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

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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-economical 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

Four factors have been developed in the first stage, coherently assessing the supply risk of Critical Raw Materials for a technology and the readiness level of components and system.

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.

Finally, this document is divided into 5 main sections: introduction, methodology created, model developed, results obtained, and conclusions of the work.

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

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$/kWh: USD per kilowatt-hour
BCRL: Battery Component Readiness Level
BESS: Battery Energy Storage Systems
BMS: Battery Management System
CAES: Compressed-air Energy Storage
CAPEX: Capital Expenditure
CRM: Critical Raw Material
DC: Direct Current
EU: European Union
EPI: Environmental Performance Index
ESSs: Energy Storage Systems
EV: Electric Vehicle
GHG: Greenhouse Gas
HHI: Herfindahl-Hirschman Index
i.e.: that is
IEA: International Energy Agency
IEM: Ion Exchange Membrane
IRENA: International Renewable Energy Agency
JSON: JavaScript Object Notation
LCOE: Levelized Cost of Electricity
LCOS: Levelized Cost of Storage
MRL: Manufacturing Readiness Level
MWh: megawatt-hours
NMC: Lithium-Nickel-Manganese-Cobalt Oxide
O&M: Operations and Maintenance
OECD: Organization for Economic Co-operation and Development
PCS: Power Conversion System
PHES: Pumped Hydro Energy Storage
RES : Renewable Energy Sources
RMIS: Raw Materials Information System
SB: Storage Block
SBOS: Storage Balance of System
TRL: Technology Readiness Level
VRE: Variable Renewable Energy
VRFB: Vanadium Redox Flow Battery
WGI: World Governance Index

1. INTRODUCTION

In this chapter, some overview of key features of the electricity generation and consumption, as well as the need of renewable energy sources (RES) integration are first introduced. The main issues related with the integration of RES to the grid and possible solutions are then presented, with a more detailed description of the main topic of this project, *i.e.* grid-scale applications of battery energy storage systems (BESS). To end up the introduction section, an overview of the objective of this project, as well as the goal for the methodology and model are highlighted.

1.1 Electricity generation and consumption

Electricity is crucial for the development of societies, playing an important role in their economies and prosperity. Currently, most of the energy sources used for electricity production are fossil fuels (*i.e.* oil, coal, and gas), supplying around 84% of humanity's primary energy[1]. These fossil fuels are a finite source of energy, and burning them is accelerating climate change, making their use unsustainable for the future and wellbeing of the planet. Added to this, energy consumption is expected to grow as the global population rises during the following decades. Figure 1 shows the expected growth of the electricity consumption globally for both OECD (Organization for Economic Co-operation and Development) and non-OECD countries until 2050, whilst Figure 2 shows the expected increase by sector[2].

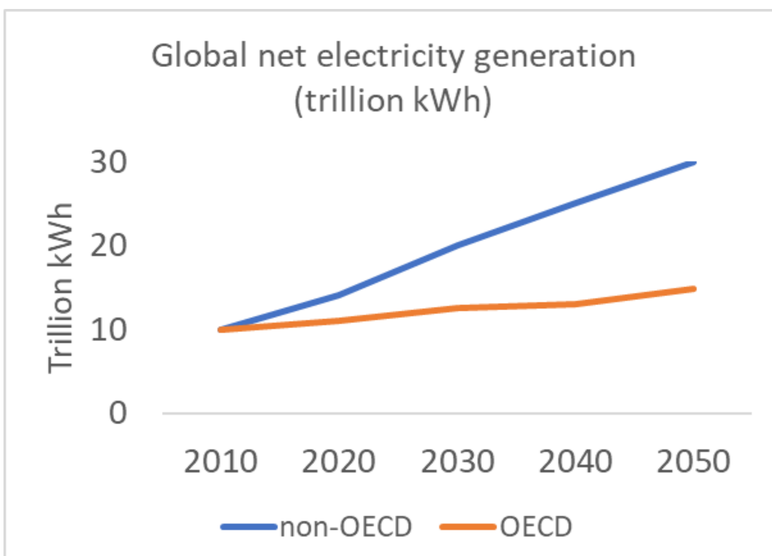

Figure 1. Adapted from reference[2]. Global electricity generation from 2010 to 2019 and projections until 2050.

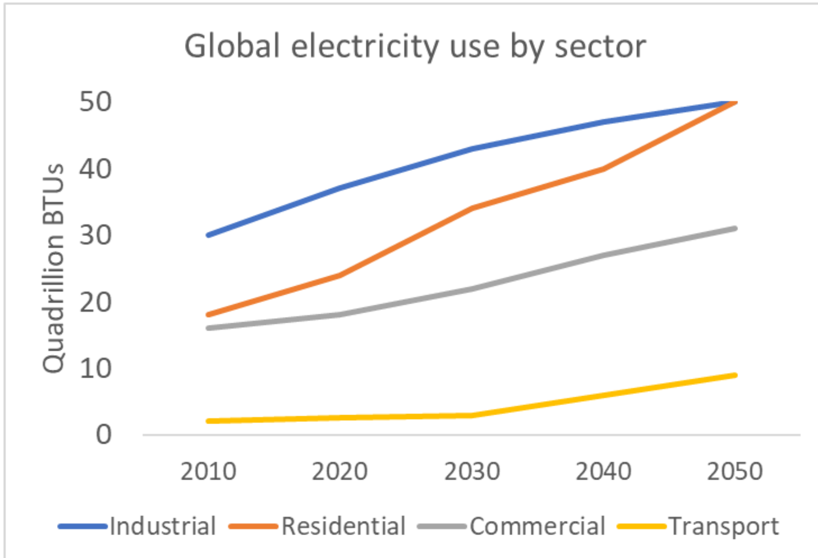

Figure 2. Adapted from reference[2]. Electricity generation from 2010 to 2019 by sector and projections until 2050.

So far, the most promising solution to cover this increasing need for electricity in a sustainable and renewable way are renewable energy sources (RES), by using the energy coming from the sun and wind to produce it. As explained in the following section, these RES come with their own set of challenges, being a variable source of energy and having to meet the consumers' demand instantaneously[3].

1.2 Grid integration of Renewable Energy Sources (RES) - Challenges

In this section, the need for the integration of RES to the electricity grid, as well as the challenges this creates for the electric grid, is presented.

After years of an alarming rate of constant global temperature rise, the Paris Agreement was signed in December 2015[4].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 (*i.e.* Portugal has set a goal to reduce between 45% and 55% the GHG by 2030, with 47% of the electricity coming from RES[5]. 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[6]. This decarbonization can be accelerated by using RES for energy generation.

Renewable energy sources have been proven effective in pursuing decarbonization goals[3,5,7]. 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[8]. As more VRE sources are installed, more obvious are the challenges to the electric grid. Four main challenges from this integration can be highlighted[9]:

1) Due to their intermittency, VRE (*i.e.* solar and wind) sources cannot provide the constant power availability needed for the electric grid.
2) Thus, the electric grid needs more flexible technologies, which can react to the demand and supply sudden variances. These flexible sources can manage the electricity needed to compensate the VRE intermittency.
3) Long-duration energy storage, balancing a power system with high penetration of VRE sources and making it more efficient, with lower marginal costs for storing the electricity.
4) Ancillary services should acquire more relevance, as they adequate the supply with the demand at any given time period. This supply-demand balance is becoming increasingly relevant as VRE installation rises.

1.3 Grid integration of RES - Solutions

The solutions for the challenges previously presented can be grouped into four different areas: demand side management, conventional energy generation, and energy storage[8–10]:

- Demand side management: its goal is to modify the user's demand for energy through methods such as behavioral change or incentives. This way the consumer can utilize less energy during peak hours, changing the energy demand curve[11].
- Conventional energy generation refers to the traditional way of producing energy by burning fossil fuels (*i.e.* coal, petroleum, natural gas). Although it is a polluting and non-renewable way of producing energy, this type of power plant has the flexibility needed to match supply and demand instantaneously[12]. Also nuclear and hydroelectric power plants can be considered in this area.
- Continental grids: refers to the possibility of transporting energy between countries by using high voltage direct current (HVDC) lines, such interconnections can be used a source of flexibility for the grid[13].
- Energy storage is the set of methods, systems and technologies that allow to transform and save the energy for future use[14,15]. Energy storage systems can be divided into different areas, as shown in Figure 3.

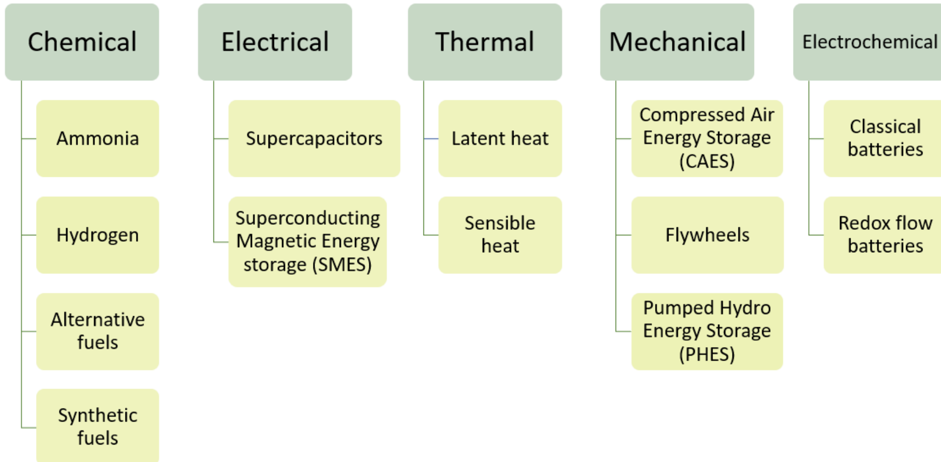

Figure 3. Adapted from reference[15]. Classification of energy storage systems (ESSs)

To solve the issues previously highlighted, these energy storage systems (ESSs) can be applied in a broad variety of purposes for several time and magnitude scales; some systems can be applied for very specific applications (*i.e.* supercapacitors for short-term power supply) or for a broader range of applications (*i.e.* compressed-air energy storage – CAES – systems for longer storage[9,14,15]. Figure 4 shows the power ratings and discharge times of various of these energy storage technologies[16].

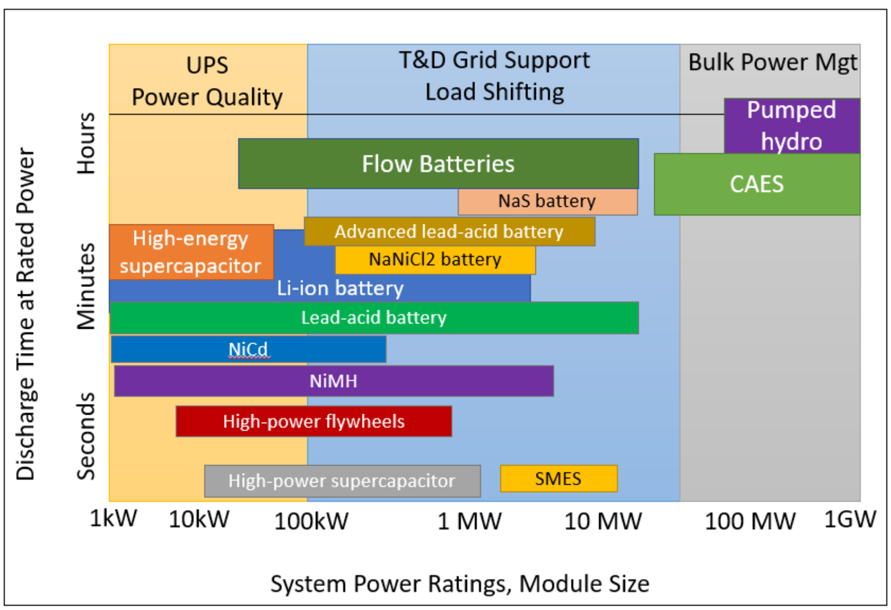

Figure 4. Adapted from reference[16] . Power ratings and discharge times of various energy storage technologies

The focus of this work will be on electrochemical energy storage, more specifically on electrochemical battery energy storage systems (BESS).

1.3.1 Battery Energy Storage Systems (BESS)

Battery Energy Storage Systems (BESS) provide more the needed flexibility to the electricity grid, due to their capacity to rapidly absorb, keep up and reinject electricity to the grid[14,15,17]. 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.

These BESS are mainly divided into behind-the-meter applications or in-front of the meter[9,15]. In-front of the meter BESS are connected to distribution/transmission networks or power-generation assets (*i.e.* wind or solar farms) and provide the solutions necessary by system operators. such as ancillary services, arbitrage or generation management[18]. This type of BESS is also known as a utility or grid-scale battery system, and these systems range from several megawatt-hours (MWh) to hundreds of MWh. On the other hand, behind-the-meter refers to batteries connected behind the utility meter of the electricity grid customers (*i.e.* industrial, residential, or commercial), usually being able to storage less energy than in-front of the meter systems. On top of arbitrage and ancilliary services, behind-the-meter systems provide the clients the option to reduce their electricity bills through demand-side management (explained in the previous section).

According to the International Energy Agency, Li-ion batteries are the most prevalent type of grid-scale BESS[19,20]. This type of electrochemical batteries is the most used for both behind-of-the-meter and grid-scale applications, as well as for portable electronic devices, such as cellphones or laptops. This type of batteries are also used in powering electric vehicles. Even though they have a series of advantages such as high energy density (i.e. amount of energy contained compared to the weight) and low maintenance[21]. Despite this advantages, lithium-ion BESS costs must decrease significantly to be able to provide the grid-support needed for the growing installation capacity of VRE sources. Added to this, they also present problems related with the raw materials availability and extraction. The abundance of lithium on earth, its mining, and its availability being one of them[22]. Additionally, the extraction of cobalt, which is used for some chemistries in the cathode, has presented a series of ethical and environmental concerns due to its extraction process. On the other hand, safety problems have increased during the past few years. According to a news report, there were 92 cases of Samsung Galaxy Note fires and 26 burns in 2016. The Federal Aviation Administration in the United States also reported 46 incidents in 2018 and one “incident” on an airplane or airport every 10 days, all related with Li-ion batteries[23]. Several cases of Tesla vehicles and other EV have been reported in the past years. Regarding BESSs, there have also been explosions reported, such as the 23 fires reported at BESS facilities in South Korea during 2018, related with Samsung and LG systems[24]. These accidents might be originated due to a mechanical, thermal, or electrical abuse in the battery.

These issues, added to other limitations present in lithium battery technologies (*i.e.* their cyclability, temperature management, or a theoretical cost competition for lower C rates - when energy/power ratio increases for longer duration storage -) and the possibility to better define power vs. density, are pushing the industry and academia to research new chemistries to solve the problems Li-ion BESS present. Some examples of failed investments are startups like Sakti3 and Nikola, which have not delivered in time the battery technologies promised to the investors[25,26]. Likewise, as previously highlighted, in-front of the meter BESS have the possibility of deliver a variety of grid applications, depending on their sizing (in MW) and discharge time. This variety of applications, added to the complicated supply chains related with batteries, make it difficult to do an accurate comparison between different technologies or to perform a realistic analysis on how feasible it is to scale that technology up to a specific capacity and need. Some approaches have been done to provide the Levelized Cost of Storage (*i.e.* the cost of energy discharged from a storage system when account for all the cost incurred, and the energy produced throughout the system's lifetime[27]) for various BESS as a cost and performance comparison tool[28–30]. Even though they provide a good economic feasibility comparison between the technologies, they do not include the whole picture. A more holistic approach is needed, which considers the possible constrains in terms of raw materials (*i.e.* current and future supply and demand or environmental impact) and manufacturing of components (*i.e.* some components need new and difficult processes, affecting the feasibility of a technology). This new perspective gives a more accurate assessment about the possibility of scaling a BESS up to a specific capacity, according to the need.

1.3.2 Goal of this project: methodology and model.

The goal of this project is therefore to develop a methodology and a model to analyze the feasibility of scaling up vel noBESS to a given capacity, it uses current lithium-ion technology as a baseline for comparison and considering the life cycle of the BESS. More specifically, 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), then calculating four different factors affecting the scalability of such system. This model is developed from zero, considering some simplifications in the formulas used to make the process and results realistic for future uses with novel technologies. More details about the assumptions made, the literature review from which the model was built, as well as a detailed explanation of the analysis and work performed, are given in the following chapters.

2. Methodology

In this section, the methodology created in this project is explained in further detail; highlighting its main assumptions, parameters considered, and limitations. Considering that this methodology is based in work previously done regarding electrochemical BESS, critical raw materials (CRMs) in the European Union, and supply chain of batteries, the literature review is first presented.

2.1 Introduction and literature review

As highlighted in previous sections, 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. Some factors around the whole supply chain of the BESS are considered as well in the comparison.

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.

On the other hand, it is important to highlight the fact that the potential supply chain's complications for a technology will influence the cost of energy ($/kWh) only. A methodology to quantify the supply chain risk is thus developed in this section.

Initial research was done regarding ESS's overview and comparison methods. Sinsel et al. analyze the challenges of introducing higher shares of variable renewable energy (VRE) to the electric grid, as well as potential technology solutions for a successful integration[8]. In the "Utility-Scale Batteries" 2019 report, the International Renewable Energy Agency (IRENA) highlight the benefits of batteries for grid-applications, giving a roadmap and highlighting the main drivers and barriers of BESS for utility-scale applications[17]. In a similar fashion, the Asian Development Bank "Handbook on BESSs" report provides an overview of various ESSs, their business models, potential applications to the electric grid, as well as the risks and challenges each technology faces[31]. In a more recent report, the National Renewable Energy Laboratory (NREL) from the U.S. Department of Energy, they use different scenarios to do predictions of the costs of BESS from 2020 to 2050[32]. All BESS analyzed are expecting to reduce capital costs by 2030. Also regarding costs of BESS, Battke et al. developed a model to address the impact of uncertainty in input parameters on lifecycle costs of BESS across different electricity system applications[29]. Even though all these articles provide a good first approach to BESSs and both technical and economical comparisons in different scales, more research on the supply chains' risk and impact on cost and feasibility of BESSs is needed.

