Quantitative Assessment of Environmental and Economic Impacts of Battery Cell Using LCA

Bc Anna Ivanichenko

Supervisor: Viera Pechancova, Ph.D., TBU
Consultant: prof. Marek Koutny, TBU
Consultant: Merve Erakca, KIT
Consultant: Hüseyin Ersoy, KIT

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ZADÁNÍ DIPLOMOVÉ PRÁCE
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Zásady pro vypracování

Vypracujte literární rešerši zaměřenou na principy Posuzování životního cyklu (Life Cycle Assessment, LCA)
Shromážděte vstupní data (Life Cycle Inventory) pro modelování dopadů životního cyklu vybraného typu baterie.
Proveďte analýzu životního cyklu vybraného typu baterie s pomocí modelovacího software se zaměřením na environmentální a ekonomické dopady.
Získané výsledky LCA interpretujte.
Práci odevzdejte v požadovaném formátu a a do stanoveného termínu.

Forma zpracování diplomové práce: **tištěná/elektronická**
Jazyk zpracování: **Angličtina**

Seznam doporučené literatury:

Kočí, Vladimír. Environmentální dopady: Posuzování životního cyklu. Praha: VŠCHT, 2013. ISBN 978-80-7080-858-0.
Hauschild, Michael Z., Rosenbaum Ralph K., Olsen Stig Irving, Life Cycle Assessment: Theory and Practice. Cham: Springer International Publishing, 2017. ISBN 978-3-319-56474-6.
Olivier Jolliet, Myriam Saade-Sbeih, Shanna Shaked, Alexandre Jolliet, Pierre Crettaz. Environmental Life Cycle Assessment. CRC Press. 2015. ISBN 978-1-4398-8766-0.

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prof. Ing. Roman Čermák, Ph.D.
děkan

Ing. Jaroslav Filip, Ph.D.
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ABSTRAKT

V poslední dekádě získal vývoj solid-state baterií značnou pozornost vědeckého světa, a očekává se, že tento typ baterií přinese podstatné zlepšení elektrochemické stability a bezpečnosti, zároveň sníží ekologickou zátěž a náklady na jejich výrobu. Nicméně, solid-state baterie jsou stále novou technologií, a jejich environmentální a ekonomické dopdady nejsou úplně pochopeny. Tato diplomní práce si klade za cíl představit posouzení životního cyklu "od kolébky po bránu" nové solid-state baterie s polymerním elektrolytem na bázi biomateriálu, to na úrovni laboratorního článku, a vyhodnotit tak environmentální dopady a identifikovat kritická environmentální místa. Hodnocení využívá metodu hodnocení dopadů ReCiPe 2016 a Environmental Prices.

Výsledky analýzy životního cyklu ukazují, že hlavní environmentální dopady laboratorních článků pochází z pouzdra mincové baterie a elektrolytu, které společně představují více než 92 % všech kategorií dopadů s výjimkou nekarcinogenních (82 %). Environmentální cena výroby jednoho článku činí 0,0156 eura. Elektrolyt významně přispívá k environmentálnímu dopadu, a to kvůli své vysoké spotřebě energie a přítomnosti složky LITFSI, která společně představují více než 83 % všech kategorií environmentálních dopadů. Citlivostní analýza ukazuje, že potenciální snížení environmentálních dopadů by bylo možné dosáhnout strategiemi, jako je optimalizace tloušťky elektrolytu a využití obnovitelných zdrojů energie v procesu výroby.

Klíčová slova: environmentální dopad, ekonomický dopad, LCA, environmentální cena, elektrolyt na bázi biomateriálu, solid-state baterie, LFP.

ABSTRACT

In the last decade, solid-state battery development has garnered significant scientific attention, expected to yield substantial improvements in mechano-electrochemical stability and safety, while also reducing environmental burden and battery costs. However, the solid-state battery is still an emerging technology, and its environmental and economic implications are not fully understood.

This thesis aims to present a cradle-to-gate life cycle assessment of a novel solid-state battery with a polymer bio-based electrolyte at laboratory-scale cell production to evaluate environmental impacts and identify environmental hotspots. The assessment utilizes the ReCiPe 2016 impact assessment method and incorporates environmental price methodology to monetize the environmental impact results.

The Life Cycle Assessment (LCA) results demonstrate that the primary environmental impact of laboratory cells comes from the coin cell container and electrolyte, which together account for over 92% of all impact categories except non-carcinogenic (82%). The environmental cost of producing one cell is 0.0156 euros. The electrolyte significantly contributes to the environmental impact due to its high energy consumption and the presence of the LITFSI component, which together account for over 83% of all environmental impact categories. Sensitivity analysis indicates that potential reductions in environmental impact could be achieved by reducing electrolyte thickness and transitioning the Czech energy mix towards more renewable sources.

