INVESTMENT DECISION-MAKING USING PROBABILISTIC LIFE CYCLE COSTING – COMPARING FLOODED LEAD-ACID AND LITHIUM ION BATTERIES FOR POWER SUPPLY BACKUP IN SUBSTATIONS

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ABSTRACT

During a power outage, substations require a power supply back-up in form of batteries to resume the control functionality. Traditionally, Flooded Lead-Acid (FLA) batteries are utilized in substations as power back-up. Even though new battery technologies have emerged, it is still the battery of choice. Lithium-Ion (Li-Ion) batteries have found wide acceptance in other areas but rarely as power back-up in substations. This is due to the high initial investment costs and the lacking experience in operation. In this study, we compare the FLA and Li-Ion batteries with a probabilistic life cycle analysis that considers both the capital costs and operational costs occurring over the whole life cycle. Applying probabilistic models and Monte Carlo simulations, the net present value can be presented as a distribution. The resulting distribution considers the risk and uncertainties in the input parameter and therefore enables a better decision-making. The results of this study show that the Li-Ion battery has the lower average life cycle costs with a lower uncertainty.

INTRODUCTION

The implementation of Smart Grid technologies into the power system has enabled distribution system operators to control and monitor distributed generation as well as their power system equipment in substations. It enables a wide range of new functions such as a self-healing compared to the traditional power system [1]. The self-healing functionality provides automatic responses to system disturbances and is a failure protection mechanism. To restore parts of a system after an outage has occurred, circuit breakers or disconnectors in substations can isolate the fault. However, during an outage the external power supply of a substation is interrupted which would disable the self-healing and control functionality and result in safety threats. Therefore, substations are required to have a power supply backup in form of battery banks. In Sweden, the most common battery type is the Flooded Lead-Acid (FLA) battery in substations [2, 3]. Thus far, this battery type has been selected due to its reliable service and cost efficiency. However, during the FLA battery life cycle, maintenance in regular intervals and additional training for technicians is required. The cumulative maintenance cost are often higher than the actual investment of the battery itself [4]. Moreover, lead-acid batteries pose a risk to a catastrophic failure [4]. Hence, other battery types such as Lithium Ion (Li-Ion), which are already common in many electronic appliances, can be an alternative to the traditional FLA batteries in substation, particularly when focusing on the life cycle costs. Reference [4] lists these costs as acquisition, administrative, battery investment, transportation, storage, installation, commissioning, regular inspection, discharge testing to verify functionality and to predict remaining lifetime, decommissioning, removal, and disposal costs. The aforementioned costs can be divided into capital expenditures (CAPEX) and operating expenditures (OPEX). The lifetime costs can be estimated with some accuracy depending on the time the costs occur, generally, the estimation accuracy decreases for costs in later lifetime stages. However, the estimation of unforeseen costs such as catastrophic battery failure costs are more difficult to predict, but are important for life cycle cost (LCC) analysis [4].

LCC analysis is a tool to compare and evaluate different technologies or investments based on the total lifetime costs. This is of particular interest for an asset manager who seeks to minimize the overall costs of an asset. A review and comparative LCC analysis of batteries as electrical storage systems has been conducted in [5]. The results suggest that cost estimations are rather dispersed and inconsistent among different sources. Uncertainty in cost estimations are not solely due to uncertain sources, but also due to the prediction of future costs and risks. One approach to account for such uncertainties is the application of probabilistic models in LCC. However, reference [5] shows that solely one out of twenty-seven publications applied probabilistic models when comparing energy storages, which is [6]. In probabilistic life cycle cost (PLCC) analysis, probability distributions are assumed for different input variables to account for the uncertainty. Using Monte Carlo simulations, the calculated LCC is not a deterministic value but rather a (LCC) distribution.

