Economical and technical analysis of electrochemical energy storage systems along their value chain: a feasibility study

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July 2022

Abstract

The goal of this project is to assess the industrial feasibility of electrochemical battery technologies, considering their whole supply chains. The Levelized Cost of Storage (LCOS) is used to realistically compare different technologies; Lithium-ion NMC chemistries are used as a benchmark. This project serves as a decision-making tool for a company to compare battery systems in a more holistic way, including factors affecting the whole supply chain and the risks associated with it. The main aims of this project are:

- To develop a methodology evaluating how supply chain risks might hinder the scalability of a technology
- To create a model where the user can enter general techno-economic factors of a system and get a set of useful comparative graphs as an output
- To analyze the impact that the factors developed might have in its LCOS

The model successfully provides graphical comparisons of the LCOS, the supply risk, and the readiness level factors, after the user inputs specific parameters. Vanadium Redox Flow Batteries are chosen as the technology to be compared to Li-ion NMC technologies, obtaining insights in how the LCOS and factors developed impact both technologies.

The promising results help to open new perspectives in the electrochemical battery systems analysis domain and provide a first-of-a-kind holistic assessment of the feasibility of development of battery energy storage systems.

- Keywords: battery, energy storage, supply chain, feasibility, LCOS

1. Introduction

After years of an alarming rate of constant global temperature rise, the Paris Agreement was signed in December 2015[1].This agreement sets a global framework to “limit global warming to well below 2°C and pursue efforts to limit it to 1.5°C”. To achieve this, countries around the globe have agreed to reduce their greenhouse gas (GHG) emissions drastically, each country setting their own reduction goals. It is important to highlight that energy (including electricity, heat, and transport) accounts for almost 75% of the total GHG emissions globally, being a key sector to decarbonize and achieve Paris Agreement’s goals[2]. This decarbonization can be accelerated by using renewable energy sources (RES) for energy generation.

Renewable energy sources have been proven effective in pursuing decarbonization goals[3–5]. These technologies, such as wind power and solar photovoltaics, differ significantly from conventional power generation sources. The main differences of variable renewable energy sources (VRE) and conventional sources can be divided into five aspects: VRE generation is variable and unpredictable, generators have lower power, location constrained, and they have low short-run costs[6]. As more VRE sources are installed, more obvious are the challenges to the electric grid. The solutions for these challenges can be grouped into four areas: demand side management, conventional energy generation, and energy storage[6–8.]

Energy storage is the set of methods, systems and technologies that allow to transform and save the energy for future use[9,10]. The focus of this work will be on electrochemical energy storage, more specifically on electrochemical battery energy storage systems (BESS). Such systems provide more the needed flexibility to the electricity grid, due to their capacity to rapidly absorb, keep up and reinject electricity to the grid[9–11]. Added to this, BESS can be installed in a variety of sites, not being constrained by geographical location as Pumped Hydro Energy Storage (PHES). Also, BESS can be sized accordingly, and easily scaled later on, to the specific need.

2. Methodology

The goal of this project is to develop a methodology and a model to analyze the feasibility of scaling up BESS to a given capacity, using current lithium-ion technology as a baseline for comparison and considering the life cycle of the BESS. The model developed takes into account the LCOS, the raw materials used for the technology, and the manufacturing of the components (*i.e.* electrodes, separator, and electrolyte). The methodology followed is based in work previously done regarding electrochemical BESS, critical raw materials (CRMs) in the European Union, and supply chain of batteries. The project compares Li-ion NMC and Vanadium Redox Flow Batteries (VRFB) chemistries, due to data availability.

a. Levelized Cost of Storage

The main challenges in the development of this methodology are to be able to come up with a realistic comparison between technologies. The Levelized Cost of Storage is used as it is considered the most accurate option to compare future BESS with current Li-ion NMC ones. Concerning the LCOS development, the formula used should not have too many parameters for an adequate functioning with new technologies, as having too many technical parameters for a new electrochemical battery technology is unrealistic. Thus, the goal is to develop a LCOS formula which can provide a realistic comparison, but with the least technical parameters as possible.