Keywords: environmental impact, economic impact, LCA, environmental price, bio-based material electrolyte, solid-state battery, LFP.

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I hereby declare that the print version of my Master's thesis and the electronic version of my thesis deposited in the IS/STAG system are identical.

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INTRODUCTION

The expansion of the global economy in recent decades has led to significant changes in climate and significant environmental degradation, manifested through many negative consequences, including the thawing of permafrost, an increase in the frequency of natural disasters, and a general increase in environmental instability. In response to these challenges, the European Union has developed a climate regulation strategy Green Deal aimed at achieving climate neutrality by 2050, which includes reducing greenhouse gas emissions, expanding the use of renewable energy sources, increasing energy efficiency, and regulating imports based on their carbon footprint.

One of the main directions of the strategy is to improve the battery energy sector in the European Union with the aim of creating more sustainable, efficient and safe batteries. This is important to drive the development and production of the next generation of batteries that take into account the entire product life cycle to accelerate the transition to decarbonized energy and achieve the sustainability goals in the energy sector as part of the Green Deal.

Among the various types of batteries, the most attention is currently paid to lithium-ion batteries, which have a wide range of applications from portable power for devices to stationary storage and power systems for vehicles. Recently, advanced solid-state battery (SSB) technology for lithium-ion batteries has been actively explored, promising significant improvements in safety, energy density and reliability, and has the potential to significantly disrupt the mobility sector. However, despite the promise of SSB, it faces a number of problems, such as insufficient ionic conductivity of the solid electrolyte, material supply risks and cost-effectiveness issues as well as a small number of studies on assessing the sustainability of SSB, making it difficult to compare them with existing technologies (Mandade et al., 2023).

Given the environmental importance of the energy sector and the need to evaluate technologies throughout a product's life cycle, the need to quantify product sustainability has arisen, spurring the development of a powerful analytical decision-making tool - life cycle assessment (LCA). LCA is a tool for assessing the potential environmental impacts and resources used throughout the entire life cycle of a product, i.e., from procurement, production and use of raw materials to waste management (ISO 140040:2006 (E)). This approach provides an opportunity to monetize environmental impacts through LCA weighting factors, which simplify the comparison of different options, facilitating process optimization, and informing policy development (Sander de Bruyn et al. 2018).

The objective of this thesis is to conduct a comprehensive environmental impact analysis of a novel SSB with bio-based electrolyte using the LCA method and assigning a monetary value to the identified environmental impacts. The thesis also includes inventories of lab-scale battery components, as well as energy and transportation requirements for production processes. The environmental impact assessment is carried out using both primary and secondary data using the Ecoinvent database (3.9.1) and ReCiPe 2016 impact assessment methodology in SimaPro (9.5.0.1) software. Monetization of defined environmental impacts is carried out using the environmental price (EP) impact assessment methodology.

It is expected, that identifying potential hotspots to develop more efficient and environmentally sustainable battery manufacturing strategies will contribute to future sustainable technological developments.

I. THEORY

1 OVERVIEW OF THE LIFE CYCLE ASSESSMENT PRINCIPLES AND METHODOLOGY

The development of the LCA method began in the 1960s. In 1990, the Society for Environmental Toxicology and Chemistry (SETAC) held the first workshops to formally introduce LCA as a method for comprehensive product analysis (Curran 2017; Amahmoud, El Attar, and Meleishy 2022). And in 1997, the European Environment Agency (EEA) published the first guide to business life cycle assessment, containing essential information on how to apply the method (Amahmoud, El Attar, and Meleishy 2022). Nowadays, three organizations are involved in the creation of the LCA: SETAC, the United National Environmental Program (UNEP) and the International Organization for Standardization (ISO) (Jolliet et al. 2016, 4). The principles and structure of LCA are standardized in the ISO 14040 (14040,14044) series of standards.

The LCA method has many applications in various fields of industry. Commonly, LCA research into electric vehicles and lithium-ion batteries has focused on the environmental aspects of various drive technologies and battery materials, including carbon emissions, water footprints and environmental impacts throughout their life cycle, and helps address issues such as process optimization to reduce negative environmental impacts, assessing the cost and environmental impact of new technologies, comparing battery remanufacturing methods for batteries (Lai et al. 2022).

1.1 LCA

LCA is a tool for assessing the potential environmental impacts and resources used throughout the entire life cycle of a product, i.e., from raw material acquisition, production and use stages to waste management (ISO 140040:2006 (E)).

1.2 General LCA principles

As stated earlier, the structure and procedure for conducting LCA is provided in the standards of the ISO and SETAC. LCA has an iterative nature and consists of four main phases: goal and scope definition, inventory analysis, impact assessment and interpretation of the results (ISO 140040:2006 (E); ISO 140044:2006 (E)).