In this study, FLA batteries and Li-Ion batteries for power supply backup applications in substations are compared based on their general characteristics, strengths, and risks but primarily on their LCCs. Information about both battery types have been gathered through literature reviews and interviews with distribution and transmission system operators. PLCC analysis is applied to determine which battery is most cost effective for the system operator. The paper is structured as follows: The next section describes the importance of considering

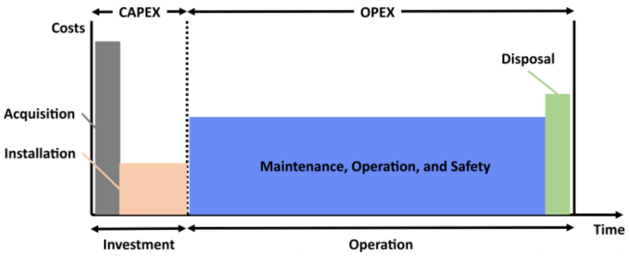

Figure 1: Abstract illustration of costs occurring during life cycle of an asset

all LCC instead of just the CAPEX and presents the method of PLCC analysis. This is followed by comparing the FLA and Li-Ion batteries in an illustrative case study. The last section concludes the work.

PROBABILISTIC LIFE CYCLE COST ANALYSIS

LCC is a tool which accommodates for all costs during the lifetime of an asset plus the initial costs for purchase, installation, and delivery. In fact, it accounts for CAPEX and OPEX which is illustrated in **Figure 1**. **Figure 1** shows that for certain assets the actual costs are occurring in later lifetime stages while the asset is in operation and are greater than the initial CAPEX. Neglecting the OPEX would bias any investment decision making particularly when deciding between two different or new and old technologies, such as in the later battery case study.

Life Cycle Cost Analysis

LCC analysis is a tool to determine the most cost-effective alternative among a variety of possible solutions to acquire. Since all costs during a life cycle must be considered, but the decision to invest is made at time *t*=0, we have to account for the time value of money by calculating the net present value (NPV). Generally, the net present value is calculated with

$$NPV(i,N)=\sum_{t=0}^{N}\frac{C_t}{(1+i)^t} \qquad (2.1)$$

where C_t denotes the cost in year t, i represents the discount rate, and N the scenario length. Since the cost is defined as a positive value in eq. 2.1, the investment is cost-effective if the NPV is minimised.

An alternative approach to compare the investments is to assess the stream of annual payments during the life cycle. Firstly, the NPV is calculated considering all LCCs using eq. 2.1. The annual stream of equivalent costs is calculated with

$$A(i,N)=NPV*\frac{i(1+i)^N}{(1+i)^N-1} \qquad (2.2)$$

where $i(1+i)^N/(1+i)^N-1$ is called the capital recovery factor. Likewise the investment decision-making with the NPV, we seek to choose the annual cost which is minimised.