Regarding the Levelized Cost of Storage (LCOS), Lazard's 2021 report on LCOS analyzed the LCOS of various energy storage systems (ESS)[33]. The focus of this report is on the LCOS for different grid applications that ESS provide, without presenting in detail the formula used for this analysis or considering the potential negative effects of supply chain issues on the final cost. In a 2014 article, Ilja Pawel shows a framework to calculate the Levelized Cost of Energy (LCOE) of a photovoltaic (PV) plant with a storage unit[34]. This article defined the LCOS by calculating the total cost of ownership over the investment period and divided by the energy delivered by the storage system, considering an extra factor to account for the energy cost of charging the system. In an article focused specifically on vanadium redox flow batteries (VRFB), Rodby et al. assess the LCOS for VRFB and potential improvement opportunities[35]. Regarding the LCOS, they consider the investment cost, the loan payments, the operation and maintenance, charging, and taxes for the cost. The article identifies opportunities to reduce the LCOS for VRFBs through different operating, performance improvements, design, or investment strategies. Belderbos et al. and Jülch et al. propose two different approaches and formulas to calculate the LCOS of technologies[36,37]. Belderbos et al. analyze three levelized cost metrics and their application to electricity storage units used for electric energy arbitrage, showing their main strengths and weaknesses. In this report, the LCOS for 7 ESS (*i.e.* Li-ion LFP, Li-ion NMC, lead-acid, VRF batteries, CAES, pumped storage hydro, and hydrogen ES), 3 different size-scales (*i.e.* 1, 10, 100MW), 5 different discharge durations (*i.e.* 2, 4, 6, 8, and 10 hours) and two different years (*i.e.* 2020 and 2030) is given. The formula used for the cost calculation is not presented, focusing more on the methodology developed and further results' comparison. This report will be used as basis for some cost assumptions regarding Li-ion NMC and VRFBs in the methodology. Schmidt et al., from the Imperial College of London, developed an article with a detailed step-by-step explanation of the LCOS[27]. In this article, they develop a model to predict the LCOS of 12 ESS between 2015 and 2050. The formula they use is very detailed, dividing the total cost of the ESS into four: investment cost, operation & maintenance costs, charging costs, and end-of-life costs. The formula considered the discount rate (*i.e.* rate at which future revenues/cost are discounted) for the system and divides the costs between the electricity discharged during the time period selected for each technology.

Coming back to the supply chain of BESS, due to the increasing need of lithium-ion batteries for the electric vehicles (EV) industry, and it being the main driver in the global battery demand, the articles related with the supply chain issues focus mainly on this li-ion batteries for EV applications. The main challenges and risk these EV batteries' supply chains face are analogous to the issues found in cell production for grid-scale BESSs. Mayyas et al. provide an analysis of the current state of manufacturing for automotive lithium-ion batteries, highlighting the issues with the obtention of critical raw materials (namely lithium, cobalt, natural graphite)[38]. They point out the potential bottleneck of component (*i.e.* electrodes, separator, electrolyte) imports, as most of the are primarily imported from Asian countries, thus the important role of improving recycling capabilities of these critical raw materials in batteries. Following a similar line, Sun et al. quantify the global competition for lithium-ion materials from 15 different categories (material-related) for sectors this battery technology, developing a "competition index", therefore addressing this competition as a potential issue for the batteries' supply chain[39]. Olivetti et al. and Xin Sun et al. address the potential problems that the supply of these raw materials (especially lithium and cobalt) could bring to lithium-ion manufacturing in the short/medium term [40,41]. Olivetti et al. article shows the intricate trade flows between countries, also showing the global availability and main producers of these critical raw materials; it is important to consider the scaling demand of materials in future technologies' development. On the other hand, Xin Sun et al. highlight the issues of supply chain in three main steps: mining, refining, and manufacturing. They conclude that the main focus should be on lithium and cobalt, and they come up with an indicator to quantify the risk and provide a probability of supply disruption of a material at any processing stage of this technology. After this analysis, it was clear that critical raw materials are one of the biggest potential bottlenecks in the supply chain of batteries. Thus, the first part of the methodology to assess the feasibility of new BESSs focuses on these critical raw materials (CRMs).

Next, regarding the raw materials found in BESSs, it is important to highlight the importance of the European Commission's data base Raw Materials Information System (RMIS), being the main source of the information and research for the methodological framework established for supply chain risks in the European Union. The European Commission's reports and studies were analyzed in detail to develop the framework around raw and processed material supply for electrochemical BESSs.

In an interesting article, Ferro et al. provide an approach to analyze the impact of the supply of critical raw materials (CRMs) in materials selection[42]. Following a similar reasoning, Xin Sun et al. develop a framework to understand the supply chain risk estimation for lithium-ion batteries[41]. Both articles provide an interesting approach by using the Herfindahl-Hirschman Index in combination with World Governance and Environmental Performance Index to assess the potential disruption in supply, in the case of the first one applied to alloy-material selection, whilst in the second applied specifically to lithium-ion battery materials. More information about these indices and how they were used in the methodology can be found in the following sections.

Next, the European's Commission report on the list of Critical Raw Materials provides information about the need to understand the critical role of raw materials for the industry, as well as giving information about the methodology used to define the CRMs for the European Union and the results obtained[43]. As part of the same group of publications, the European Commission's Critical Raw Materials Factsheets gives detailed information of each of the 28 materials considered as critical[44]. This report provides an in-depth analysis of the market, as well as the demand and supply in the European Union for each CRM. As mentioned above, the main tool used to obtain data on the raw materials' comparison in this project is the Raw Materials Information System database, created by the Joint Research Center and the European Commission. In 2020, Huisman et al. published the Raw Materials in the Battery Value Chain report, used as a complement of the stated database[45]. This report provides insights on the supply/demand, flows, and end-of-life of materials used in the production of battery technology, focusing on a European perspective. Also following the same group of publications on raw materials by the European Commission, the “CRMs for Strategic Technologies and Sectors in the EU” offers an understanding on potential competition problems that may arise between specific strategic technologies (*i.e.* li-ion batteries, fuel cells, drones, or 3D printing manufacturing) and between strategic sectors (*i.e.* renewable energy, defense and aerospace, e-mobility)[46]. The 2021 European Commission’s “Raw Materials Scoreboard” looks at a range of raw materials used in the European Union, discussing topics related with the supply of materials (domestic and global), providing 27 different indicators throughout the materials’ supply chains[47].

After understanding the raw materials’ importance and their role in the supply chain, the goal of this next section is to understand the risks and challenges in the manufacturing processes of different battery technologies overall, so that a coherent methodology to assess the feasibility of new BESSs can be developed. Liu et al. summarize the main manufacturing processes for lithium-ion batteries and future improvements they may have[48]. In a similar way, Hawley et al. highlight current and future manufacturing of lithium-ion batteries, focusing more on the manufacturing of the electrodes in particular the main issues to be solved[49]. These article shows the technical manufacturing steps of Li-ion cells, as well as future improvements, but getting this level of detail for the manufacturing of new technologies would be unrealistic. Thus, the methodology is focused on an assessment of the Technology Readiness Level (TRL) and/or Manufacturing Readiness Level (MRL). The TRL is a scale that assesses the maturity of a specific technology, so that the comparison between multiple technologies can be consistent. It was developed by NASA and is divided in 9 different levels, depending on the level of technological maturity of the system analyzed. Later on, the European Union developed a very similar scale to assess technological maturity. On the other hand, the MRL scale was established by the U.S. Department of Defense to evaluate the maturity of manufacturing, following a similar approach to the TRL scale. They are quantitative measures to assess the maturity of a system or component from a manufacturing point of view[50]. Therefore, a combination of both TRL and MRL scales would be convenient in the feasibility assessment of the readiness level of a battery technology. In a 2021 study, Greenwood et al. came up with a framework assessing the Battery Component Readiness Level (BC-RL)[51]. In this scale, they combine both the TRL and the MRL scales to specifically evaluate the readiness level of battery components. The scale is divided into 3 types that compare the battery technology to already existing technologies and processes (*i.e.* type 1 means the technology uses existing component production and cell assembly processes, whilst type 3 means the technology needs big modifications or novel process steps in the production steps), and 9 stages (*i.e.* stage 1 means that the technology is still in a theoretical concept development, whilst stage 9 refers to big-scale cell production already established), following a similar structure than the one use for the TRL scale. The second section of the supply chain methodology of this work is based on this BC-RL scale.

2.2 General assumptions and considerations

For this methodology, Li-ion NMC (111) technologies were considered as the base case scenario. The rest of the technologies introduced by the user in the model will be compared with data given for this technology. This technology is chosen due to its technological and market maturity, as well as availability of data. In order to assess the performance of the model and obtain results, Vanadium Redox Flow Batteries (VRFBs) will be used as comparison. Considering the supply chain of BESS part, the four steps considered are: raw materials, processed materials, components, cells. Finally, an assessment of the expected vs. current installation of that BESS is provided, relating it to the System Readiness Level scale (see section "System Readiness Level" for more information). The first part of this methodology (*i.e.* CRM methodology) englobes the first two parts of the supply chain, whilst the second part (*i.e.* revised BC-RL scale) incorporates the third. The assessment of the cells is taken into account by the System Readiness Level scale, which takes into account the technological maturity of the battery.

2.3 Methodology

The methodology for the comparison of the feasibility of new battery technologies against Li-ion NMC batteries is divided into four main parts: Levelized Cost of Storage (LCOS) assessment, supply chain part 1 (Critical Raw Materials), supply chain part 2 (Battery Component-Readiness Level), and System Readiness Level. The LCOS serves as the comparison scale between technologies, whilst the other three stages provide an analysis on the risk in both the supply chain and scalability of the technology due to technological maturity risks.

2.3.1 Levelized Cost of Storage assessment

The Levelized Cost of Storage should consider the total costs of the BESS, including the capital expenditure (CAPEX), the fixed and the variable costs related with the operation and maintenance of the system (O&M), the costs associated with the electricity needed to charge the BESS, and the potential costs/value at the end-of-life of this system (which can be positive if the technology's materials are recycled and hold some market value, or negative if not)[27,34–37,52]. It is important to consider the O&M costs required for the whole useful life of the system, the fixed O&M costs are considered per each year, whilst the variable costs are considered per unit of energy. On the other hand, the discount rate of the BESS is needed to be considered for more precise results. Due to the difficulty of comparing energy storage systems, and for the purpose of having an accurate assessment, all the costs previously listed are then considered for the total energy delivered through the system's lifetime. To do this evaluation, the technical and application parameters of the studied BESS are considered.

Figure 5 shows all the costs related with the development of a BESS project. It is important to highlight the fact that this project will compare the technologies against lithium-ion NMC chemistries, so some parameters will be assumed as equal, and others will not be considered in this study due to the lack of information for new technologies[52].

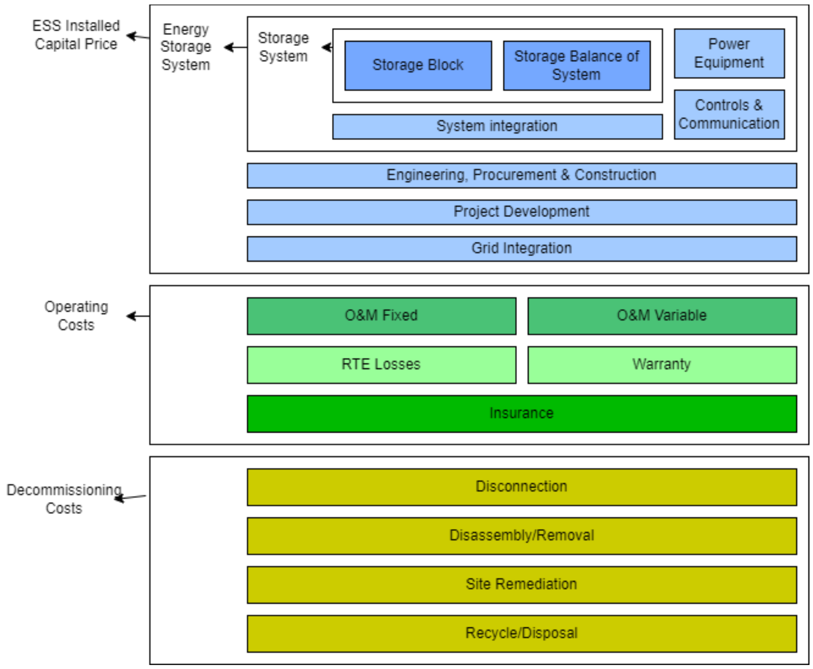

Figure 5. Costs involved in a BESS, most of them are considered in the LCOS explained in this section

A simplified version of the LCOS formula used by Schmidt et al. is used as a basis for this section[27]. 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 original formula proposed by Schmidt et al. In the article, they use this formula to analyze the LCOS of 9 storage technologies, in 12 different applications, and in a time range from 2015 to 2050.

$$LCOS\left[\frac{\$}{MWh}\right] = \frac{Investment\ cost + \sum_{n}^{N}\frac{O\&M}{(1+r)^n} + \sum_{n}^{N}\frac{Charging\ cost}{(1+r)^n} + \frac{End-of-life\ cost}{(1+r)^{N+1}}}{\sum_{n}^{N}\frac{Electricity_{Discharged}}{(1+r)^n}} \quad (1)$$

Equation 1. Taken from reference [27]. Levelized Cost of Storage formula[27]

As previously stated, the End-of-life costs are not considered in this work due to the lack of information for new technologies regarding them. Also, they consider the replacement cost of equipment, here the replacement interval is considered, which is determined by the full equivalent cycles requiring replacement relative to annual cycles of the system. For this study, the replacement costs will not be considered either due to the lack of this information for novel BESS. The year of operation of the technology (n) is not considered for the study, the calculation is done considering the year of operation as 0 and taking into account only the operational lifetime of the technology (N). On the other hand, when comparing technologies to Li-ion NMC, the charging costs are considered equal for both technologies and not taken into account in the comparison.

After these considerations, the simplified LCOS formula used in the scope of this project is:

$$LCOS \left[\frac{\$}{MWh}\right] = \frac{Investment\ cost + \sum_0^N \frac{O\&M}{(1+r)^N}}{\sum_0^N \frac{Electricity_{Discharged}}{(1+r)^N}} \tag{2}$$

Equation 2. Adapted from reference [27]. Simplified LCOS for comparison of BESS

The investment costs englobe both the cost related with power (*i.e.* power conversion system (PCS) of the battery) and the energy-related cost of the storage system. The energy cost is considered only for the storage block and storage balance of the system, without considering the system integration or the controls & communication equipment earlier highlighted in Figure 5. The Storage Block (SB) includes the price of the most basic direct current (DC) element in an energy storage system. For example in the case of a Li-ion system, this cost includes the battery module, the rack, and the battery management system (BMS). Regarding the Storage-Balance of the System (SBOS) costs, it includes supporting components for the Storage Block (*i.e.* cabling, switchgear, ventilation, etc.). Equation 3 shows the costs related with investment (or CAPEX).

$$Investment\ cost = C_P \cdot Cap_{nom,P} + C_E \cdot Cap_{nom,E} \tag{3}$$

Equation 3. Adapted from reference [27]. Cost of investment in the LCOS simplified formula

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). The user of the model needs to enter the size and the discharge duration parameters for the technology to be compared, thus the $Cap_{nom,\ E}$ is calculated by multiplying the nominal power times the discharge duration. After having this data, the model automatically checks the value of them for Li-ion NMC. More information regarding this process is given in the “Model” section of this work. For the nominal energy capacity, the user should also enter the duration of discharge of the system studied,

Next, regarding the O&M costs, they are divided into fixed and variable costs. Equation 4 shows the O&M part of the LCOS simplified formula used for this project.

$$\sum_0^N \frac{Fixed\ O\&M\ costs + Variable\ O\&M\ costs}{(1+r)^N} = \sum_0^N \frac{CAPEX \cdot 0{,}02 + CAPEX \cdot 0{,}005}{(1+r)^N} \tag{4}$$

Equation 4. Adapted from reference [27]. Operation & Maintenance costs of a BESS, used to calculate the LCOS of the technology

Here, fixed costs are considered in \$/kW per each year. As mentioned in the previous section, N is the lifetime (in years) of the BESS, whilst n is the operating year that will be considered as 0 for the scope of this work. The fixed O&M costs are the necessary costs to maintain the storage system operational throughout its life and that do not fluctuate due to energy output (*i.e.* labor and benefits for staff, planned maintenance). The discount rate is r, it is assumed to be 8%. Variable costs are measured in \$/kWh and account as an average for the total period mentioned, these costs are associated with non-fuel consumables necessary to operate the BESS throughout its economic life. Both are calculated as a percentage of the investment cost. The fixed operations and maintenance costs are considered to be 2% of the CAPEX, whilst the variable O&M costs are considered to be 0.5% of the total CAPEX, both data were chosen as a generalization and following the work of the U.S. Department of Energy on "Grid Energy Storage Technology Cost and Performance assessment"[52]. The user of the model will not need to have these O&M costs due to the little availability of data for BESS that are still not in a commercial scale. The model assumes the same percentages for VRFBs, more details are given on the "Model" section.