Here, it considers the total costs of the BESS, including the capital expenditure (CAPEX, including cost of energy and power (i.e. PCS of the battery)), the fixed and the variable costs related with the operation and maintenance of the system (O&M), and the energy discharged during the system's lifetime. For simplification purposes, this project does not considers the charging costs and end-of-life value, and it only considers the storage block and storage-balance of the system (*i.e.* cabling, switchgear, etc.) for the cost of energy. The fixed O&M costs are considered per each year, whilst the variable costs are considered per unit of energy, both are considered as a percentage of the investment cost. On the other hand, the discount rate of the BESS is considered as 8%.

A simplified version of the LCOS formula used by Schmidt et al. is used as a basis for this section[12]. After discussing with experts in the topic of innovation of BESSs, the conclusion reached implied that the formula needed to be adjusted due to the lack of data provided for these new BESS. Equation 1 shows the simplified formula used for this methodology, where the charging and end-of-life costs are not considered:

$$LCOS\left[\frac{\$}{MWh}\right] = \frac{C_P \cdot Cap_{nom,P} + C_E \cdot Cap_{nom,E} + \sum_0^N \frac{CAPEX \cdot 0{,}02 + CAPEX \cdot 0{,}005}{(1+r)^N}}{\sum_0^N \frac{Electricity_{Discharged}}{(1+r)^N}}$$

Equation 1. Simplified LCOS for comparison of BESS

Here, C_P refers to the cost of power (in \$/kW), $Cap_{nom,\,P}$ refers to the nominal power (size) of the BESS (in kW), C_E is the cost of energy (in \$/kWh), and $Cap_{nom,\,E}$ is the nominal energy capacity (in kWh). Equation 2 shows the detailed formula of the electricity discharged by the BESS throughout the its lifetime. It considers the cycles per year, depth of discharge, nominal energy, roundtrip efficiency, self discharge, cyclce degradation and discount rate for the technology.

$$\sum_0^N \frac{Electricity_{Discharged}}{(1+r)^N} = Cycles_{p.a.} \cdot DoD \cdot Cap_{nom,E} \cdot \eta_{RT} \cdot (1-\eta_{self}) \cdot \sum_{n=0}^{N} \frac{(1-Cycle_{deg})^{(n-1)\cdot Cycles_{p.a.}}}{(1+r)^N}$$

Equation 2. Electricity discharged by the BESS in the determined period of time, considered in the LCOS formula

b. Supply chain methodology – Part 1: Critical Raw Materials

The supply chain of a BESS is simplified considered to be composed by the four steps: raw materials, processed materials, components, and cells. This first part of the methodology focuses on the raw materials' extraction and processing. For accuracy reasons and the accessibility to data regarding new battery technologies, the tool only considers if the Storage System has one or more of the critical raw materials (CRMs) proposed by the European Commission stated in previous section, considering the risk of supply of both the primary and the refined forms of this materials. The methodology developed focuses then on analyzing the supply risk of primary and processed CRMs in batteries. For Li-ion NMC batteries, which will be used as the baseline for comparison in this project, three CRMs can be found: lithium, cobalt, and natural graphite. The following parameters are considered:

- Countries supplying the material to the European Union: the top-3 countries acting as a source of supply for the European Union (primary and processed materials) were considered, in total percentage that a specific country provides for the total material sourcing in the E.U.
- World Governance Indicator[13]: this is an indicator developed by the World Bank and it assesses six different aspects in a country: Voice and Accountability, Political Stability and Absence of Violence/Terrorism, Government Effectiveness, Regulatory Quality, Rule of Law, and Control of Corruption. These indices give a general perspective on the risk of supply due to the state of a country's political panorama. The scale goes from -2.5 (worst) to 2.5 (best). For the scope of this project, it was scaled from 0 to 1 using Equation 3. According to this equation, 0 – Worst (lowest World Governance Index) and 1 – Best (highest possible WGI).

$$WGI_{scaled} = -0.2 \cdot WGI + 0.5$$

Equation 3. Formula used to scale the WGI from 0 to 1

- Environmental Performance Index[14]: this scale is proposed by the University of Yale in the United States, they use 32 performance indicators across 11 issue categories to assess how close 180 countries are to achieve already established environmental policy targets. These indices provide practical guidance for countries, providing insights on best practices, and problems. The scale goes from 0 (worst) to a 100 (best). For the scope of this methodology, it is scaled from 0 to 1.
- Herfindahl-Hirschman Index (HHI)[15,16]: this index gives an indication of the level of concentration of production of a raw material within one country, in terms of its annual worldwide production. In the scope of this methodology, the HHI for CRMs is scaled and slightly modified, it is calculated by using the percentage of the total imports of the European Union provided by any one country, in percentage units. The countries considered are the top-3 countries producing the material for the E.U., both for primary as well as for refined

materials, as given by the RMIS database.

