOD Scenario

DOD	**Total kWhs out of the battery (kWh)**	**Battery per kWh cost ($)**	**Return ($)**	**Profit ($)**
90%	1,973,537	0.152	686,791	386,791
80%	2,036,844	0.147	719,006	419,006
70%	1,866,698	0.161	632,811	332,811

Note that the profit calculated excludes other costs such as the cost of the inverter, cables, thermal management, protection equipment, maintenance, safety, etc. Even if these costs are considered, the scenario with 80% DOD will still be the most profitable because it will have the lowest cost and highest power generation. The graph in figure 3 gives a clear comparison of the profits calculated.

The column chart presented above shows a comparison of return and profit amounts for different depths of discharge cases. The x-axis represents the DOD Cases, while the y-axis represents the amount in dollars. Each column in the chart corresponds to a specific DOD case, with the blue columns indicating the return amounts and the orange columns representing the profit amounts. The height of each column corresponds to the respective return or profit value.

According to the figure shown above, as the DOD changes, the return fluctuates. At a DOD of 90%, the return is $686,791 and the profit is $386,791. As we move to a lower DOD of 80%, the return rises to $719,006, resulting in a profit of $419,006. Further decreasing the DOD to 70%, the return decreases slightly to $632,811 and yields a profit of $332,811.

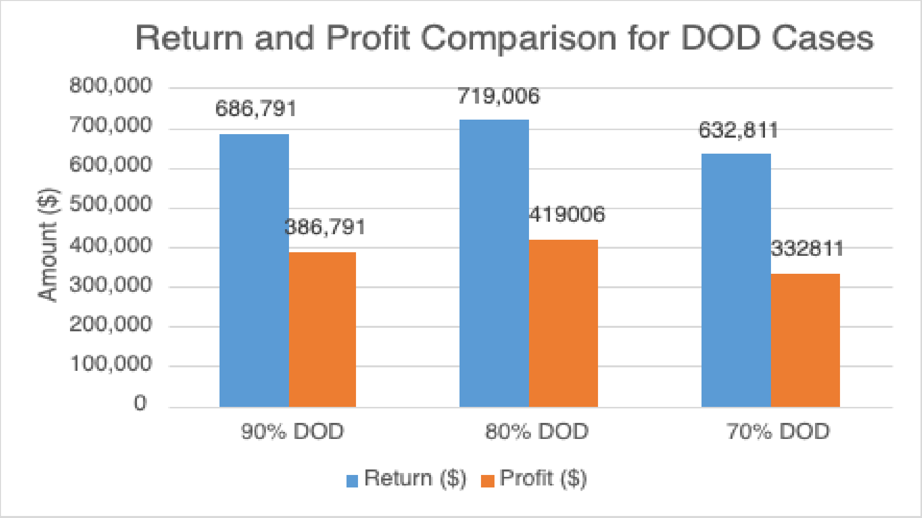

Fig. 3: Return and Profit Chart

4. Conclusion

After observing the effect of different DOD scenarios, it was noticed that in the case of 90%, DOD, the battery reaches its service life when its SOH hits the predetermined 60% cutoff. However, for the other cases (80% and 70% DOD), the battery reaches its service life after the calendar life is reached. In other words, the relationship between the DOD and the calendar life is an inverse relationship. After calculating the profits from each scenario, it was found that the most economic case occurs when the battery's depth of discharge is at 80%. This area of research has a big potential, and the selected parameters can be modified according to the battery chemistry and characteristics. With more information on the SOH curves and the aging mechanism of batteries, the selection of the most economic DOD can be further optimized.

References

[1] Wang, J., Yang, X., Chen, Z., & Wang, Z. (2019). *A review of state of charge estimation methods for lithium-ion batteries in electric vehicles.* Applied Energy, 253, 113542.
[2] Chen, H., Chen, Y., & Chen, Z. (2019). *A review of lithium-ion battery state of charge estimation and management system in electric vehicle applications.* Journal of Power Sources, 438, 226976.
[3] Utilities One. (n.d.). *Large Scale Battery Storage Systems Balancing Renewable Energy Supply*.
[4] Foxtron Power Solutions. (n.d.). *Depth of Discharge*.
[5] Grepow. (n.d.). *Lithium-ion Battery Cycle Life VS. Calendar Life VS. Shelf Life.*
[6] PowerTech Systems. (n.d.). *Lithium Iron Phosphate (LiFePO4).*
[7] Ark Corporation US. (n.d.). *Deep Cycle LiFePO4 vs. Lead Acid - Pros and Cons.*
[8] PowerTech Systems. (n.d.). *Lead Acid Battery Downsides & Maintenance*.
[9] Chen, X., Wang, X., Zhong, L., & Wu, Y. (2021). *A Review of State of Charge Estimation for Lithium-Ion Batteries Based on Fractional Order Techniques*. Applied Sciences, 11(3), 1099.
[10] Jiang, J., Sun, S., & Liu, X. (2017). *Review of lithium iron phosphate (LiFePO4) batteries*. Materials, 10(3), 314.