For the final part of the equation, the electricity discharged must consider several technical and application parameters of the BESS. Equation 5 shows the detailed formula for this electricity discharged by the BESS throughout the period calculated.

$$\sum_{0}^{N} \frac{Electricity_{Discharged}}{(1+r)^N} = Cycles_{p.a.} \cdot DoD \cdot Cap_{nom,E} \cdot \eta_{RT} \cdot (1-\eta_{self}) \cdot \sum_{n=0}^{N} \frac{(1-Cycle_{deg})^{(n-1)\cdot Cycles_{p.a.}}}{(1+r)^N} \qquad (5)$$

Equation 5. Adapted from reference [27]. Electricity discharged by the BESS in the determined period of time in LCOS

This equation considers:

- Cycles per year ($cycles_{p.a.}$): the amount of charge-discharge cycles the battery performs during a year. Depending on this, the lifetime of the BESS might decrease.
- Depth of Discharge (DoD): refers to how much energy is cycled out of the battery in one cycle. It is expressed as a percentage of the total capacity of the battery. In this assessment, it will be considered 80% for Li-ion NMC technologies.
- Nominal energy capacity ($Cap_{nom,E}$): the energy that can be withdrawn from the BESS at a specific constant current, starting from a fully charged state. It is measured in kWh.
- Roundtrip efficiency (η_{RT}): the difference between the charged and discharged energy (in kWh) measured in % of the total energy charged. The higher it is, the less the energy lost in the storage process.
- Self-discharge (η_{self}): the amount of energy that is lost in the battery due to internal chemical reactions inside the BESS. It is measured in % of total capacity and, for the scope of this project, it is assumed to be of 1% of the total capacity per month for Li-ion NMC and the technology to be compared[52].
- Cycle degradation ($Cycle_{deg}$): degradation of nominal energy storage capacity, it is measured in % of capacity loss. In this analysis, it is considered to an end-of-life value of 80% relative to the initial capacity ($Cap_{nom,E}$). The cycle life is the total cycles the BESS can go through its lifetime. See Equation 6 for more details.

$$Cycle_{Deg}\left[\frac{\%_{capacity}}{cycle}\right] = 1 - 80\%^{\left(\frac{1}{Cycle_{life}}\right)} \quad (6)$$

Equation 6. Adapted from reference [27]. Cycle degradation formula of a BESS

- Lifetime of the technology (N): maximum life of the system regardless of operating conditions, measured in years. Some parameters such as ambient temperature and state of charge (SOC) affect this lifetime in BESS.
- Year of operation (n): the year of operation of the BESS. In this project, it is assumed to be 0 and the LCOS is considered for the whole lifetime of the technology.
- Regarding the temporal degradation of the BESS, it is assumed to be already considered in the cycle degradation of the technology.

This LCOS provides an efficient comparison between different BESSs. Due to the uncertainty and lack of information of some systems that will be studied using this methodology, the LCOS formula provided loses some accuracy on the results but gives a general perspective on the cost of technologies. In the section "Limitations of the methodology", more information about this is given.

Table 1 provides a summary of the data used for the Li-ion NMC technologies, as well as the assumptions used in the calculations. The same process is performed for each technology to be compared (*i.e.* VRFBs for the scope of this project), as well as the methodology process for the supply chain and system's sections. The data and assumptions used for both Li-ion NMC and VRFBs are based on the detailed analysis performed in the U.S. Department of Energy 2020 report previously highlighted[52].

Table 1. Data and assumptions used for Li-ion NMC technologies. *More details are given in the "Model" chapter

Variable in LCOS	Value	Assumptions/comments
Cost of power (C_P)	From U.S. Department of Energy report	Model goes check to table (see Figure 14) depending on nominal energy
Nominal power ($Cap_{nom,P}$)	Entered by the user for technology to be compared	Used to obtain nominal energy
Discharge duration (h)	Entered by the user for technology to be compared	Used to obtain nominal energy
Cost of energy (C_E)	From U.S. Department of Energy report	Model goes check to table depending on nominal energy
Nominal energy ($Cap_{nom,E}$)	Nominal power*Discharge duration	

Fixed O&M costs	2% of CAPEX	Assumed the same for all technologies
Variable O&M costs	0.5% of CAPEX	Assumed the same for all technologies
Discount rate	8%	Assumed the same for all technologies
Cycles per year ($Cycles_{p.a.}$)	One cycle per day (365)	
Depth of Discharge (DoD)	80%	
Roundtrip efficiency (η_{RT})	86%	
Self-discharge (η_{self})	1%	
Cycle degradation ($Cycle_{deg}$)	Follows the formula using the cycle lifetime of the technology	

2.3.2 Supply chain methodology – Part 1: Critical Raw Materials

To assess the feasibility of scaling up a battery technology for utility-scale applications, it is important not only to consider its LCOS and technical parameters for a specific application, but also the possible risk associated with its supply chain. In this section, the methodology followed to consider the risk associated with potential disruptions in the supply chain of battery's raw materials is stated.

The supply chain of a BESS is simplified considered to be composed by the four steps highlighted in Figure 6. 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.

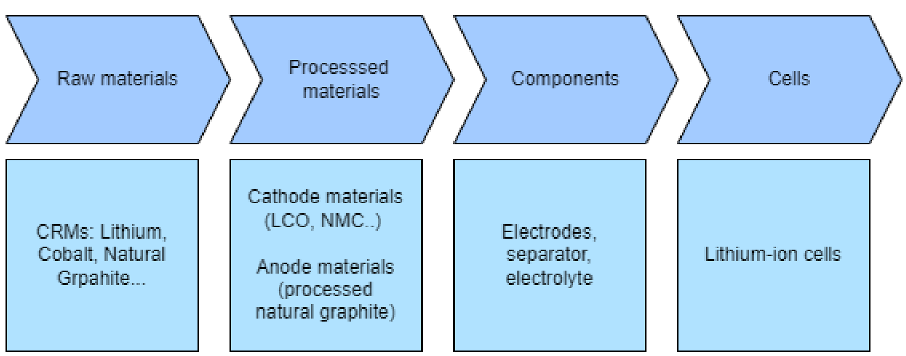

Figure 6. Adapted from reference[46]. Supply chain of batteries, using lithium-ion as an example.

The methodology developed focuses then on analyzing the supply risk of primary and processed CRMs in batteries. It is imperative to highlight once again that the database of the Raw Materials Information System of the European Commission is used for this evaluation of supply risk. For demonstration processes, the methodology of supply risk for Li-ion NMC batteries is given. For the model, the user should enter the CRMs the technology has, and the same process as for this Li-ion NMC methodology is followed to assess the risk supply. More details on this are given in the "Model" section.

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 supply risk evaluation and methodology are developed for the European Union (EU) limits. For a precise assessment of the supply risk of these materials, the following parameters are considered:

- Main countries supplying the material to the European Union: the top-3 countries acting as a source of supply for the European Union (both for primary and processed materials) were considered. The unit used for these parameters is the total percentage that a specific country provides for the total material sourcing in the EU
- World Governance Indicator[53]: 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 7. According to this equation, 0 – Worst (lowest World Governance Index) and 1 – Best (highest possible WGI).

$$WGI_{scaled} = -0.2 \cdot WGI + 0.5 \quad (7)$$

Equation 7. Adapted from reference [53]. Formula used to scale the WGI from 0 to 1

- Environmental Performance Index[54]: 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, targets, 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)[41,42]: 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. It goes from 0 (widely distributed production) to 10.000 (production is highly concentrated in a small number of countries). 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. Equation 8 shows the formula used for the calculation, where S is the concentration of that CRM in the EU sourcing country, i refers to the country producing this material. The countries considered are the top-3 countries producing the material for the EU, both for primary as well as for refined materials, as given by the RMIS database. A higher value means a higher concentration of production by a country, thus meaning an increased risk of supply.

$$HHI = \sum_i S_i^2 \tag{8}$$

Equation 8. Adapted from reference[42]. Calculation of Herfindahl-Hirschman Index (HHI) for supply concentration (S) in a country (i)

  - $HHI_{WGI\text{-}EPI}$: for the purposes of this project, the Herfindahl-Hirschman Index is then multiplied by the scaled World Governance Indicator and the scaled Environmental Performance Index, as shown in Equation 9. This modified index indicates not only the risk of supply due to a high concentration of production/sourcing by a country, but also adds the risk of geopolitical instability in a given country, as well as potential restrictions of supply due to environmental protection measures in the future.

$$HHI_{WGI-EPI} = \sum_i S_i^2 \cdot WGI_i \cdot (1 - EPI_i) \tag{9}$$

Equation 9. HHI considering the political instability and environmental performance of the country

- European Union's Import Reliance (EU-IR): refers to how much the European Union is dependent on the rest of the world regarding the obtention of that specific material. Information obtained directly from the RMIS database (access May 2022).
- End-of-Life Recycling Input Rate (EoL-RIR): it measures the 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 10. As previously mentioned, the closer each parameter is to one, the higher the risk of supply. For this reason, the EPI (in the HHI), as well as the Recycling Input Rate (in the Supply Risk formula) are subtracted to one.

$$Supply\ risk = HHI_{WGI-EPI} \cdot (IR) \cdot (1 - EoLRIR) \tag{10}$$

Equation 10. Supply risk equation. Both for primary and refined Critical Raw Materials (CRMs) in this methodology

Regarding CRMs contained in the technology, the following data were obtain for the lithium-ion NMC technology:

Table 2. Data taken from references[42,45,53,54]. Data for Li-ion NMC technologies (HHI, WGI scaled, EPI scaled, EU-IR, EoL-RIR)

	CRM	Country	Supply concentration	HHI	WGI_{scaled}	EPI_{scaled}	$HHI_{WGI-EPI}$	Final $HHI_{WGI-EPI}$	EU-IR	EoL-RIR
Lithium	Primary	Australia	87%	0,7569	0,19	0,75	0,0360	Li primary	87%	0%
		Portugal	13%	0,0169	0,29	0,67	0,0016	0,04		
	Refined	Chile	78%	0,6084	0,31	0,55	0,0849	Li refined	100%	0%
		U.S.	8%	0,0064	0,50	0,69	0,0010			
		Russia	4%	0,0016	0,63	0,50	0,0005	0,09		
Cobalt	Primary	D.R. Congo	68%	0,4624	0,82	0,36	0,2427	Co primary	86%	22%
		Finland	14%	0,0196	0,15	0,79	0,0006	0,24		
	Refined	Finland	54%	0,2916	0,15	0,79	0,0092	Co refined	27%	22%
		Belgium	7%	0,0049	0,26	0,73	0,0003			
		Norway	7%	0,0049	0,15	0,78	0,0002	0,01		
Natural graphite	Primary	China	68%	0,4624	0,57	0,37	0,1660			
		Brazil	14%	0,0196	0,55	0,51	0,0053	Nat. graph. (pr)	98%	2%
		Norway	5%	0,0025	0,15	0,78	0,0001	0,17		

It is important to highlight that:

- Only the top 2 or 3 countries shown in the RMIS European Commission's database were considered for this calculation
- The World Governance Indices were calculated by doing an average of the six indicators for the last three years of available data (2018, 2019, 2020) to increase accuracy.
- The Environmental Performance Indices were given in percentual values and scaled in a 0 to 1 scale. The latest data available was used (2020).
- Both the EU-Import Reliance and the EU-End-of-Life Recycling Input Rate were obtained from the RMIS European Commission's database with the latest information published (access March 2022).

The following Supply Risk Indicators were obtained for the three CRMs present in Li-ion NMC BESSs:

Table 3. Supply risk indicators for the CRM contained in a Li-ion NMC battery

CRM	Supply risk
Li (primary)	0,033
Li (refined)	0,087
Co (primary)	0,163
Co (refined)	0,002
Natural graphite (primary)	0,164

The supply risks of all the CRMs present in a technology are then summed up to give the first factor of comparison. In the case of Li-ion NMC, the total supply risk of CRMs is 0.45. All the other technologies entered in the model will be compared against this indicator. For the scope of this project, VRFBs technology will be compared to Li-ion NMC. More information about the process of the comparison is given in the "Comparison of factors" section.

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, obtaining the following results:

- 46% of Cobalt imported to the E.U. is used for battery production
- 32% of Li is used for this purpose
- 16% of natural graphite

Following the same procedure as for the other factors, the percentages are scaled from 0 to 1. The average of the competition factors is then calculated. Finally, for consistency reasons, this result is subtracted to 1, as it is more logical to associate a higher value to a higher competition in the market rather than the other way around. Thus, Equation 11 is used for the purpose of this calculation:

$$Competition\ in\ E.U.market = 1 - \frac{\sum Competition\ percentages}{\#\ of\ CRMs} \quad (11)$$

Equation 11. Competition % taken from[45]. Competition indicator formula

Therefore, this first section of the methodology provides the first two risk factors related with supply chain risks of the technology:

- Factor 1 – Supply risk of CRMs for the EU: this factor shows the potential risk in supply for that CRM to the EU, considering the percentage of the CRM only in one country, the governance levels of those countries, how close are they to achieve their environmental goals, how much does the EU depend on other countries to import the material, and how much of the material is recycled for manufacturing new components. Finally, the supply risk of all the CRMs present in the technology are summed up to give one single supply risk factor.
- Factor 2 – Competition in the EU market: gives an overview on the allocation of the CRM specifically for battery manufacturing. The higher the percentage of the CRM used specifically for battery production, the less the risk of potential supply risks due to competition.

2.3.3 Supply chain methodology – Part 2: Battery Components 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. The readiness level of the system as a whole (including casing, connections, and considering all the extra equipment and scaling needed for a successful installation to the grid) is considered in the following section, the focus in here is to determine the Battery Component Readiness Level. The methodology established in this second part of the supply chain is based on the "Battery Component – Readiness Level framework" published by Greenwood et al. in 2022[51]. As explained earlier on, they propose a framework combining the Technology Readiness Level (TRL) scale proposed by NASA and the Manufacturing Readiness Level (MRL) scale proposed by the U.S. Department of Defense focused exclusively on the battery cell components. The goal of this framework is to "enable clear and accurate communication between personnel of various backgrounds, by finding a balance between the detail necessary for robust analysis and the brevity necessary for ease of use". Figure 7 shows the nine stages proposed by the scaled Component-Readiness Level (CRL) framework. In this methodology, the stages will be "absorbed" by the five bigger groups on the right-hand side of the image, so giving place to five stages for each one of the four main components considered.

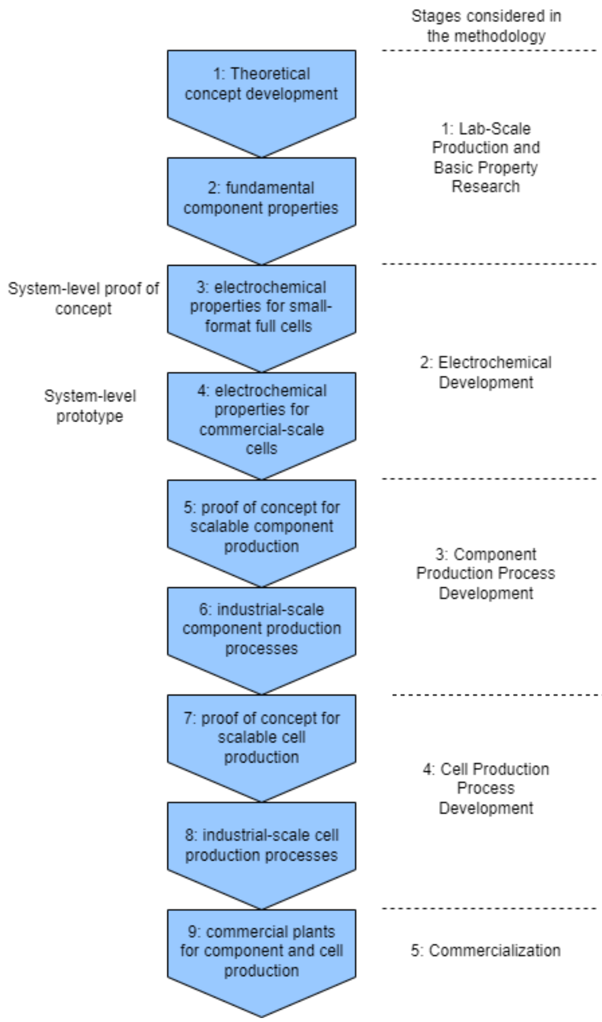

Figure 7. Stages on the Battery Component-Readiness Level scale. The 5 stages on the right are used in this methodology[51].

To facilitate the decision-making process of the stage at which each of the battery's components are, a checklist will be developed in the model for each stage. The checklists for all the stages can be found in the "Appendices" section. Figure 8 shows an example of the mentioned checklists for Stage 1.

STAGE 1: CHECKLIST		
Known	Possible Projections	Fully Unknown
Component properties	Theoretical component/cell properties	Manufacturability (component and cell)
Material cost	Component production cost (low accuracy)	Environmental impact
	Supply risk	Practical cell properties
		Cell production cost

Figure 8. Example of the checklist provided to the user to determine the battery component's stage

After following these steps, the user chooses between a Scale of 1 to 5 for each of the four components. Therefore, the maximum possible score is 20 (all components are in Stage 5), whilst the lowest possible score is 4 (all components in Stage 1). Following the same logic as in the first part of the supply chain's methodology for the supply risk of CRMs, this score is then scaled from 0 to 1, as shown in Equation 12.

$$CRL_{scaled} = \frac{\sum Stages_{comp} - Min\ value}{Max\ value - Min\ value} = \frac{\sum Stages_{comp} - 4}{20-4} = \frac{\sum Stages_{comp} - 4}{16} \quad (12)$$

Equation 12. Adapted from[51]. Component Readiness Level scale from 0 to 1. The stages of the components must be summed up.