- $HHI_{WGI-EPI}$: the HHI is multiplied the scaled WGI and the scaled EPI, as shown in Equation 4. This modified index indicates the risk of supply due to a high concentration of production/sourcing by a country, the risk of geopolitical instability in a given country, and potential restrictions of supply due to environmental protection measures in the future.

$$HHI_{WGI-EPI} = \sum_{i} S_i^2 \cdot WGI_i \cdot (1 - EPI_i)$$

Equation 4. HHI considering the political instability and environmental performance of the country

- European Union's Import Reliance (EU-IR): how much the European Union is dependent on the rest of the world regarding the obtention of that specific material[17].
- End-of-Life Recycling Input Rate (EoL-RIR): contribution of recycled materials from EoL products to raw materials demand. Taken directly from the RMIS database, calculated as the input of post-consumer secondary market to the total input of material (primary or secondary).

Finally, the formula used to calculate the supply risk of each CRM (both primary and refined) is given by Equation 5.

$$Supply\ risk = HHI_{WGI-EPI} \cdot (IR) \cdot (1 - EoLRIR)$$

Equation 5. Supply risk equation. Both for primary and refined CRMs

After having this supply risk indicator, the methodology also considers the percentage of this CRM that is used specifically for battery technologies, thus showing potential competition bottlenecks around it. The data regarding this competition factor is also obtained from the European Commission RMIS portal. The same process is then followed to calculate the technology to be compared.

c. Supply chain methodology – Part 2: Battery Component Readiness Level

To provide a more precise supply risk perspective that englobes the whole supply chain of a battery technology, it is important to consider the level of maturity of the individual components of the battery system. In this section, the focus is on the main four components of an electrochemical battery: anode, cathode, separator, and electrolyte, determining the Battery Component Readiness Level (BCRL) of each. This is based on the "Battery Component – Readiness Level framework" published by Greenwood et al. in 2022[18]. The Battery Component Readiness Level goes from 1 to 5 for each of the components in this project, the maximum possible score being 20 and the lowest 4. It is then scaled from 0 to 1.

d. System Readiness Level

After considering the supply chain of the technology, it is important to consider the maturity level of the system as a whole. Thus, in this section the System Readiness Level scale is proposed, following a similar framework as the Technology Readiness Level scale proposed by NASA, and adopted by the European Union [19,20]. The scale used in this project has 10 different stages, depending on the maturity level of the system as a whole. In a similar fashion as with previous scales in this methodology, the user will decide the stage of the system studied, entering a stage between 1 and 10. Then the result will be scaled from 0 to 1 as for previous indicators considered in this methodology for consistency purposes.

e. Model developed

It is important to highlight that the model has been developed entirely by me, no baseline code could be found on the internet to be used as a starting point.

First, the data related with the baseline technology has to be entered into the model. The model uses 3 separate Python files with information regarding specifically about Li-ion NMC technologies, 3 containing information about VRFB, and one file containing common information. Additionally, there is a file containing the main code collecting the information around Li-ion NMC and VRFB to calculate the LCOS and do the final graphical comparisons. Added to this, there are two separate files that contains the functions to calculate the LCOS, two containing the costs of power and energy for both technologies (calculated depending on the energy density entered by the user), another two calculating the supply risk depending on CRMs' data, and finally one containing the BCRL of both Li-ion NMC and VRFB. On the other hand, there is the main file of the code which contains the user's inputs, collects all the information, and finally gives the visual comparative results. Figure 1 shows the flowchart of the process of this model:

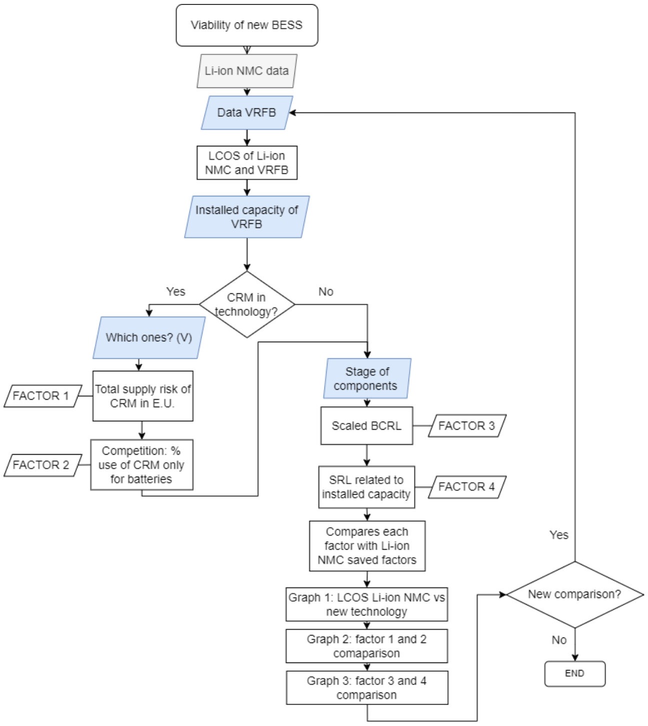

Figure 1. Simplified flowchart of the model

3. Results

For the results the data is collected by iterating the model for systems with sizes 0.5, 1, 5, 10, 50, 100, and 150 MW and discharge durations starting from 2 until 8 hours with a 1-hour discharge duration increment. In this section, the results for a 1MW and 4h system is highlighted. Figure 2 first compares the results of the LCOS of 1MW Li-ion NMC and VRFB systems

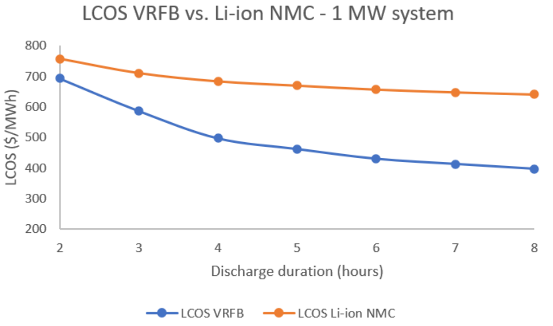

Figure 2. LCOS comparison for 1 MW systems

It can be observed that the LCOS of VRFB present a steeper decline as the discharge duration increase, as the costs of sizing up such systems are lower than the cost associated to scaling up Li-ion NMC systems. The costs of installing VRFB systems are higher, but the energy delivered throughout their lifetimes is also higher. This energy delivered come from the cyclability of the technologies, the data taken considers only 1200 cycles for Li-ion NMC, and 5201 cycles for VRFB technologies, which provides this lower LCOS for the second system. The CAPEX and O&M costs for Li-ion NMC results are lower than for VRFB (*i.e.* the total cost for 1 MW, 2h system are 1,104,000 $ for VRFB and 573,000 $ for Li-ion NMC technologies, but the electricity deliver by a VRFB is 1.59 GWh, compared to 0.76 GWh for Li-ion NMC). It is important to stress once again that the LCOS formula used is highly simplified to be used for novel technologies, generalizing technical parameters of the technology and considering only a simplified version of the capital costs and operation and maintenance costs. Also, the data used for the costs of power and energy are used in a generalized way for coherency reasons in this simplification. Figure 3 shows the results and insights provided by the 3 output graphs as a whole are shown. In this section, figures obtained for a 1 MW and 4 hours of discharge system are shown.