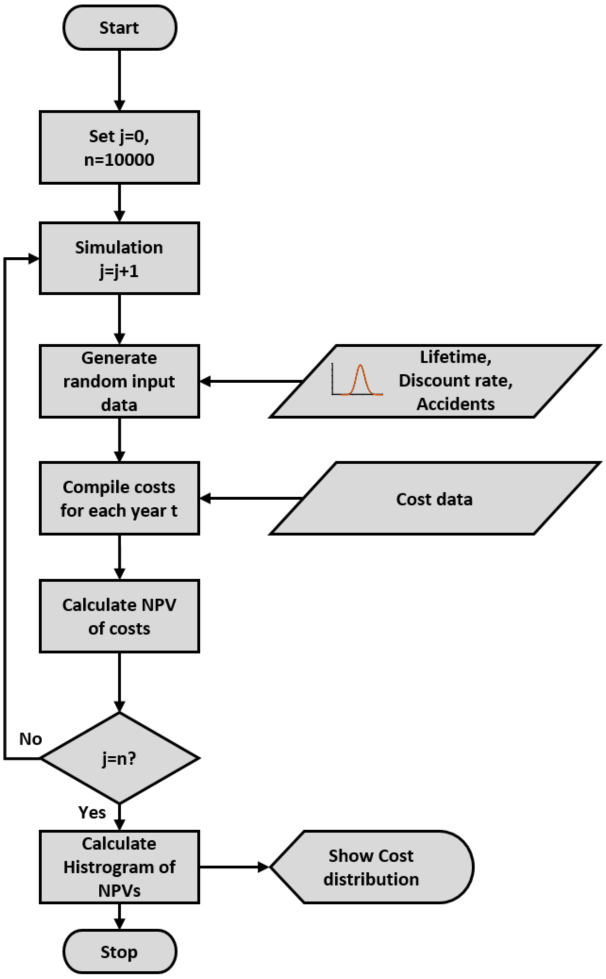

Figure 2: Simplified flow chart of probabilistic life cycle cost analysis

Probabilistic Models

The traditional LCC approach is deterministic and hence does not reflect any uncertainty in the input parameters such as lifetime and discount rate, for example. Combing probabilistic models and Monte Carlo simulations with the traditional LCC approach, the result becomes probabilistic with a cost distribution. This distribution visualises the uncertainty in the input parameter and provides the decision maker with additional insights. The general method is illustrated in a flow chart in **Figure 2**. Firstly, the number of iterations *n* is chosen with *n*=10000. Secondly, the probabilistic input parameter are generated from related distributions such as a Weibull or Normal distribution. Thirdly, all costs are compiled for each year *t* and the NPV is calculated. The result is stored and the process is conducted again until 10000 iterations are completed. The NPV of these iterations can be visualised with a histogram and parameters such as average NPV, the standard deviation, and confidence interval, can be calculated to provide a better overview of the investment costs and uncertainty.

CASE STUDY

Substations rely on power back-up batteries to restore the

Table 1: Characteristics of FLA and LI-ION Batteries [7]

	FLA	Li-Ion
Voltage increments (V)	2.23	3.70
Expected lifetime in [years]	12-15	>20
Maintenance	Yes	No*
Robustness	Yes	No
Temperature sensitivity in [°C]	>25	>45
Operation Temperature [°C]	+15 to +25	+18 to +30
Energy Density in [Wh/L]	80	250
Specific Energy in [Wh/kg]	30-50	100-250
Charging efficiency in [%]	80-85	100

*However, BMS- Battery Management System is required

power system after an outage. Therefore, these batteries must be reliable. Traditionally, FLA batteries are used in substation back-up power supply applications in Sweden [2, 3]. FLA batteries have met system operators service requirements in the past and thus are the battery of choice [4]. However, different battery types have emerged over the last decades such as Li-Ion, which is common type in many electronic applications nowadays. Even though Li-Ion batteries have a higher energy density and can be operated in higher temperatures, there are solely a few cases where Li-Ion batteries have been applied in substations due to their high investment costs and the little operational experience. Particularly these high initial investment costs have become an obstacle, although maintenance costs are lower and the risk of a catastrophic failure is significant lower compared to FLA batteries [4]. **Table 1** presents the general characteristics of FLA and Li-Ion batteries and **Figure 3** depicts the battery lifetime models modelled with Weibull distributions.

Substation Standby Power Requirements

The steady state standby 110 V DC current requirements for a 132 kV substation are 40A for 6 hours [8]. In fact, 240.6 Ah multiplied with the 110 V gives the captivity of 26.5 kWh required. These requirements are assumed for this case study.