The closer the result is to 1, the higher the readiness level of the 4 components. This indicator adds more accuracy to the potential issues in the deployment of the technology, due to low readiness levels of one or more components.

For this methodology, the result obtained is then compared with the results obtained by Li-ion NMC. The data obtained for Li-ion NMC is given in Figure 9.

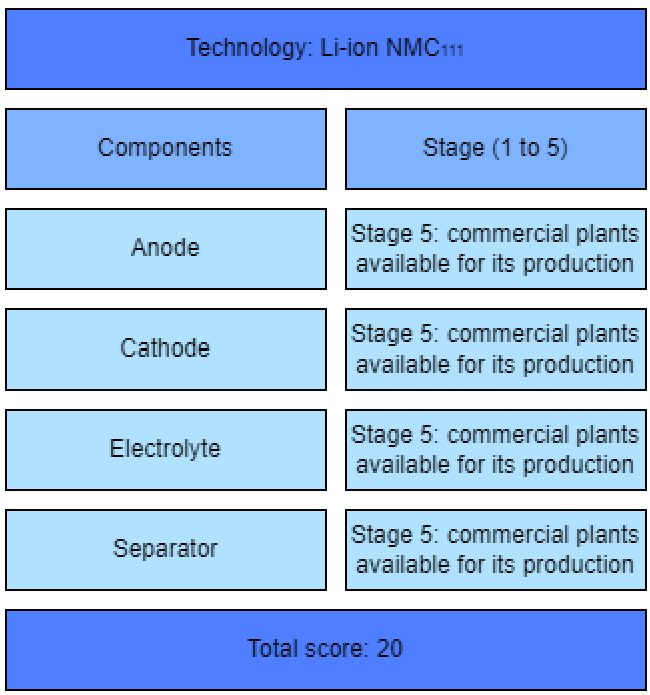

Figure 9. Adapted from reference[51]. CRL scale for Li-ion NMC_{111} technologies.

Considering the technological maturity of the individual components of the battery system, as well as the commercial level of these Li-ion NMC batteries, it is considered that it has the highest level possible of 20 points. All four components considered in this part of the methodology (*i.e.* anode, cathode, electrolyte, and separator).

This second section of the supply chain focused on the methodology provides the third risk factor that will be considered in the model.

- Factor 3 – Battery Component Readiness Level (BCRL)

2.3.4 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 [55]. The scale used for this purpose in the scope of this work takes this NASA-developed TRL scale (which has 9 different stages for the technology) and a TRL scale developed by the International Energy Agency (which has 11 stages) as a basis[56]. 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. Figure 10 shows the stages considered for this work, also adding examples of the stage in which different ESSs are.

System Readiness Scale methodology

TRL	Description of rating	Example technologies
1	Initial idea: basic principles have been defined	Li-Air EV batteries
2	Application formulation: concept and application of solution formulated	Multivalent ions EV batteries
3	Concept needs validation: solution needs to be prototyped and applied	Chemical reaction thermochemical heat storage
4	Early prototype: prototype proven in test conditions	Active latent heat storage
5	Large prototype: components proven in conditions to be deployed	Solid state + Li-metal EV batteries
6	Full prototype at scale: prototype proven at scale in conditions to be developed	Building integrated phase change materials
7	Pre-commercial demonstration: prototype working in expected conditions	High-temperature latent heat storage
8	First of a kind commercial: commercial demonstration, full-scale deployment in final conditions	Compressed air energy storage (CAES)
9	Commercial operation in relevant environment: commercially available, needs improvements to stay competitve	Flywheel, Li-ion batteries
10	Proof of stability reached: predictable growth	Pumped hydro storage (PHS)

Figure 10. System Readiness Level scale used for this section of the methodology. Adapted from[56,57].

This SRL factor is attached to the installed capacity that the technology has. Following the same scale proposed by the IEA previously mentioned and after performing literature research on the technologies that are in that specific readiness level, the following relation between installed capacity and SRL is developed to be used in the methodology and model:

- After assessing it with experts in the industry, the conclusion is reached that there is no installed capacity between SRLs 1 and 5, considering the technology's maturity at those stages. Thus, if there is no installed capacity, the user should enter the SRL of the technology (between 1 and 5) in the model.
- After reviewing literature sources, the installed capacity of the technology-SRL relationship is stablished as[56,57]:
    - Up to 9.999 kWh (less than 10 MWh), the SRL = 6
    - Between 10.000 and 99.999 kWh (less than 100 MWh), the SRL = 7
    - Between 100.000 and 999.999 kWh (less than 1 GWh), the SRL = 8
    - Between 1.000.000 and 49.999.999 kWh (less than 50 GWh), the SRL = 9
    - More than 50.000.000 (more than 50 GWh), the SRL = 10

It is important to highlight the fact that some technologies, such as Compressed Air Energy Storage (CAES), have an are intrinsically bigger capacity per system installed due to technology-specific parameters (*i.e.* CAES is installed in big caves and one single system ranges in the hundreds of MWhs). Regarding battery technologies, the scale-up process between BESSs is usually comparable, thus not affecting the installed capacity-SRL relationship proposed.

The last comparison factor around BESSs is obtained in this section:

- Factor 4 – System Readiness Level. Relates the installed capacity of the technology to the readiness level of the whole system, going from 1 to 10 and scaled to 0 to 1. Levels 1 to 5 have no installed capacity yet. For Li-ion NMC, the scaled SRL is 0,9 (level 9).

2.3.5 Comparison of factors

The four factors obtained will be compared to the VRFBs factors, providing a general guideline to the user. The four factors will be presented in two different graphics, one related with supply chain risks (which will include factor 1 – Supply risk of CRMs for the E.U and factor 2 – Competition in the EU market) and the second one related to the readiness level (including factor 3 – BCRL and factor 4 – SRL). Added to the LCOS comparison, the three graphs will provide more insights to the user about potential risks associated with that specific battery technology. More details about this comparison are given in the "Model" section of the work.

2.4 Technology to be compared – Vanadium Redox Flow Batteries (VRFB)

For the scope of this work, only one technology will be compared to Li-ion NMC, following the methodology previously described. The technology chosen is Vanadium Redox Flow Batteries (VRFB), due to the availability of data of this technology and to the fact that it has some interesting differences with traditional electrochemical batteries, especially in terms of scalability of components. This difference provides an interesting challenge in the comparison, also serving as a base for comparing redox flow technologies with traditional electrochemical ones using this model in the future. In the following sections, the main considerations for each of the four steps of the methodology regarding VRFBs is presented. The detailed calculations for the factors and indicators are not presented here but can be found in the "Appendices" section. The information collected regarding VRFBs will be entered into the model as a user input, whilst the Li-ion NMC-related data will be entered as part of the model to serve as a comparison baseline.

For the purpose of the methodology considerations around VRFBs, it is vital to mention the main differences between such VRFB technologies with most traditional electrochemical batteries. This section serves as an illustration of the main differences between the configurations.

First, VRFBs store the electricity in liquid electrolytes, and the electrodes act as catalytic sites for electrochemical reactions[58–60]. The electrodes themselves do not change, just serving as a surface where redox reaction occur. Secondly, the electrolytes are stored in different tanks and do not degrade. In this redox-flow batteries configuration, the nominal power can be managed separately from the nominal energy of the batteries. Figure 11 summarizes the main differences between VRFBs and Li-ion batteries.

	VRFB	Li-ion
Life span	15-20 years	3-5 years
Power and capacity	Unlinked	Linked
Depth of Discharge	100% (+10.000 cycles)	80% (2500 cycles)
Operational risks	Intrinsically safe (aqueous electrolyte)	Protective circuitry needed, possible thermal runaway when crushed

Figure 11. Adapted from reference[60]. Main differences between VRFB and Li-ion technologies

2.4.1 LCOS – VRFB

Some assumptions regarding the LCOS are different for this technology. For example, the Depth of Discharge (DoD) is assumed to be 80% for Li-ion NMC technologies, but 100% for VRFB; the roundtrip efficiency (η_{RT}) is lower than for Li-ion NMC technologies, being of around 60% against 86% for Li-ion[35,61,62]. This VRFBs present capacity fade, which is irreversible capacity losses, whilst self-discharge losses are reversible. The fading can be due to vanadium crossover which can be fully recovered via electrolyte rebalance, or due to irreversible materials decay that requires replacement of components to recover performance. This capacity fading is considered negligible for the scope of this project, so it is not considered in the calculation of LCOS for VRFBs. The self-discharge of the technology is assumed the same as for Li-ion technologies, unless stated otherwise by the user. The model assumes a calendar life of 15 years and one cycle per day, with 5% of that time allocated to downtime, corresponding to a total cycle life of 5,201 cycles[52].

2.4.2 Supply chain – CRMs

Regarding CRMs present in the technology, it is important to highlight that the program will consider two different aspects:

1) Supply risk parameters of the CRMs: the supply risk indicator considering all the CRMs in the technology, its formula contains the different indicators (*i.e.* $HHI_{WGI-EPI}$, EU-IR, EU-EoL)
2) Percentage of Vanadium that is used specifically in batteries in the European market, this will serve as a basis for competitor analysis. The data is also taken from the RMIS platform of the European Commission.

First, regarding the amount of CRMs present in the technology. Li-ion NMC has lithium (Li), cobalt (Co), and natural graphite, all three of them being part of the battery's electrodes. In the case of VRFBs, and considering the most typical configuration of a VRFB (which uses graphite as the electrode felt and a solution containing vanadium and sulfuric acid as the electrolyte), the CRMs used in the technology are vanadium (V) and natural graphite[63,64].

After following the same calculations detailed in the previous section for the CRM methodology for Li-ion NMC, the supply risk of vanadium for VRFB is 0,02. Summing up the supply risk of natural graphite calculated in the previous section, the total supply risk of CRMs for VRFB is 0.18. The detailed calculations of the supply risk for vanadium can be found in the "Appendices" section of the work.

Thus, the following factors are obtained for VRFB:

- Factor 1 (VRFBs) – Supply risk for EU: 0,18
- Factor 2 (VRFBs)– Competition in the EU market: less than 2% used in batteries. 1% will be assumed in the scope of this work. Data from the RMIS European Commission's database is used.

2.4.3 Supply chain – CRL

The CRL scale for VRFB is analyzed in more detail in this section. The same scoring process as for Li-ion NMC (111) batteries previously explained is used for the analysis of the CRL of VRFB as well. The process starts by performing an extensive literature review on the characteristics of each of the VRFB components, following the checklists provided in the previous sections[58–60,65–70]. The results obtained are:

- Electrodes (anode and cathode): level 5. These electrodes are commercially available carbon-based materials.
- Electrolyte: level 5. Most electrolytes used in VRFBs are prepared using a solution of H_2SO_4 and/or HCl acids containing V, so the electrolyte readiness level complies with the conditions proposed by stage 5.
- Separator: level 4. There is still a lack of better development for membranes specific for the role needed in VRFB, as most commercially available ion-exchange membranes (IEMs) have not been developed for the application in VRFBs and have some specific functional shortcomings. It is important to highlight currently state-of-the-art ion-exchange membranes account for around 30-40% of the total cost of the VRFB hardware[71].

This gives a total score of 19 out of 20 possible points, when scaled from 0 to 1 it gives us a value of 0.94 for the BCRL of VRFBs, providing the third comparison factor of VRFBs:

- Factor 3 – Battery Component Readiness Level of VRFBs: 0,94

It should be pointed out that each technology requires specific components (apart of the four main components considered in this section) for the correct functioning of that system. Those components not necessarily contain a CRM but can have complicated supply logistics that hinder the development of the technology. This possible complications in logistics remains outside the scope of this work.

This section provides the third comparison factor of VRFBs:

- Factor 3 – Battery Component Readiness Level of VRFBs: 0,94

2.4.4 System Readiness Level

For the SRL as a whole, and according to a study made by the Environmental and Energy Study Institute in the U.S., VRFBs are considered to be in a level 8, compared with a level 9 for lithium-ion batteries[56]. RFBs represent less than 5% of the battery market. These technologies present low commercial maturity and lower energy densities, more commercial demonstrations in relevant environments are needed. Li-ion batteries on the other hand represent more than 90% of the global battery markets, having several projects around the world. This technology shows more commercial maturity, and it has been proved in a relevant environment, more improvements need to be done for the technology to remain competitive.

The scalability potential of these technologies differs from Li-ion battery systems due to the fact that capacity and energy are not linked in VRFBs, as their energy capacity can be increased by increasing the size of the tanks containing the electrolyte solution.

- Factor 5 – System Readiness Level for VRFBs: 8. SRL scaled = 0,8. This SRL is not fixed in the model, as the user can enter the installed capacity following the ranges provided in previous sections.

2.5 Limitations of the methodology

In this section, the main limitations of the methodology proposed are provided. Regarding the LCOS of the technologies, it is important to mention that the generalization of technical parameters (*i.e.* assuming depth of discharge, self-discharge, etc.) reduces the precision on the costs of the system, but it provides a framework to do a more realistic and simpler comparison between technologies, considering the information available. Therefore, this lack of data of most novel BESS, as well as the complexity and variability of technical parameters depending on the application, pushed the work towards finding a simple but still accurate approach for comparison. It is important to highlight that some technologies need more frequent and more expensive replacements than others. For example in the comparison used for this work, Li-ion NMC technologies would need more frequent components' replacements than VRFBs, having an impact in the total cost of the system. Unfortunately, this replacement information is usually not possible to obtain for novel technologies, so the decision of not considering it in the LCOS comparison of this project is made, despite hindering the precision of the results. Added to this, the data acquired for lithium-ion NMC technologies might rapidly change during the following years, especially the investment costs, so it should be updated for more precise results. Also, only the information for the CRMs present in Li-ion NMC and VRFB technologies (*i.e.* Li, Co, natural graphite, and V) are available in this first version of the model, the rest of the CRMs' information needs to be uploaded in the future. More information about this can be found in the "Model – Future updates" section.

Regarding the supply chain methodology section, it is important to highlight that the volatility of raw materials makes it practically impossible to give an accurate prediction of their possible situation in the future. In order to reduce this potential inaccuracy in results, the supply risk methodology considered the most advanced governance and environmental parameters available, thus considering both the political stability and the environmental development status of the exporting countries. Added to this, reliable data provided by the European Commission regarding the import reliance and the rate of recycling in the EU is used to reduce this uncertainty. Here, it is important to highlight that the rate of recycling might increase significantly in the near future, especially considering the new European regulations regarding batteries and currently under revision[72]. A substantial increase in this rate of recycling could decrease in a significant way the potential supply chain risks and disruptions of these CRMs, so it is crucial to highlight that this is a data that might limit the model accuracy in the future. Also, the data provided (*i.e.* WGIs, EPIs, EU-IR, etc.) for the calculation of the supply risk has to be constantly updated for more precise results. Only the information for the CRMs present in Li-ion NMC and VRFB technologies (*i.e.* Li, Co, natural graphite, and V) are available in this first version of the model, the rest of the CRMs' information needs to be uploaded in the future. More information about this can be found in the section "Model – Future updates needed".

On the second section of this methodology, the Battery Component Readiness Level approach has a strong embedded subjectiveness. Thus, the checklist method is proposed to reduce this subjectiveness in the results, serving as a guide to provide the accurate stage of this component. An extra limitation this section has is the potential lack of information of individual components for very novel battery technologies, making it more complicated to give the stage for all four main components proposed. In this case, if the stage of only one or a few components is known, it should be used as the baseline for all components (*i.e.* it is known that the cathode is in Stage 2, but information about the other three components is not given, one should assume all four components are Stage 2). The same subjectiveness is present in the Technology Readiness Level for the whole system, so in this case the System Readiness Level is linked with the installed capacity of the technology to reduce the uncertainty in the results. If the technology still does not have any installed capacity, the user should follow the same checklist method to determine the level between 1 and 5 of such system.

Regarding the effects of each of the supply chain stages to the LCOS of the technology, a graphic comparison between the four factors is provided that serves as an extra tool in the decision-making process regarding novel BESSs. Given the uncertainty and volatility of global supply chains in recent years, there is the possibility that a supply chain disruption in the future impacts the final LCOS of a battery technology in a completely different way than proposed here. The work provides a comparison directly with Li-ion NMC cost, supply chain risk, and system readiness level with current data available (*i.e.* 2022).

Finally, it is important to highlight as well that the main goal of this work is to act as a first approach to compare battery technologies in a more holistic way with data available nowadays, by considering their supply chain's risk and maturity level into their Levelized Costs of Storage, serving as a decision-making tool for future investments. This work should not be used or considered as a tool to calculate precise LCOS for technologies, but as a general comparison method between them.

3. MODEL

3.1 Introduction

In this section, a detailed explanation of the coding developed to implement the methodology previously mentioned is given. The programming language used in this modelling is Python v3.10, using Visual Studio Code as the code editor. The final goal of the code is to show to the user a graphical comparison of the LCOS of the technology chosen with lithium-ion NMC batteries, used as a baseline. The model also compares the four factors related with both the supply risk and the readiness levels of the technology and gives a graphical comparison of these factors as well. The flowchart showing the structure of the code is shown in Figure 12.

Table 4. Model's structure and functioning summary

Step in the model	Function
Li-ion NMC data	Data of Li-ion NMC batteries is pre-entered in the model by the user (LCOS, CRM…)
Data VRFB	Data of VRFB is pre-entered in the code. Model asks only for cost of energy of the technology.
LCOS calculations	In this part, the formula to calculate the LCOS with the data provided is provided.
Installed capacity	Here, the model asks for the installed capacity of the technology to be compared.
CRM in technology	The program asks if the system to be compared contains or not a CRM.
Which ones	If the answer is positive, the program asks which is the CRM in the technology.
Total supply risk EU	Depending on the CRM, the program calculates its supply risk with data pre-entered.
Competition	Depending on the CRM, the program calculates its competition taking the data pre-entered.
BCRL and SRL	After calculating the CRM section, the program calculates its BCRL and SRL.
Graphs	Finally, the model graphs the LCOS, supply risk and readiness levels of the technology.