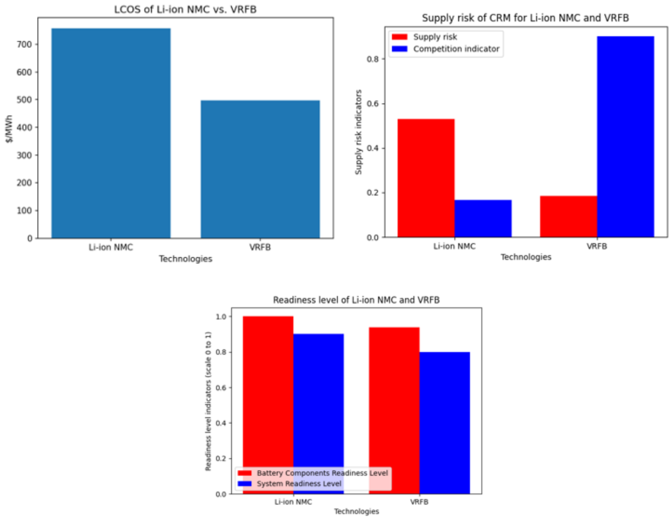

Figure 3. Output graphs of the model proposed for a 1MW and 4 h system

Bearing in mind that this approach is optimized to be as realistic and robust as possible taking into account the potential limitation in data availability for novel battery technologies, the following points are observed:

- By comparing the results of the three graphs of such system with current market dynamics (where the adoption of Li-ion NMC for BESSs is significantly higher than VRFB systems), we can observe that the competition factor of a CRM, added to lower SRL and BCRLs, might play an important role in the development of a technology.
- Regarding the supply risk of CRM and as for now, it might not be enough to detriment the deployment of a technology if there is a strong market need, but this may shift in the following years due to the increased cost and supply risk of these materials, as well are the development of novel, safer, and better performing battery technologies.

- The LCOS of Li-ion NMC is significantly higher than for VRFB, which is given by the fact of the lower cycle life of the first technology, limiting the energy delivered throughout its useful life. VRFB present higher CAPEX and O&M costs, which can also play a role in their large-scale deployment, even if the electricity delivered during their lifetimes provide better LCOS values.

It can be noted that the total costs of installing VRFB systems are higher than the installation and operation costs associated with Li-ion NMC, but during the LCOS calculation this price is balanced by the fact that the electricity delivered by Li-ion NMC 1 MW systems (for any duration ranging between 2 and 8 hours) is around half of the electricity delivered during the lifetime of a comparable VRFB system. A similar pattern is observed during all sizes and discharge durations and arises from the fact that the cycle, and thus the calendar, life of Li-ion NMC systems are more than 4 times less than for VRFB. Using different technological parameters would of course provide different results. The same data is used throughout the model for consistency purposes.

4. Conclusions

The goal of this project was to assess the feasibility of electrochemical battery technologies, considering economical and technical factors in the evaluation, being part of the work performed at the EDP Innovation – Energy Storage & Flexibility department. This project is the first stage of the development of a decision-making tool for the company to compare battery technologies in a more holistic way, including factors involving the whole supply chain and the risks associated with it.

The technologies selected for the project were Vanadium Redox Flow Batteries (VRFB) and lithium-ion NMC (Li-ion NMC) batteries, due to the availability of data of both technologies. Li-ion NMC was chosen to the baseline comparison technology, all future technologies input into the model will be compared to this battery chemistry.

The Levelized Cost of Storage (LCOS) was chosen as the baseline method of comparison between the technologies, as it shows a realistic comparison on the cost of a battery system depending on the total electricity it delivers. A simplified version of the LCOS formula was built, so that a realistic comparison with the little data availability can be performed. Next, following the supply chain risks, four different factors were developed during this work: supply risk, competition, BCRL, and SRL. The first two focusing on the raw and processed materials, whilst the last two focus on the component, cell and system as a whole.

Then, a model that calculates the LCOS and indicators was developed in Python. This model lets a user enter the main techno-economical parameters of a technology, as well as the CRMs present in it, giving as an output a series of comparative graphs between Li-ion NMC and, for the scope of this work, VRFB. The graphs show a comparison between: the LCOS of the technologies, the first two indicators related with the supply risk, and a final graph showing the readiness level factors of both technologies. The data used for this calculation was taken following the work of the United States Department of Energy, thus the results are presented in USD per MWh.

This work proved to be an innovative tool to assess in a more holistic way the feasibility of developing a battery system, by introducing a series of factors that might hinder its growth due to an impact in different areas of the supply chain. The results obtained by iterating the model provide a user with a more robust perspective on what might impede the battery system to be scaled-up.

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