Life Cycle Costs for Flooded Lead-Acid Batteries

To fulfil the requirements, twenty 6V FLA batteries with 224 Ah are necessary. Ensuring redundancy, two battery banks with twenty batteries each are installed for an estimated acquisition cost of 150000 SEK [9]. The installation is assumed to take four days, where each working day is 8 hours and each working hour costs 600 SEK. In total, the installation costs are 28800 SEK. After several month, a commissioning control is performed to ensure the functionality. In addition, a similar guarantee control is conducted after two years of operation. Both require five working days. A capacity test is done in the fifth, seventh, and ninth year. Thereafter, the capacity test is conducted every year until replacement. For FLA batteries, visual inspection takes place every month for 0,5 h to discover leakages, loose bolts, temperature changes, or ventilation defects, for example. Moreover, twelve litres of deionised water is required for the battery banks annually, where the litre is estimated with 12.5 SEK/litre and adding the water requires two working hours [9]. The residual value of the batteries is 3,5 SEK/kg and having forty batteries with 46 kg each, we get 6440 SEK. Note that costs are assumed positive so the residual value is negative in the LCC analysis. Accidents are estimated to cost 21600 SEK, which is mainly the replacement of the technicians for 3 working days per accident. The probability of accidents is modelled with a negative binomial distribution with the parameters r=0.1 and p=0.7. This results in a probability of P(0)=0,965, P(1)=0,03, and P(2)=0.005.

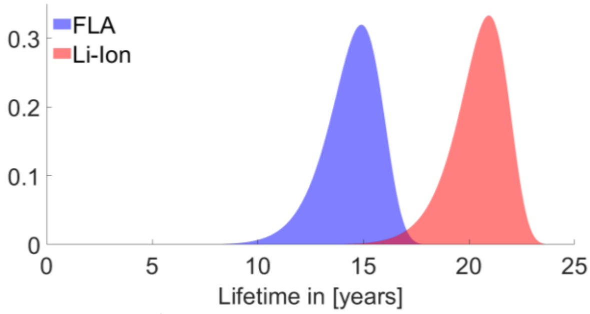

Figure 3 Battery lifetime models based on Weibull distributions with α=15 and β=13 and α=21 and β=19 for the FLA lifetime distribution (blue) and the Li-Ion lifetime distribution (red), respectively.

Life Cycle Costs for Lithium-Ion Batteries

Installing twenty-five 12V Li-Ion batteries with 90Ah each covers the required power back-up. Considering two battery banks again, the acquisition costs are 224700 SEK. The installation requires eight working days and a Battery Management System (BMS) is required for a total of 13500 SEK. As aforementioned, there is no maintenance required for Li-Ion batteries, however, a visual inspection similar to FLA batteries is conducted every month. In contrast to the FLA batteries, Li-Ion batteries have a residual cost of 36 SEK/kg. Each Li-Ion battery is 15kg and having fifty batteries results in a residual cost of 27000 SEK.

General Assumptions

The market interest rate is assumed to have an average of 4,55 % according to [10] and we assume that the interest rate has a normal distribution with a standard deviation of 2.4 and is truncated to a range of 1 to 12 %. The LCC analysis is conducted twice with a ten and a thirty-five year scenario length, which would represent a short-term and long-term investment.

Results

The results of the PLCC analysis are shown in **Figure 4** and **Figure 6** for NPV calculation of the 10 and 35 year scenario, respectively. The NPV distribution parameters are presented in **Table 2**. In both scenarios, the mean of NPV distribution of Li-Ion batteries is smaller compared to the FLA battery. The standard deviation (SD) for the Li-Ion battery is smaller as well, which shows that the uncertainty in the NPV is lower. The higher uncertainty of