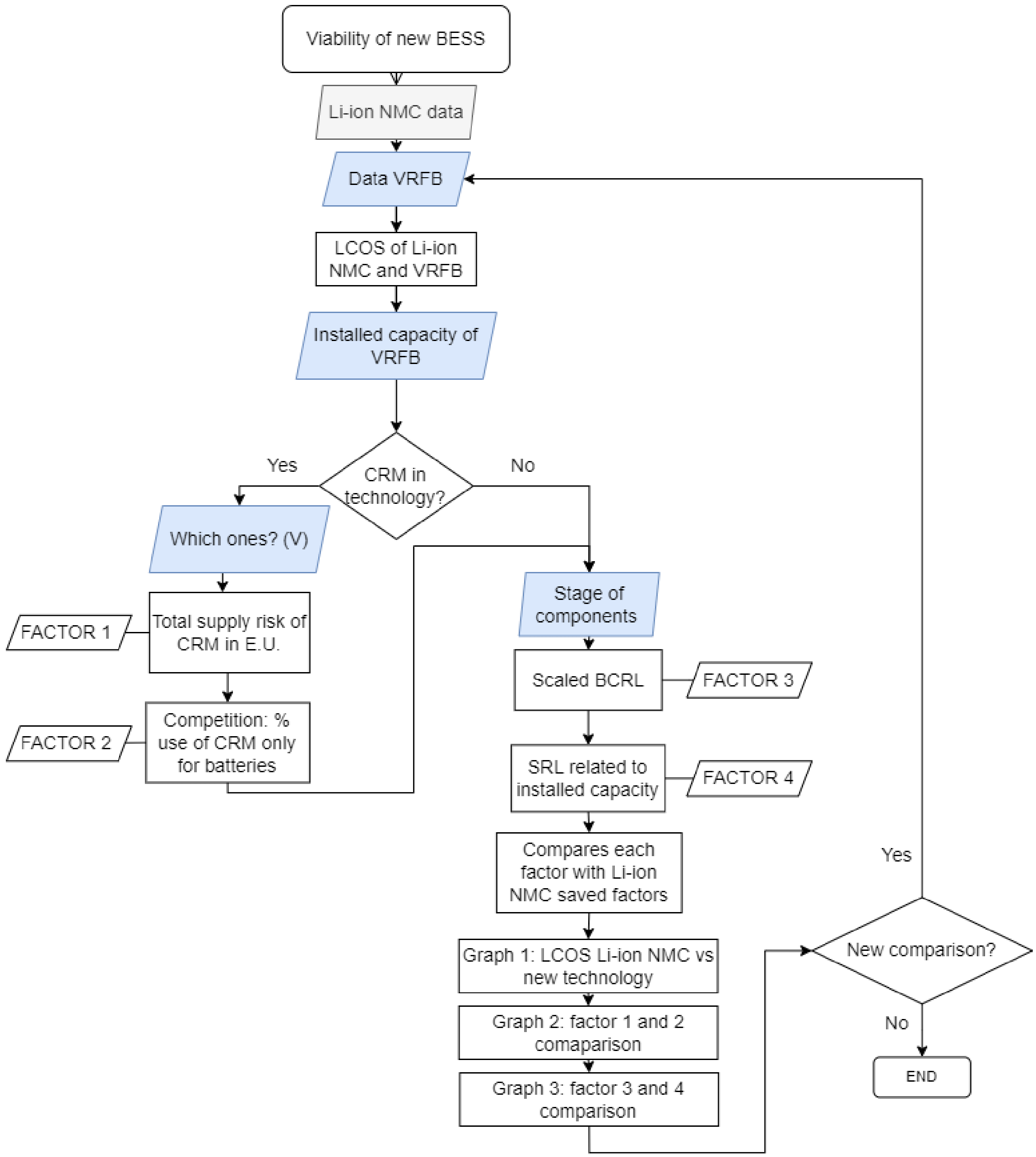

Figure 12. Simplified flowchart of the model

3.2 Data considered in the model

The data considered for the comparison of this work both for Li-ion NMC and VRFBs is taken from the "2020 Grid Energy Storage Technology Cost and Performance Assessment" report done by the U.S. Department of Energy and the Pacific Northwest National Laboratory (PNNL)[52]. They have performed a thorough analysis of costs for energy storage technologies and the data is reliable enough to be used as the basis for this model. The data calculated in the report takes into a series of considerations, such as one cycle per day for the technology, a specific cycle life, depth of discharge, roundtrip efficiencies and self-discharge, as well as a percentage of the CAPEX to be considered as the operation and maintenance cost. Also, the data considered includes the costs of energy and power depending on the energy density of the system, as there is data available for systems of 1, 10 and 100MW with discharge durations of 2, 4, 6, 8, and 10 hours. For the results sections, the calculations are performed also for systems of 0.5, 5, 50 and 150 MW in a discharge duration range between 2 and 8 hours, with a 1-hour interval. In the model, a linear interpolation between the two closest values is considered depending on the user input. The cycle degradation calculation, discount rate, and general LCOS formula is taken from the Schmidt et al. 2021 article as described in the previous sections[27]. As highlighted in the methodological section, all the data considered regarding critical raw materials is taken from the RMIS European Commission database, whilst the supply risk factor considers a combination of data both from the EU RMIS database and the World Governance Index and Environmental Performance Index[45,53,54].

3.3 Structure

It is important to highlight that the model has been developed entirely by me. Considering that the project itself uses a novel methodology and approach to the feasibility of BESSs, 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 technologies and VRFB to calculate the LCOS and do the final graphical comparisons. Regarding all the files that are called by the main file, 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. In this section, the programming performed in each of the files and the general functioning of the code is explained in more detail.

It should be noticed that data will be saved in separate files using other programs embedded in Python. JSON (JavaScript Object Notation) is a lightweight data-interchange format that facilitates data saving and processing, it will be used to save most of the data processed in the model. Pandas (Python Data Analysis Library) will be used to store and manipulate data stored in spreadsheets/databases, as it makes the data exploration and processing easier.

- Li-ion NMC LCOS data collection: main.py, costs_LiNMC.py

The objective of these files is to get and process the data to get the LCOS for Li-ion NMC. It is important to highlight that the program takes into account the nominal power and discharge duration provided by the user for the 2nd technology to be compared (VRFB for the scope of this work), so that a coherent comparison between the technologies can be made. Thus, the main code saves this data entered by the user in a separate JSON file, this data will be used in the LCOS_func_Li.py file to calculate the LCOS of the technology. On the other hand, the second file (*i.e.* costs_LiNMC.py) contains the data regarding the cost of energy and power of Li-ion NMC depending on the nominal energy of the system.

First, the data regarding nominal power and discharge duration is taken from the main code, which asks the user inputs and saves it in a separate JSON file. The nominal power is entered in MW and the discharge duration in hours. Figure 13 shows this process:

```
Power_and_discharge = {"Nom_p":int(input("Enter the nominal power of the technology (MW): ")),
"Discharge_duration": float(input("Enter discharge duration (h): "))}
json_variables = json.dumps(Power_and_discharge)

with open('json_variables.json', 'w+') as file:
    file.write(json_variables)
```

Figure 13. User input regarding size (in kW) and discharge duration (hours) of the system to be compared

Then, the program takes the nominal energy (nominal power times discharge duration) and looks for the price related to this specific nominal energy in the pandas file created in the “costs_LiNMC” file, using the data taken from the U.S. Department of Energy 2020 report as previously mentioned. The first section of the “main.py” code goes to this file and looks for the cost of energy and power accordingly. All the data considered for this section can be found in the “Appendices” section, whilst Figure 14 shows this process, as well as the calculations of the costs of power and energy. The information is available from systems of sizes 0.5, 1, 5, 10, 100 and 150 MW with discharge durations of 2 to 8 hours (in 1 hour interval periods), in a similar fashion that for the VRFB systems. For more precision in the results considering the data available, the LCOS of both technologies can only be calculated with the previously mentioned power capacities and discharge duration. The input nominal power is multiplied by 1000 to get the right units (kW) for the LCOS calculations.

```python
import json
with open('json_variables.json', 'r') as f:
    Input_variables = json.load(f)
Nom_e = float((Input_variables["Nom_p"]*1000)*Input_variables["Discharge_duration"])

print('This is the data set for Li-ion NMC: ')
from costs_LiNMC import data
Ce1 = data.loc[data.Nom_e1==Nom_e].energy
Cp1 = data.loc[data.Nom_e1==Nom_e].power
Ce1 = Ce1.to_list()
Cp1 = Cp1.to_list()
Ce_Li = Ce1[0]
Cp_Li = Cp1[0]
print(Ce_Li)
print(Cp_Li)
```

Figure 14. Cost of energy and power depending on user input Li-ion NMC

Next, the data used for the calculation of the LCOS is saved in a JSON file, which changes depending on the user inputs mentioned before. Figure 15 shows this part of the code, including the assumptions mentioned in the methodology section regarding technical parameters of Li-ion NMC.

```python
#O&M info for Li_NMC technology
Fixed_OM =0.02*((Cp_Li*(Input_variables["Nom_p"]*1000))+(Ce_Li*Nom_e)) #Fixed Operation and maintenance costs, assumed 2% of the cost of CAPEX
Variable_OM=0.005*((Cp_Li*(Input_variables["Nom_p"]*1000))+(Ce_Li*Nom_e)) #Variable O&M costs, assumed 0.5% of the CAPEX
Cycle_life = 1200 #Amount of cycles the technology can perform, in number of cycles
Cycle_deg=1-0.8**(1/Cycle_life) #Degradation of the technology, related with cycle life
Cycles_pa = 365 #Cycles the technology does in one year
#Depth of discharge DoD (in %), assumed to be 80% for Li-ion NMC for this work
#Round-trip efficiency RTE (in %), assumed to be 86% for Li-ion NMC for this work
#Self-discharge (in %), assumed to be 1% per year

import json
LCOS_LiNMC = {"Cp": Cp_Li, "Nom_p": (Input_variables["Nom_p"]*1000), "Discharge_duration": Input_variables["Discharge_duration"] ,
"Nom_e": Nom_e, "Ce": Ce_Li,"FixedOMcosts": Fixed_OM, "VariableOMcosts": Variable_OM,"Cycles_pa": Cycles_pa,
"Calendar_life": Cycle_life/Cycles_pa, "DoD":0.8, "RTE":0.86,
"Self_dis":0.01, "Cycle_deg": Cycle_deg, "Discount_rate": 0.08
                }
json_LiNMC=json.dumps(LCOS_LiNMC)

#Saving the data in json file
with open('json_data_LCOS_LiNMC.json','w') as outfile:
    outfile.write(json_LiNMC)
```

Figure 15. JSON file containing the data needed for LCOS of Li-ion NMC

- Li-ion NMC LCOS calculations: LCOS_func_Li.py

Once all the data needed is collected and saved, this third file contains the functions needed to perform the calculation for the LCOS of this technology, following the formula mentioned in the methodology section. The file "LCOS_func_Li" opens the data saved in the JSON file previously mentioned, and uses the formula mentioned in the "Methodology" section, using the data saved in the JSON file. This file has the values for the total cost of CAPEX, O&M (both fixed and variable), and the electricity discharged during the technology's lifetime. The final value of the LCOS of Li-ion NMC is calculated in the main code. Figure 16 shows the calculation of the CAPEX, O&M and electricity discharged for Li-ion NMC:

```
#Formula Investment cost LCOS_json data download
LCOS_CAPEX= (LCOS_data["Cp"]*(Input_variables["Nom_p"]*1000))+(LCOS_data["Ce"]*LCOS_data["Nom_e"])
LCOS_CAPEX_k = LCOS_CAPEX/1000
format_LCOS_CAPEX= "{:.0f}".format(LCOS_CAPEX_k)

#Formula Operating & Maintenance costs_json data download
LCOS_OM= (0.02*LCOS_CAPEX)+(0.005*LCOS_CAPEX)
LCOS_OM_k=LCOS_OM/1000
format_LCOS_OM= "{:.0f}".format(LCOS_OM_k)

#Formula Electricity discharged_json data download
LCOS_ED_Li_1=(LCOS_data["Cycles_pa"]*LCOS_data["DoD"]*LCOS_data["Nom_e"]*LCOS_data["RTE"]*(1-LCOS_data["Self_dis"]))
LCOS_ED_Li_Sum = LCOS_data["Calendar_life"]-1
LCOS_ED_Li_Cycledeg = ((1-LCOS_data["Cycle_deg"])**(((LCOS_data["Calendar_life"]-1)*LCOS_data["Cycles_pa"])))/
((1+LCOS_data["Discount_rate"])**LCOS_data["Calendar_life"])
LCOS_ED_Li = LCOS_ED_Li_1*(LCOS_ED_Li_Sum*LCOS_ED_Li_Cycledeg)
LCOS_ED_GWh=LCOS_ED_Li/1000000
format_LCOS_ED_Li= "{:.2f}".format(LCOS_ED_GWh)
```

Figure 16. Calculation of parameters (CAPEX, O&M, electricity delivered) for LCOS of Li-ion NMC

- Li-ion NMC CRMs supply risks calculations: CRMs_LiNMC.py

This file contains all the information and calculations of the amount of CRMs present in Li-ion NMC, as well as the supply risk indicator. First, some information about the countries importing the material to the EU is entered manually, following the steps and data considered in the methodology section. Once the data about the supply concentration of the main 3 countries importing to the EU for both primary and refined Li and Co, as well as for primary natural graphite, the program calculates the HHI for the country. After this, the WGI previously explained is entered manually after doing an average of the data of the last 3 years available (*i.e.* 2018 to 2020) for all 6 indicators related to the WGI (see section “Supply Chain Methodology – Part 1: Critical Raw Materials” for more information). The WGI is scaled to 0 to 1. Once the WGI has been calculated, now the scaled EPI indicator is manually entered. Then the HHI containing both WGI and EPI indicators is calculated by the model. The EU-IR and the EoL-RIR Are manually entered after taking the data from the EU-RMIS webpage. After all these data has been calculated, the supply risk indicator for each CRM can be calculated. Figure 17 shows this final step of the supply risk indicator calculation, the detailed process of the calculations of the HHI, WGI, EPI, IR and EoL-RIR is explained in previous sections.

```
EU_IR_Lipr= 0.87
EoL_RIR_Lipr= 0
Supplyrisk_Lipr=HHI_WGI_EPI_Lipr*EU_IR_Lipr*(1-EoL_RIR_Lipr)
format_Supplyrisk_Lipr="{:.3f}".format(Supplyrisk_Lipr)
print('The supply risk for the EU of primary Li is equal to ' +str(format_Supplyrisk_Lipr))
```

Figure 17. Supply risk calculation of Li-ion NMC

The exact same process is then repeated for the rest of the CRMs present in Li-ion NMC chemistries.

- Li-ion NMC and VRFB information about Battery Component Readiness Level: BCRL.py

This file contains the Battery Component Readiness Level of both Li-ion NMC and VRFB technologies. It is important to mention that this section needs previous research and a comparison with the provided checklist to assess the readiness level of each of the components. In this case, the research is done for the technologies involved in the scope of this work. In further uses of the model to compare other technologies with Li-ion NMC the user should do some research and provide the readiness level manually.

The decision-making process for the values provided in this section can be found in the "Methodology" section. Figure 18 shows the values and the scaling process followed by the model. It is important to consider that these values will be saved as a "Factor 3" for comparison to assess the potential effects on LCOS. The checklist provided to the user can be found in the "Appendices" section.

```
#BCRL_LiNMC
BCRL_Anode_LiNMC= 5
BCRL_Cathode_LiNMC= 5
BCRL_Electrolyte_LiNMC= 5
BCRL_Separator_LiNMC= 5
CRL_level_LiNMC= BCRL_Anode_LiNMC+BCRL_Cathode_LiNMC+BCRL_Electrolyte_LiNMC+BCRL_Separator_LiNMC
CRL_scaled_LiNMC= (CRL_level_LiNMC-4)/(20-4)
#BCRL_VRFB
BCRL_Anode_VRFB= 5
BCRL_Cathode_VRFB= 5
BCRL_Electrolyte_VRFB= 5
BCRL_Separator_VRFB= 4
CRL_level_VRFB= BCRL_Anode_VRFB+BCRL_Cathode_VRFB+BCRL_Electrolyte_VRFB+BCRL_Separator_VRFB
CRL_scaled_VRFB= (CRL_level_VRFB-4)/(20-4)
```

Figure 18. BCRL of Li-ion NMC and VRFB technologies

- VRFB LCOS calculations: LCOS_func_VRFB.py

This file contains the exact same formula that in the "LCOS_func_Li.py" file, following the same procedure explained and using the data provided for VRFB mentioned in the "Methodology" section (*i.e.* higher cycle life, depth-of-discharge, etc.)

- VRFB CRMs supply risks calculations: CRMs_tech2.py

This is the file containing all the information regarding the CRM present in VRFB (*i.e.* Vanadium and natural graphite) it follows the exact same procedure as explained in the sections "Supply Chain Methodology" and "File containing the calculations about CRMs in Li-ion technologies". The data used for the calculation of these indices regarding V can be found in the "Appendices" section.

- VRFB + Li-ion NMC data processing: calculations and comparison: main.py

This is the main file of the code, where the comparison of the LCOS of the technologies occurs, as well as the calculations on the supply chain and technological readiness level risks and the graphical representation of both. As a side note, it is important to note that for VRFB systems the cost of power is considered to be of 155 $/kW for systems with nominal energy capacities ranging between 0 and 40 MWh, 133 $/kW for systems between 40 and 400 MWh, and 115 $/kW if the nominal energy capacity of the system is more than 400 MWh. Due to the data availability, the maximum nominal energy capacity that the model can process are 1200 MWh.

The first section of this file has been previously explained (see section "Li-ion NMC LCOS data collection"), where the user inputs the nominal power and discharge duration of the system, and the program calculates the Li-ion NMC data needed for the calculation of its LCOS. The calculation of the cost of power for VRFB is performed in a similar way than for Li-ion NMC technologies (see Figure 14), taking the data from a pandas file named "costs_VRFB.py" containing all the values for the different nominal energies of VRFB systems. Then the "main.py" file takes the data from this file, as shown in Figure 19. Secondly, this file calculates the LCOS of VRFB, following the similar procedure previously explained by Li-ion NMC in the "main_LCOSLi.py" section. Figure 20 shows an overview of the calculation, where the user enters the system size (in MW) and discharge duration (in hours) desired, this file also uses a "LCOS_func_VRFB.py" file including the detailed formulas for the LCOS calculations, which is very similar to the "LCOS_func_Li.py" one. The data entered by the user, as well as the technical parameters of the technology, are both saved in separate JSON files. Following the formula provided in the methodology section and considering CAPEX, O&M costs and electricity discharged during the system's lifetime.

```
from costs_VRFB import data2
Cp_VRFB = data2.loc[data2.Nom_e2==Nom_e].power2
Cp_VRFB = Cp_VRFB.to_list()
Cp = Cp_VRFB[0]
```

Figure 19. Cost of energy and power considered in the calculation of the LCOS of VRFB

```python
import json
LCOS_VRFB = {"Cp": Cp, "Nom_p":Nom_p_kW,"Discharge_duration": Discharge_duration , "Nom_e": Nom_e, "Ce": Ce,
            "FixedOMcosts": Fixed_OM, "VariableOMcosts": Variable_OM,
            "Cycles_pa": Cycles_pa,"Calendar_life": Cycle_life/Cycles_pa, "DoD":0.9, "RTE":0.68,
            "Self_dis":0.01, "Cycle_deg": Cycle_deg, "Discount_rate": 0.08
            }
json_VRFB=json.dumps(LCOS_VRFB)

#Saving the data in json file
with open('json_data_LCOS_VRFB.json','w') as outfile:
    outfile.write(json_VRFB)

#Calculating the LCOS of the technology using json data

# LCOS calculation
from LCOS_func_VRFB import LCOS_CAPEX_V
from LCOS_func_VRFB import LCOS_OM_V
from LCOS_func_VRFB import LCOS_ED_V

LCOS_VRFB= (LCOS_CAPEX_V+LCOS_OM_V)/LCOS_ED_V
LCOS_VRFB_MWh = LCOS_VRFB*1000 #LCOS of VRFB in $/MWh
format_LCOS_V= "{:.0f}".format(LCOS_VRFB_MWh)
print('The LCOS of the VRFB technology is '+ str(format_LCOS_V) +' $/MWh')
```

Figure 20. LCOS calculation of VRFB

After this, the model saves the value of both LCOS of Li-ion NMC calculated in the files previously highlighted and the values of LCOS for VRFBs. Once this information is known, the model starts with the part related with the 4 factors that could potentially increase the cost of such technology compared:

- Factor 1 – Supply risk for EU: this factor shows the potential risk in supply for that CRM to the EU, considering the percentage of the CRM only in one country, the governance levels of those countries, how close are they to achieve their environmental goals, how much does the EU depend on other countries to import the material, and how much of the material is recycled for manufacturing new components.
- Factor 2 – Competition in the EU market: gives an overview on the allocation of the CRM specifically for battery manufacturing.
- Factor 3 – Battery Component Readiness Level. Shows the readiness level of the 4 main components of a BESS: anode, cathode, electrolyte, and separator.
- Factor 4 – System Readiness Level. Relates the installed capacity of the technology to the readiness level of the whole system, going from 1 to 10. Levels 1 to 5 have no installed capacity yet.

Regarding Factor 1, the model asks the user if the technology has CRMs or not, then making the user choose which CRM specifically. Once the user has chosen, the file looks the information related with CRM in the "CRMs_tech2.py" file explained in the previous section. The model saves this information for further comparison with Li-ion NMC data. Figure 21 shows this section of the model:

```python
#CRM assessment
while True:
    Num_CRM = input("Does the technology uses a CRM? (Yes/No): ")
    if Num_CRM == "Yes" or Num_CRM == "yes":
        num = True
        CRM_in_tech = input("Which one does it have? (options: V, Li, Co, Nat. graphite): ")
        if CRM_in_tech == "V" or CRM_in_tech == "Li" or CRM_in_tech == "Co" or CRM_in_tech == "Nat. graphite":
            crm = True
            from CRMs_tech2 import Supplyrisk_Vref
            print("The supply risk of V (Factor 1) = " + "{:.2f}".format(Supplyrisk_Vref))
            break
        else:
            print("Answer should be V, Li, Co or Nat. graphite... Enter again! ")
    elif Num_CRM == "No" or Num_CRM == "no":
        break
    else:
        print("Answer should be Yes or No...")
```

Figure 21. Factor 1 - CRM assessment of VRFB

The data related with Factor 2 – Competition is taken from the RMIS European Commission's database and entered manually; the values are shown in Figure 22. A simple average is then calculated before the visual comparison at the end of the file.

```python
#Factor 2: % of CRM only used for batteries (assess competition)

#In VRFB:
Factor_2_V = 0.02
#In Li-ion NMC:
Factor_2_Li = 0.32 #32% of Li in EU used only for batteries
Factor_2_Co = 0.46 #46% of Co in EU used only for batteries
Factor_2_NG = 0.16 #16% of NG in EU used only for batteries
```

Figure 22. Factor 2 – Competition around CRMs in EU market

Next, the Factor 3 data is downloaded from the BCRL.py explained beforehand. This information will be used for the visual comparison as well. Figure 23 shows the variables import performed in this section of the code:

```python
#Factor 3: BCRL comparison
from BCRL import CRL_scaled_LiNMC
Factor_3_LiNMC=CRL_scaled_LiNMC
from BCRL import CRL_scaled_VRFB
Factor_3_VRFB=CRL_scaled_VRFB
```

Figure 23. Factor 3 – BCRL information

For the calculation of the final factor, the code first asks the user if the technology has any installed capacity. If the answer is positive, the program then asks for the user to enter a value in MWs of the capacity available, calculating the System Readiness Level (SRL) accordingly and following the ranges showed in the methodological section. Figure 24 displays this interaction, providing one example of the ranges mentioned as well. If the answer is negative, the user has to enter manually the SRL ranging between 1 and 5, as shown in Figure 25.

```
#Factor 4: SRL
while True:
    Installed_cap = input("Does the technology has any installed capacity? (Yes/No): ")
    if Installed_cap == "Yes" or Installed_cap == "yes":
        num = True
        Factor_SRL_VRFB= ()
        Installed_capacity = int(input("Enter the installed capacity of the technology (in MW): "))
        if Installed_capacity in range(1,9999//1000):
            Factor_SRL_VRFB = 6
```

Figure 24. Factor 4 – SRL and relation with installed capacity

```
if Installed_cap == "No" or Installed_cap == "no":
    Factor_SRL_VRFB = int(input("Please enter the SRL of your technology (from 1 to 5) according to the checklist
    print("The SRL of your technology is " + str(Factor_SRL_VRFB))
    break
else:
    print("Answer should be Yes or No... Enter again! ")
```

Figure 25. Factor 4 – SRL and user input if there is no installed capacity

Once all the needed data regarding LCOS and the four factors of both technologies has been calculated, the code can show the graphical comparison. The goal of this section is just to display the logic and programming performed; the detailed analysis of the results is provided in further sections.

First, a graphic comparison of the LCOS of Li-ion NMC and VRFB is provided, using the matplotlib library to create the plots. In this section, the code takes the values regarding the LCOS of Li-ion NMC performed in the “LCOS_func_Li.py” file, as explained earlier. The code executed to provide this result can be seen in Figure 26, while Figure 27 shows an example result for a 1000kW and 4-hour VRFB system. More details on the results are given in the “Results” section of the work.

```
#Graphic comparison of LCOS
import matplotlib.pyplot as plt
import numpy as np
from LCOS_func_Li import LCOS_CAPEX
from LCOS_func_Li import LCOS_OM
from LCOS_func_Li import LCOS_ED_Li

LCOS_Li_ion= (LCOS_CAPEX+LCOS_OM)/LCOS_ED_Li
LCOS_li_ion_MWh = LCOS_Li_ion*1000 #LCOS of Li-ion NMC in $/MWh
format_LCOS_li= "{:.0f}".format(LCOS_li_ion_MWh)
print('The LCOS of a comparable Li-ion NMC is '+ format_LCOS_li +'$/kWh')

Technologies = ['Li-ion NMC', 'VRFB']
USD_per_MWh = [LCOS_li_ion_MWh, LCOS_VRFB_MWh]

plt.bar(Technologies, USD_per_MWh)
plt.title('LCOS of Li-ion NMC vs. VRFB')
plt.xlabel('Technologies')
plt.ylabel('$/MWh')
plt.show()
```

Figure 26. Graphic comparison of LCOS of Li-ion NMC vs. VRFB

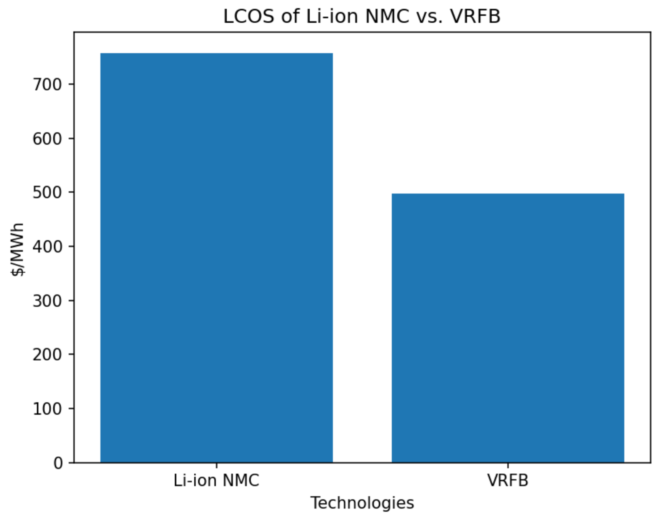

Figure 27. Example of LCOS comparison for a 1MW and 4h system (758 $/MWh vs. 497 $/MWh)

After performing this comparison, the program gives two extra graphs. The first graph provides a comparison including the first two factors (supply risk and competition), whilst the second provides a comparison of the readiness level of the technology (including the Battery Component Readiness Level and the Systems Readiness Level scales in the same graph). Figure 28 shows the process followed by the program to plot the comparison of the first two factors. This first comparison gives an overview of the possible risks in supply chain surrounding each of the technologies, whilst the second one gives an overview of how mature the technology is. A combination of the three graphs provides the user with a useful tool to assess potential problems around the technology, giving an idea of where the major risks are and how feasible the system is overall.

```
from CRMs_LiNMC import Supplyrisk_Lipr
from CRMs_LiNMC import Supplyrisk_Liref
from CRMs_LiNMC import Supplyrisk_Copr
from CRMs_LiNMC import Supplyrisk_Coref
from CRMs_LiNMC import Supplyrisk_NGpr
from CRMs_tech2 import Supplyrisk_Vref
Factor_1_LiNMC = Supplyrisk_Lipr+Supplyrisk_Liref+Supplyrisk_Copr+Supplyrisk_Coref+Supplyrisk_NGpr
Factor_1_VRFB= Supplyrisk_Vref+Supplyrisk_NGpr
Technologies_1 = ['Li-ion NMC', 'VRFB']
Supply_risk = [Factor_1_LiNMC, Factor_1_VRFB]
Factor_2_LiNMC = 1-(Factor_2_Li+Factor_2_Co+Factor_2_NG/3)
Factor_2_VRFB = 1-(Factor_2_V+Factor_2_NG/2)
Competition = [Factor_2_LiNMC, Factor_2_VRFB]

X_axis = np.arange(len(Technologies_1))

plt.bar(X_axis- 0.2, Supply_risk, 0.4, color ='red', label = 'Supply risk')
plt.bar(X_axis + 0.2, Competition, 0.4, color='blue', label = 'Competition indicator')
plt.xticks(X_axis, Technologies_1)
plt.title('Supply risk of CRM for Li-ion NMC and VRFB')
plt.xlabel('Technologies')
plt.ylabel('Supply risk indicators')
plt.legend(loc = 'upper left')
plt.show()
```

Figure 28. Graphical comparison of the supply chain CRMs factors (supply risk and competition) of Li-ion NMC vs. VRFB

Figure 29 shows the process followed to graph the last comparison (of factors 3 and 4), while Figures 30 and 31 display the example result, using the same 1000kW and 4h values as before. Regarding the second comparison, the example considers 100 MWh of installed capacity of VRFBs.

```
#Factor 3: BCRL + Factor 4: SRL

Factor_4_LiNMC = 0.9
Factor_4_VRFB = Factor_SRL_VRFB/10
BCRL = [Factor_3_LiNMC, Factor_3_VRFB]
SRL = [Factor_4_LiNMC, Factor_4_VRFB]

X_axis = np.arange(len(Technologies_1))

plt.bar(X_axis- 0.2, BCRL, 0.4, color ='red', label = 'Battery Components Readiness Level')
plt.bar(X_axis + 0.2, SRL, 0.4, color='blue', label = 'System Readiness Level')
plt.xticks(X_axis, Technologies_1)
plt.title('Readiness level of Li-ion NMC and VRFB')
plt.xlabel('Technologies')
plt.ylabel('Readiness level indicators (scale 0 to 1)')
plt.legend(loc = 'lower left')
plt.show()
```

Figure 29. Graphical comparison of the readiness level factors (BCRL and SRL) of Li-ion NMC vs. VRFB

As an added note, the higher the first two factors are (related with supply chain), the higher the potential risk in supply. It is important to note that the second factor, related to competition level, is subtracted to 1, as the higher is the percentage used specifically for battery production, the lower the potential disruption in its supply. On the other hand, the higher the last two factors are (readiness level), the higher is the readiness level. So, it is important to have in mind that a higher value of the graphic comparing Factor 1 and 2 of the technology represent a higher risk, which is worse for that technology. To the contrary, a higher value in the graph representing the Factors 3 and 4 show a higher readiness level, which is better for that system.

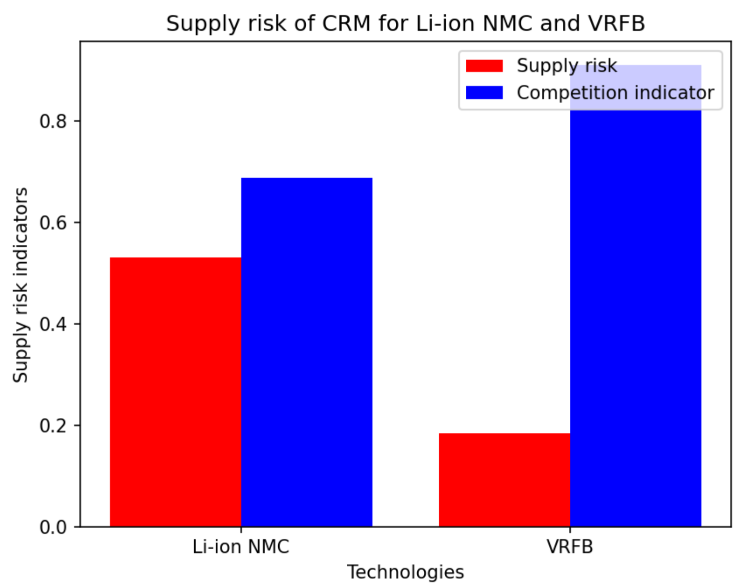

Figure 30. Example of supply chain CRMs comparison for a 1MW and 4h system (Factor 1: 0.53 vs.0.18, Factor 2: 0.69 vs. 0.90)

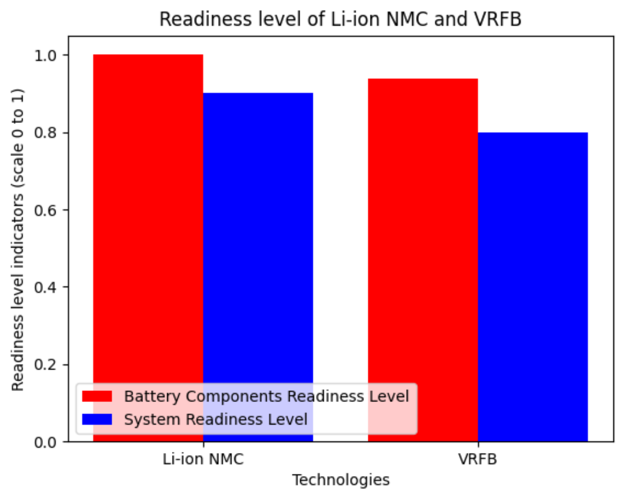

Figure 31. Example of readiness level factors comparison for a 1MW and 4h system (Factor 3: 1.0 vs.0.94, Factor 4: 0.9 vs. 0.8)

It is noteworthy to mention that the data used for the calculations of VRFBs is also taken from the U.S. Department of Energy and PNNL report mentioned. Thus, the user interaction and inputs added serves as a basis for the program to be used in the future for comparisons between Li-ion NMC chemistries and other technologies aside of VRFBs. This added features also leaves the possibility to the user of entering costs taken from external sources and still provide a valid comparison with the Li-ion NMC pre-established values. These future possibilities and updates that the program could need are highlighted and developed in more detail in the next section. This section differs from the final section "Future work" as it serves the purpose of analyzing the possibilities surrounding exclusively the model, whilst the last section focuses on the work overall.