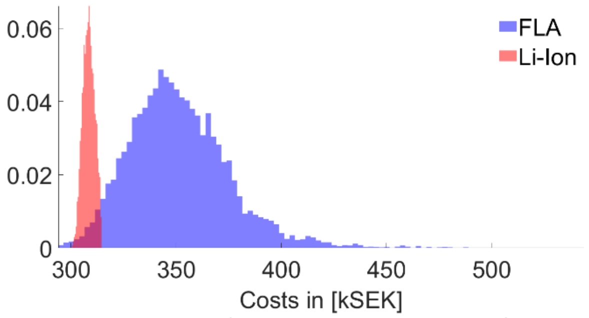

Figure 4: NPV distribution for FLA and Li-Ion Batteries for the 10 year scenario

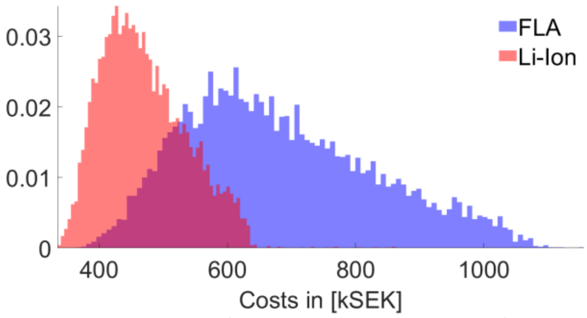

Figure 6: NPV distribution for FLA and Li-Ion Batteries for the 35 year scenario

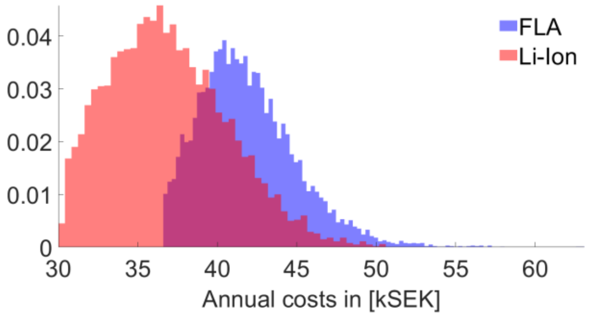

Figure 5: Annualised costs for FLA and Li-Ion batteries for the 10 year scenario

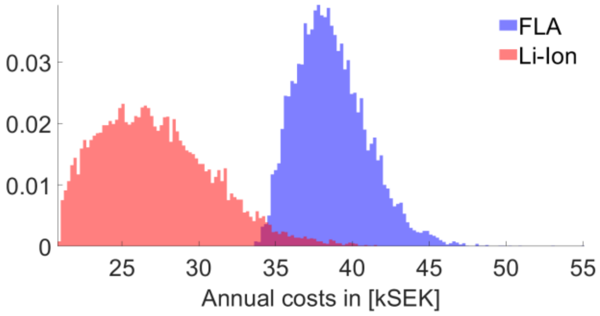

Figure 7: Annualised costs for FLA and Li-Ion batteries for the 35 year scenario

Table 2: NPV distribution parameters for the 10 and 35 year scenarios

Values in [kSEK]	10 year scenario		35 year scenario	
	FLA	Li-Ion	FLA	Li-Ion
Mean	351,4	308,4	682,1	470,5
SD	24,3	2,8	148,3	66,3
Percentile	316,8	303,8	472,5	378,1
[5, 50, 95]	348,8	308,3	660,5	461,1
	395,1	313,1	962,9	594,7
Minimum	294,5	300,6	370,9	336,0
Maximum	520,0	314,3	1155,1	861,1

the FLA battery is due to the maintenance costs and the higher replacement rate, particularly in the 35 year scenario. The annualised costs for both scenarios are presented in **Figure 5** and **Figure 7** and their distribution parameter are presented in **Table 2**. The mean of the Li-Ion cost distribution is lower, however, the uncertainty is greater. A sensitivity analysis has been conducted in [7], which shows that the maintenance and the acquisition costs have the greatest impact. Considering both scenarios, the Li-Ion battery is the preferred investment.

CONCLUSION

This study applies PLLC analysis to compare the battery types FLA and Li-Ion for the application as power back-up in substations. PLLC utilises probabilistic models and Monte Carlo simulations to get a probabilistic estimate of the NPV for investment decision-making instead of the traditional LCC approach, which is deterministic. The results are presented as a NPV distribution for a short-term and long-term investment scenario. Comparing the distributions for both battery types, the Li-Ion battery has generally a lower mean and standard deviation. This translates to lower uncertainty in the cost estimates and the lower mean value makes it the preferred investment option. Moreover, this study considers both CAPEX and OPEX costs. Particularly, the OPEX are having a high impact on the NPV and it becomes clear that although the initial investment is higher for the Li-Ion battery, the overall LCCs are lower. This case study is an excellent example that particularly with new technologies, the whole LCC should be considered and not solely the initial investment.

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