3.4 Future updates

The model is developed to calculate the LCOS difference between Li-ion NMC (111) and VRFB technologies, considering potential risk associated with the 4 factors related to supply risk to the EU, competition within the EU market, Battery Component Readiness Level, and installed capacity/System Readiness Level. Regarding this LCOS, an increase in data availability of BESSs could give place to the possibility of a future update in which the user can vary different technological parameters and still obtain a realistic comparison of LCOS of the technologies. Also, this data readiness would provide the possibility to include the value at the EoL of the technologies into the calculation and provide more precise results.

It would be useful to validate the model by using historical data for various parameters, refining it by using real results. This analysis of results would considerably expand the precision and capabilities of the model, as well as its future use with novel technologies.

For the scope of this work, the program only handles data related with the CRMs present in these two technologies (V, Co, Li, and natural graphite), serving as a methodological baseline for future uses with other technologies. In order to compare other battery technologies using different CRMs, the methodology regarding competition and supply risk of these materials should be repeated and the data available for all the CRMs in the RMIS database can be used. The factors used for the supply risk calculation should be constantly updated for more precision in the results. External political, economic, and social factor deeply affect the supply chains of such materials to the EU, so the values considered in this model can suffer significant alterations in the following years. Also, it would be interesting to add the materials' predicted future requirements in the model, as some materials could potentially become CRMs in the upcoming years. For the first section of the supply risk calculation, all three factors considered (the HH index, the WGI, and the EPI) are related with the countries importing the most to the EU with the latest data available in the RMIS database, but this dynamic is expected to change in the upcoming years due to more energy independency and the creation of internal supply chains in the EU Due to this same fact, the Import Reliance and the End-of-Life Input Recycling Rate are expected to improve in the coming years as well, as the EU decreases its dependency in inputs (so decreasing the Import Reliance factor) and increasing the rate of recycling in CRMs present in batteries. Therefore, Factor 1 – Supply risk has the biggest potential of changing in the following years due to these dynamics. As mentioned previously, adding some level of forecast (*i.e.* introducing historic values and predictions) to the model would improve the precision of the results, in this case a more precise EoL-RIR and IR factors for a specific material.

Next, Factor 2 related with the competition inside the EU market is expected to improve, as the share of CRMs used for batteries is predicted to increase during the following years[41,44,45,72]. This factor should be updated using the RMIS database information.

Regarding Factors 3 and 4, the technological development of VRFBs in terms of components improvements and scalability should be updated if needed for more precise results.

In a similar fashion and as an extra layer, the impact on the LCOS of the factors vary from traditional electrochemical batteries and redox flow batteries. The effect that each component of the system has in the overall system is different in both technologies, so a methodology around how the CRMs impact such cost could be developed for more robustness in the results.

4. RESULTS

In this section, an overview of the results after doing some iterations and an analysis of the comparison between Li-ion NMC and VRFB technologies are provided. The section is divided into four different parts, providing the main results and the analysis of:

- The LCOS comparison of the technologies
- The supply risk indicators of the technologies and the competition in the EU market
- The Battery Component Readiness Level comparison
- The System Readiness Level comparison

4.1 LCOS – Results

For this section, data is collected by iterating the model for systems with sizes 0.5 MW, 1 MW, 5 MW, 10 MW, 50 MW, 100 MW, and 150 MW and discharge durations starting from 2 hours until 8 hours with a 1-hour discharge duration increment. After this process, the results obtained for the 1, 10 and 100 MW systems are plotted, as shown in Figure 32. The data used for these calculations regarding the cost of power and cost of energy can be found in the "Appendices – Cost of VRFB" section. For systems lower than 2.000 kWh of energy size and for systems having nominal energy ranging in between the data available, a linear interpolation of data is made to get the costs of energy. The cost of power is assumed to be the same for 0.5, 1 and 5 MW systems (155 $/kW), for 10 and 50 MW is assumed to be 133 $/kW and for 100 and 150 MW systems is assumed to be 115 $/kW). For example, if a system of 0.5 MW and 3 hours of discharge duration (1.500 kWh of nominal energy) is entered in the model, the cost of energy and cost of power are taken considering the linear interpolation between 2.000 kWh system's cost values and 0. The same procedure is then taken for Li-ion NMC for the comparison of the LCOS in this section. The complete data set used to create Figure 32 can be found in the "Appendices – Data LCOS Results" section, as well as the graphs created for systems of size 0.5, 5, 50 and 150 MWh.

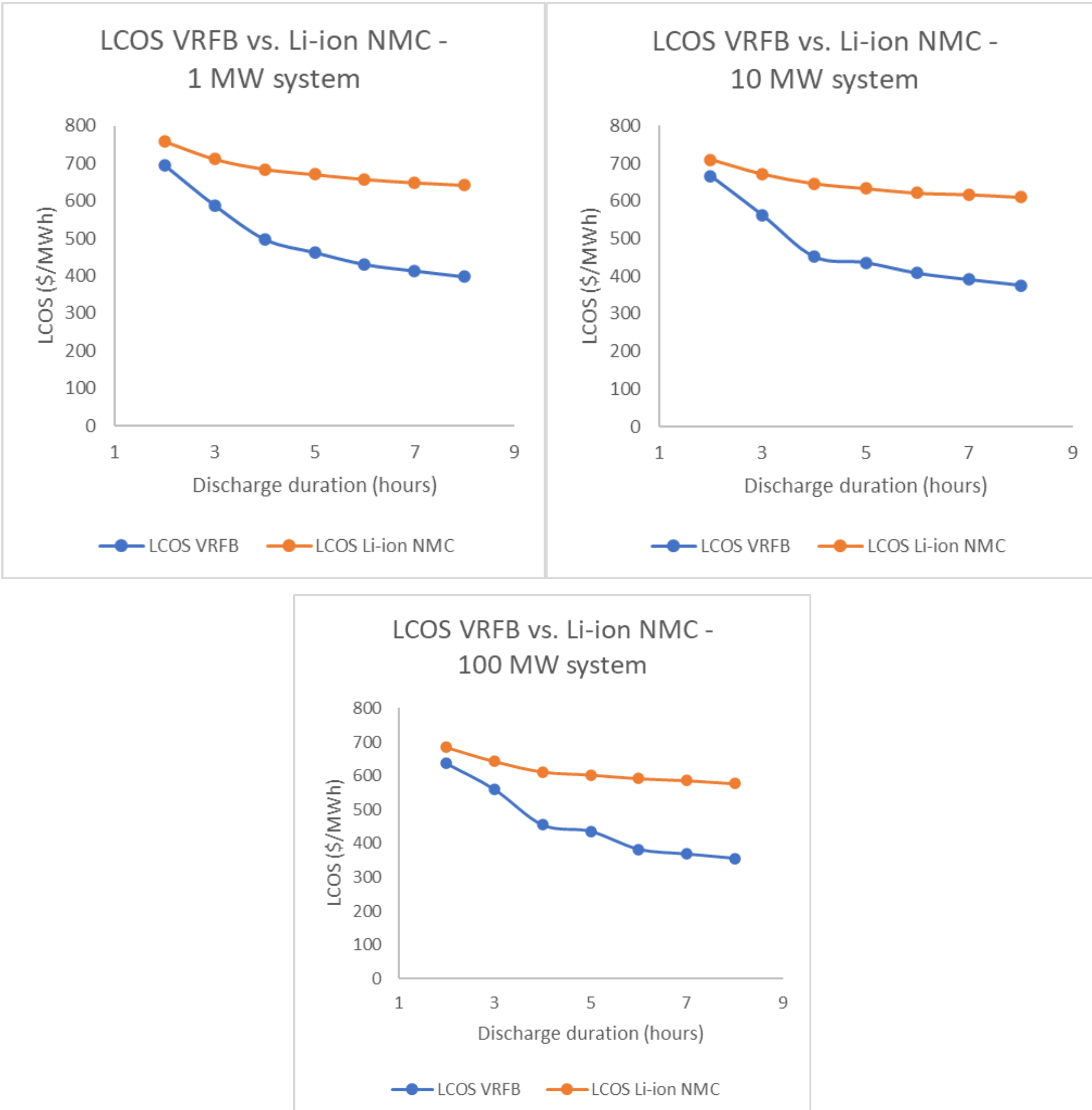

Figure 32. LCOS comparison for 1, 10 and 100 MW systems

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, confirming the technical characteristics regarding such systems explained in the “Methodology” section. 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 1.200 cycles for Li-ion NMC, and 5.201 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). Please refer to

Figure 38 for more information. It is also important to notice the similar LCOS values for Li-ion NMC for all 1, 10, and 100 MW systems, which range between 758 and 641 $/MWh for the 1 MW system, and between 685 and 577 $/MWh for 100 MW systems.

Also regarding this LCOS, the results obtained using the data from the U.S. Department of Energy, and the number of simplifications previously explained, are significantly higher than in other approaches. For example, for a 1 MW /2MWh system, Lazard study gives a range of LCOS between 442 and 643 $/MWh for storage with Li-ion chemistries, whilst the calculations used in this project gives a LCOS of 758 $/MWh for a similar system[73]. This approach follows a different methodology, without expressing the formula followed. On the other hand, an approach provided by Schmidt et al gives a LCOS of around 325 $/MWh for such a system[27]. 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 simplificaition. Finally, the data used considers a low cyclability is for the technologies, having a direct impact in the LCOS results.

4.2 Supply chain (risk index and competition) – Results

In this section, the results obtained regarding the supply chain methodology are analyzed in more detail. Figures 33 the supply risk index of Vanadium, without considering the supply risk of natural graphite, which should be summed up to this value to obtain the total supply risk index of VRFBs. The results for the rest of the CRMs are shown in Table 2 in the "Methodology" section.

Here, the most important results of the calculations are commented. The goal of this section is to point out in more detail how the formula (Equation 10, "Methodology" section) works and the effects of each index in the total supply chain risk, as well as to mention the dynamics surrounding the supply chain of materials.

CRM		Country	Supply concentration	HHI	WGI_{scaled}	EPI_{scaled}	$HHI_{WGI-EPI}$	Final $HHI_{WGI-EPI}$	EU-IR	EoL-RIR	Supply risk
Vanadium	Refined	Austria	52%	0,2704	0,21	0,80	0,0113	0,045	0,47	0,01	0,02
		Russia	32%	0,1024	0,63	0,50	0,0321				
		China	6%	0,0036	0,57	0,37	0,0013				

Figure 33. Supply risk index – Vanadium (the total Supply Risk of VRFB is the sum of Vanadium + Natural Graphite's indexes).

Regarding the calculations around Li-ion NMC technologies (Table 2), the first thing to notice here is the high supply risks of primary cobalt and natural graphite. The high values come from an increased concentration of the supply in the Democratic Republic of Congo (DRC) and China respectively. Both countries present a high World Governance Index (of 0,82 and 0,57 respectively), it is important to mentioned that the WGI contains information about: voice & accountability, political stability, government effectiveness, regulatory quality, rule of low, and control of corruption. In the case of the DRC, it has a higher score than 0,75 (in a scale from 0 to 1, 1 being the worst) in all 6 aspects, showing not only a higher political instability, but high instability in many social aspects around the country. All of these factors directly or indirectly affect the supply chain of cobalt. On the other hand, China only scores higher than 0,75 in the voice & accountability factor, having better results (around 0,50 in the other aspects). This voice & accountability factor might have a more indirect impact in the supply chain risk of natural graphite than others. Added to this, it can be noted that both Australia and Chile have a high supply concentration for primary and refined lithium, but the risk is diluted by low WGI and better environmental performance than the countries previously mentioned. As a future update in this section, a more thorough analysis on the impact of each factor inside the World Governance Index in the supply chain risk of materials could be developed.

Secondly, the impact of the EU Import Reliance and End-of-Life Recycling Input Rate should be noted. The positive effects of having reduced import reliance and higher recycling input rates inside the EU has in the supply risk index developed can be best seen in the 5 times risk reduction in refined cobalt risk due to higher EU-IR and EoL-RIR values, a similar behavior can be observed in the supply risk index of vanadium in Figure 33.

It is important to highlight that these results regarding supply risk will remain constant throughout the model's iterations (see Figure 30), as the methodology focuses on the presence or absence of a CRM in a technology and associates it to the indexes specific of that material. This work does not consider the potential effect of scaling up of a specific system may have with the CRMs supply chain risks or competition, as the scale up threat is considered separately by Factor 3 and 4 which relate with the readiness level of the components and system. In this section, the risk is consider intrinsic to the material's extraction and supply chain and not related to the sizing of the system. Also, it is important to highlight that (as of May 2022) and due to the Russia-Ukraine conflict, the RMIS (Raw Materials Information System) European Commission's webpage has already to published one analysis related to potential supply disruptions in materials (*i.e.* Potash) and a second one related with Titanium potential supply chain disruption is in progress. Even though this political conflict is not expected to directly influence the supply chains of the CRMs contained in Li-ion NMC and VRFB technologies, the uncertainty, and the potential supply risk in materials that political regimes in countries bring should be noted. This is correctly addressed by the Herfindahl-Hirschman Index and World Governance Indexes in this supply risk section.

4.3 Battery Component Readiness Level – Results

Here, a deeper analysis on the results and limitations of this part of the work is made. The framework of this section focuses on the development level of the four main components of a battery: electrodes (anode and cathode), separator, and electrolyte. Please bear in mind that the decision-making process of this section contains a higher level of subjectiveness than others, which is mitigated by the creation of the BCRL checklists provided in the “Appendices” section, and that it requires a significant investment of time on research to effectively assess the maturity level of each specific component. The BCRL methodology proposed by Greenwood et al. is taken as a basis and modified to make it simpler to use for the analysis of novel battery technologies in the future[51]. For the scope of this work, ss the technologies analyzed here (*i.e*. Li-ion NMC and VRFBs) already present high maturity level, all of their components excepting the separator of VRFBs are considered to have be in stage 5. As mentioned in the “Methodology” section, the ionic exchange membrane (IEM) in VRFB is considered to be in stage 4 as it has not been specifically developed for this system, and still present some technical and economic challenges. Also, this BCRL section will remain constant throughout the model’s iterations (see Figure 31), as the readiness level of the two technologies compared will not change depending on the system’s size or discharge duration.

4.4 System Readiness Level – Results

For this section, it is worth bearing in mind that the System Readiness Level of the system of VRFB has been defined as 8 (scaled = 0,8), following the readiness level scale proposed by the IEA. Despite this, the model is structured in a way in which the user can enter a specific installed capacity and the system gives back the SRL of that technology. The goal of this modification is to pave the way for future uses of the program involving novel technologies, in which the SRL might be unknown and where this SRL-installed capacity relation brings an extra level of objectiveness to the subject. Also, this SRL section will remain constant throughout the model’s iterations (see Figure 31), as the readiness level of the two technologies compared will not change depending on the system’s size or discharge duration.

4.5 Overall analysis – Results

The goal of this section is to analyze the results and insights provided by the 3 output graphs as a whole. Here, the analysis of how to use the information provided by the model is provided. In this section, the same figures obtained for a 1 MW and 4 hours of discharge system are used. The graphs were previously showed in Figures 27, 30 and 31; Figure 34 shows the three of them are grouped for illustrative purposes.

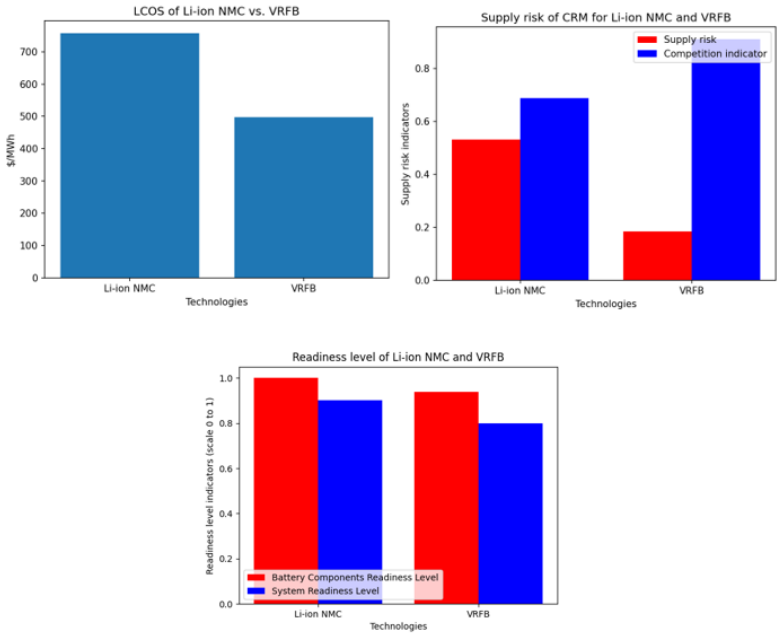

Figure 34. Output graphs of the model proposed for a 1MW and 4 h system

First, it should be noted that all three graphs should be used and analyzed simultaneously in the scope of this work. As noted in previous sections, a lot of work has been done to assess each of the outputs (*i.e.* LCOS, supply chain risks, readiness level) individually, but there is very limited information providing a holistic comparison of BESSs. This first comparison between Li-ion NMC and VRFB offers some valuable initial insights by using this complete view of the battery technologies' supply chain, costs, and technical performance. Also, it is important to bear 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 main 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.

- Finally, is important to bear in mind that the goal of this model is to give a general overview of the effects of some supply chain risk factors might have in the deployment of a technology, with a significant focus on serving as a decision-making tool in the investment of future electrochemical BESSs.

It is also important to show the impact that the costs and electricity deliver have in the LCOS obtained in this model. Figure 35 show the total investment (*i.e.* CAPEX + O&M fixed and variable costs), whilst Figure 36 displays the electricity discharged for both VRFB and Li-ion NMC systems of capacity of 1 MW and discharge durations between 2 and 8 hours. The goal of this Figure is to highlight the effect each of them have on the final LCOS results, both for VRFB and Li-ion NMC systems.

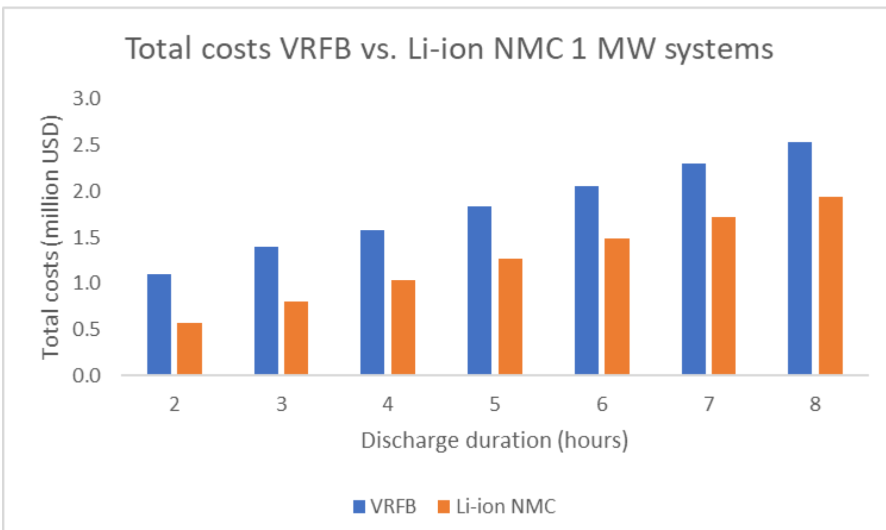

Figure 35. Total cost comparison of 1 MW system VRFB vs. Li-ion NMC

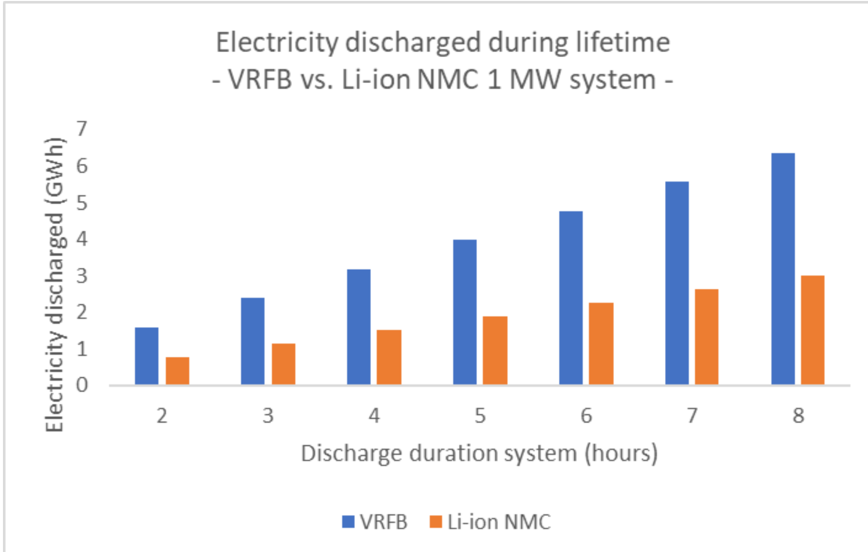

Figure 36. Total electricity discharged during lifetime of 1 MW system VRFB vs. Li-ion NMC

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 (see "Methodology" section, the cycle life considered for Li-ion NMC technologies is of 1.200 cycles, whilst VRFB have a cycle life of 5.201 cycles). Using different technological parameters would of course provide different results. The same data is used throughout the model for consistency purposes.

5. 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 development of the methodology and the model 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 factor: focusing on the materials and including the top 3 importing countries to the European Union (EU), the concentration of it in each country, the political and environmental situations in the importing country, the import reliance, and the recyclability input in the EU
- Competition factor: considering the percentage of the material that is used specifically for the battery industry in the EU market
- Battery Component Readiness Level: assessing the readiness level of the main four components in a battery system (*i.e.* anode, cathode, electrolyte, and separator).
- System Readiness Level: giving a value of the readiness level related to the total installed capacity of a technology.

The first two factors showed the risks that the supply of Critical Raw Materials (CRMs) might play in the development of a technology, following the work and data collected by the European Commission and with a strong focus of the risk of supply in the European Union. The last two factors presented a general overview of the technological readiness level and relates it to the global installed capacity of the technology.

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 model developed serves as a baseline to deliver straightforward and useful visual descriptions in the assessment of electrochemical battery systems, paving the way for future updates in which more novel battery systems can be compared. 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.

6. FUTURE WORK

In this section, an overview of the future perspectives around this work are highlighted. First, it should be emphasized once again that the final goal of the development of this model is to be applied to technologies that are still in different stages of development, which involves a high level of uncertainty. The work serves as a first approach to consider the many variable factors surrounding the scale-up of a technology in a single methodology. As explained in the “Model - Future updates” section, it would be interesting to improve the model by introducing historical data for the calculation of the LCOS and the different factors considered. This improvement would be the immediate next step of this work, as training and optimizing the model would provide a more solid framework to obtain less uncertain results when used with novel BESSs.

Added to this, it could be interesting to prove the relevance of this assessment in a further study by analysing the path to scale of Li-ion batteries. This path to bankability takes a long time and this work could serve in the future to have a holistic view of what might hinder a technology to reach profitability.

Finally and in a further horizon, it would be stimulating to develop a similar model with a different baseline chemistry. In order to develop a coherent methodology with actual data, Li-ion NMC technologies were chosen as a baseline, which is one of the most prevalent grid-scale chemistries used nowadays. It is crucial to consider that BESSs are rapidly evolveing towards cobalt-free chemistries so, depending on market dynamics, it would be motivating in the future to modify the baseline chemistry (*i.e.* LFP batteries) for a different analysis and comparison. In this way, different risk factors might emerge, as CRMs play a smaller role in the supply chain risks of such technologies.

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8. APPENDICES

8.1 Calculations of supply risk for V

Table 5. Supply risk calculations for Vanadium.

CRM		Country	Supply concentration	HHI	WGI_{scaled}	EPI_{scaled}	$HHI_{WGI-EPI}$	Final $HHI_{WGI-EPI}$	EU-IR	EoL-RIR	Supply risk
Vanadium	Refined	Austria	52%	0,2704	0,21	0,80	0,0113	0,045	0,47	0,01	0,02
		Russia	32%	0,1024	0,63	0,50	0,0321				
		China	6%	0,0036	0,57	0,37	0,0013				

8.2 Checklists for BCRL stages

Table 6. Battery Component Readiness Level Stage 1 checklist

STAGE 1 – Lab-scale and basic property research		
Known	Possible projections	Fully unknown
Component properties	Theoretical component/cell properties	Manufacturability (component
Material cost	Component production cost (low accuracy)	Environmental impact
	Supply risk	Practical cell properties
		Cell production cost

Table 7. Battery Component Readiness Level Stage 2 checklist

STAGE 2 – Electrochemical development (still academic/industrial environment)		
Known	Possible projections	Fully unknown
Component properties	Component and cell production cost (low accuracy)	Component manufacturability
Material cost	Component and cell environmental impact (low accuracy)	Cell manufacturability
Supply risk	Commercial cell properties (moderate accuracy)	

Table 8. Battery Component Readiness Level Stage 3 checklist

STAGE 3 – Component Production Process Development		
Known	Possible projections	Fully unknown
Component properties	Component production cost (moderate accuracy)	Cell manufacturability
Component manufacturability	Component and cell environmental impact (moderate accuracy)	
Commercial-scale cell properties	Cell production cost (low accuracy)	
Material cost		
Supply risk		

Table 9. Battery Component Readiness Level Stage 4 checklist

STAGE 4 – Cell Production Process Development		
Known	Possible projections	Fully unknown
Component properties	Component and cell production cost (moderate to high accuracy)	Efficiency and consistency in cell manufacturability
Component manufacturability	Component and cell environmental impact (moderate to high accuracy)	
Commercial-scale cell properties	Commercial cell properties (moderate accuracy)	
Material cost		
Supply risk		
Cell manufacturability		

Table 10. Battery Component Readiness Level Stage 5 checklist

STAGE 5 - Commercialization		
Known	Possible projections	Fully unknown
Physical and electrochemical properties		
Manufacturability		
Costs		
Supply risk		
Environmental impact		

8.3 Cost of Li-ion NMC: power and energy-related costs of Li-ion NMC depending on nominal energy input

Table 11. Cost of energy and power for Li-ion NMC technologies

Nominal energy (kWh)	Cost of energy ($/kWh)	Cost of power ($/kW)
2.000	237	85
4.000	231	85
6.000	228	85
8.000	226	85
10.000	225	85
20.000	225	73
40.000	220	73
60.000	217	73
80.000	216	73
100.000	214	73
200.000	216	63
400.000	210	63
600.000	208	63
800.000	205	63
1.000.000	205	63

8.4 Cost of VRFB: power and energy-related costs of VRFB depending on nominal energy input

Table 12. Cost of energy and power for Li-ion NMC technologies

Nominal energy (kWh)	Cost of energy ($/kWh)	Cost of power ($/kW)
2.000	461	155
4.000	347	155
6.000	308	155
8.000	289	155
10.000	277	155
20.000	439	133
40.000	330	133
60.000	294	133
80.000	275	133
100.000	264	133
200.000	418	115
400.000	313	115
600.000	278	115
800.000	262	115
1.000.000	251	115

8.5 Data LCOS Results

Table 13. Results for LCOS of VRFB technology

Size (MW)	Discharge duration (h)	From model: LCOS VRFB ($/MWh)	Nominal energy (kWh)	Linear interpolation: VRFB Cost of energy ($/kWh)	Linear interpolation: VRFB Cost of power ($/kW)
0.5	2	397	1,000	230.5	155
	3	512	1,500	345.75	155
	4	644	2,000	461	155
	5	597	2,500	432.5	155
	6	554	3,000	404	155
	7	513	3,500	375.5	155
	8	472	4,000	347	155
1	2	694	2,000	461	155
	3	587	3,000	404	155
	4	497	4,000	347	155
	5	462	5,000	327.5	155
	6	430	6,000	308	155
	7	413	7,000	298.5	155
	8	397	8,000	289	155
5	2	457	10,000	277	155
	3	528	15,000	358	155
	4	616	20,000	439	155
	5	571	25,000	411.75	155
	6	529	30,000	384.5	155
	7	489	35,000	357.25	155
	8	425	40,000	330	155
10	2	666	20,000	439	155
	3	562	30,000	384.5	155
	4	452	40,000	330	155
	5	436	50,000	312	133
	6	408	60,000	294	133
	7	391	70,000	284.5	133
	8	376	80,000	275	133
50	2	426	100,000	264	133
	3	503	150,000	346	133
	4	595	200,000	428	133
	5	549	250,000	399.25	133
	6	506	300,000	370.5	133
	7	465	350,000	341.75	133
	8	403	400,000	313	133
100	2	637	200,000	428	133
	3	560	300,000	390.5	133
	4	455	400,000	353	133
	5	436	500,000	315.5	115
	6	383	600,000	278	115
	7	369	700,000	270	115
	8	356	800,000	262	115
150	2	459	300,000	289.5	115
	3	412	450,000	281.25	115
	4	389	600,000	273	115
	5	371	750,000	264.75	115
	6	355	900,000	256.5	115
	7	341	1,050,000	248.25	115
	8	309	1,200,000	240	115

(Yellow) Data taken from the U.S. Department of Energy 2020 Report (35)
The rest of the data were calculated using linear interpolation

Table 14. Results for LCOS of Li-ion NMC technology

Size (MW)	Discharge duration (h)	Nominal energy (kWh)	From model:	Linear interpolation: Li-ion NMC	
			LCOS Li-ion NMC($/MWh)	Cost of energy ($/kWh)	Cost of power ($/kW)
0.5	2	1,000	777	243.5	85
	3	1,500	727	240.25	85
	4	2,000	700	237	85
	5	2,500	686	235.5	85
	6	3,000	673	234	85
	7	3,500	665	232.5	85
	8	4,000	655	231	85
1	2	2,000	758	237	85
	3	3,000	711	234	85
	4	4,000	684	231	85
	5	5,000	670	229.5	85
	6	6,000	657	228	85
	7	7,000	648	227	85
	8	8,000	641	226	85
5	2	10,000	757	225	85
	3	15,000	725	225	85
	4	20,000	687	225	73
	5	25,000	659	223.75	73
	6	30,000	638	222.5	73
	7	35,000	627	221.25	73
	8	40,000	621	220	73
10	2	20,000	709	225	73
	3	30,000	671	222.5	73
	4	40,000	646	220	73
	5	50,000	633	218.5	73
	6	60,000	621	217	73
	7	70,000	617	216.5	73
	8	80,000	610	216	73
50	2	100,000	679	214	73
	3	150,000	649	215	73
	4	200,000	635	216	73
	5	250,000	622	214.5	73
	6	300,000	610	213	73
	7	350,000	599	211.5	63
	8	400,000	591	210	63
100	2	200,000	685	216	63
	3	300,000	643	214	63
	4	400,000	612	212	63
	5	500,000	603	210	63
	6	600,000	592	208	63
	7	700,000	586	206.5	63
	8	800,000	577	205	63
150	2	300,000	676	205	63
	3	450,000	626	205	63
	4	600,000	607	205	63
	5	750,000	590	205	63
	6	900,000	584	205	63
	7	1,050,000	580	205	63
	8	1,200,000	577	205	63

8.6 Graphs LCOS – 0.5, 5 and 50 MW systems

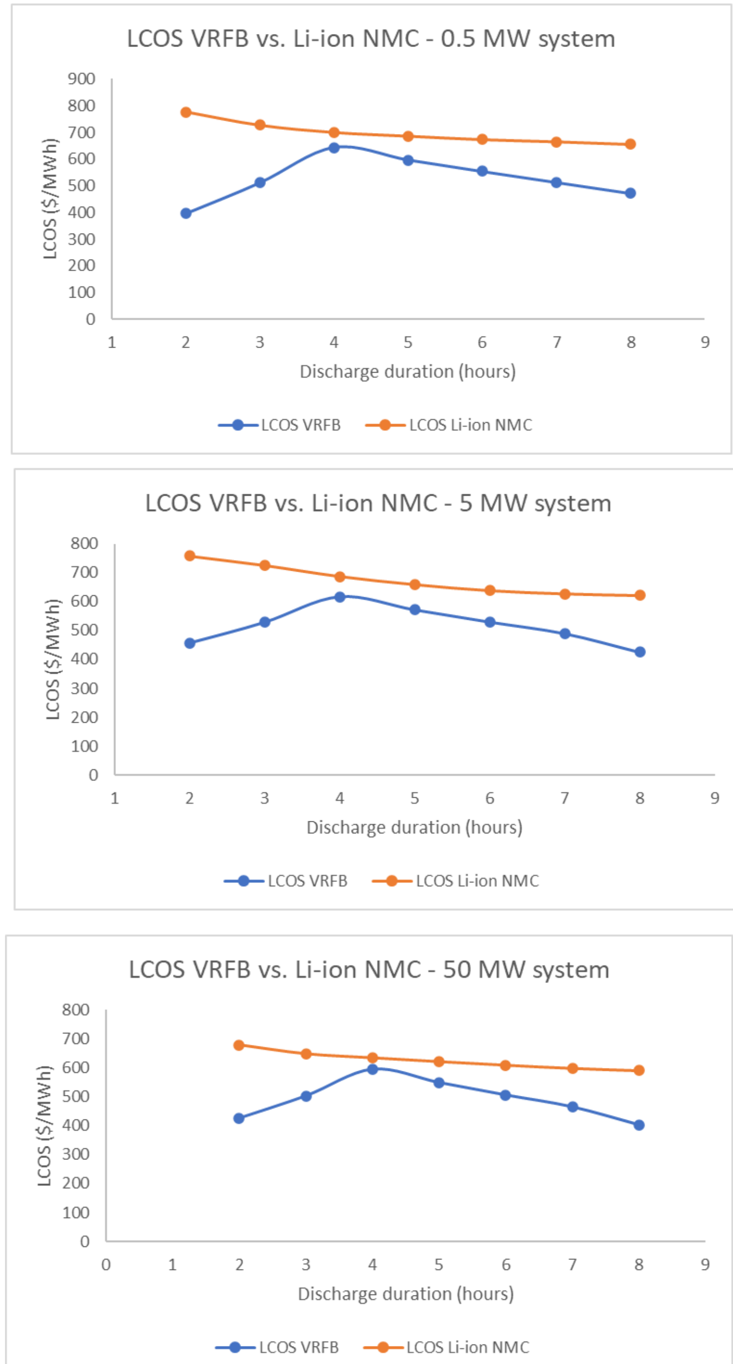

Figure 37. LCOS results for both VRFB and Li-ion NMC for 0.5, 5 and 50 MW systems between 2 and 8 hours of discharge

It is important to notice the strange up and down behavior of the VRFB LCOS curves. This comes due to the fact of data availability, as the systems represented were interpolated from the data available for 1, 10 and 100 MW systems. The 2- and 3-hour systems shows in this 0.5, 5 and 50 MW systems have nominal capacities of 1000, 1500, 100.000 and 150.000 MWh, whose values are obtained from the cost of energy and power given for the other systems, so reducing the precision in the results.