1.2.1 Goal

The goal definition of an LCA is one of the main stages, which could be revised during the course of the study, which once again confirms the iterative approach of this method. At this stage, the researcher must answer questions such as:

- Reasons and purposes of the study,
- The audience for which the study is intended is,
- Possible areas of application of the results,
- Ability to use results in comparative statements open to the public,
- Limitations of the study.

When conducting LCA, every point must be considered, since LCA begins with a carefully considered and documented project goal (Hauschild, Rosenbaum, and Olsen 2018, 61,67-81; ISO 140044:2006 (E)).

1.2.2 Scope

The scope of the study determines the starting point and end point of the analysis, the geographic and time frame of the analysis. It is including the definition of the product system, its function and functional unit, its boundaries and limitations, choice of methodology and impact categories (Curran 2017, 5–7). At the stage of determining the scope of LCA, there are two types of analysis modeling - attributional and consequential.

The goal of the attributional LCA is to understand how products or services affect the environment based on existing data and conditions within the boundaries of the system that is defined. The goal of the consequential LCA is to consider not only the direct impacts of products or services, but also their possible external consequences, such as changes in production chains or policy decisions, to predict how it will affect the environment in the future (Curran 2017, 7–9). The two methods have their advantages and disadvantages, are not mutually exclusive, and both results are important and could influence decision-making (Jolliet et al. 2016, 25), (Curran 2017).

System Function and Functional Unit

LCA studies product systems that usually consist of many elements. To compare systems, it is necessary to know an accurate quantitative description of the functions they provide. The system function is the basis for defining the functional unit (FU) and system boundaries of the LCA (Hauschild, Rosenbaum, and Olsen 2018, 83; Jolliet et al. 2016, 26).

The FU is a quantitative description of the function of a system for use as a reference unit (ISO 140040:2006 (E); Tillman 2010). It serves as a basis for normalizing input and output data and should be consistent with the goal and scope of the study. Therefore, it must be accurate, fully reflect the performance of the selected system function, and be defined broadly enough to be able to compare different scenarios and systems (Hauschild, Rosenbaum, and Olsen 2018, 83–89). To define a functional unit for a study on batteries, we need to consider all aspects of their function (How much? For how long/how many times? What? Where? How well?). (Hauschild, Rosenbaum, and Olsen 2018, 84). For example, storing 15 kWh of electrical energy in Germany for 10 years in residential premises with an efficiency of at least 92%; driving an electric vehicle for a total distance of 150,000 miles, with an average energy usage of 0.4 kWh per mile and a battery lifespan of 5 years.

System definition

Each system consists of unit processes that are determined as an element in a life cycle inventory model, representing a single process or an entire facility with input and output data quantified in six categories: materials, energy, resources, products, waste to treatment, and emissions (Hauschild, Rosenbaum, and Olsen 2018, 76–77). For example, battery unit processes may include materials for the production of battery components, manufacturing, assembly, use of the battery, and recycling or disposal of the battery at the end of its life. These unit processes are linked in the model, with the outputs of one process serving as inputs to the others, and belong to the foreground or background system (Hauschild, Rosenbaum, and Olsen 2018, 76–77). In a battery industry the output from the production of battery components serves as input to the manufacturing process.The foreground system includes specific processes that could be collected from battery manufacturers, suppliers, or through measurements and observations and could be changed by the decision-maker. The foreground system is modeled using primary data (energy consumption, raw material usage, emissions, waste). The background system consists of general processes outside its control and is usually formed using life cycle inventory (LCI) databases, scientific research data, averages for industry, etc. (Hauschild, Rosenbaum, and Olsen 2018, 79–81). To display all the individual processes and their interactions with each other, use a flowchart/flow diagram or process tree (Jolliet et al. 2016, 36–37).

System boundaries

The system boundaries determine the unit processes that will be included in the analysis (ISO 140044:2006 (E)), as well as the geographic and time frame of the system under the study (Tillman 2010). The choice of boundaries determines the complexity, credibility and level of transparency of the analysis (Hauschild, Rosenbaum, and Olsen 2018, 100-103). There are four primary boundary approaches for investigating LCA battery models:

Cradle-to-grave: includes the stages of battery manufacturing, use and maintenance to the disposal stage.

Cradle-to-cradle: all of the above steps are taken into account, as well as battery collection and sorting for subsequent recycling and reuse of battery materials.

Well-to-wheel: this is a special LCA of a vehicle to evaluate the overall energy consumption or energy conversion efficiency, as well as the impact of the vehicle's emissions, including its upstream processes to produce the fuel (or electricity) for the drive energy. Normally the construction of the vehicle is not included, but for an comparison of different alternative powertrains (combustion engine, fuel cell and battery electric) it is required including the construction of the different powertrain components.

Each stage of the life cycle has its own elementary flow: inputs (resources, energy) and outputs (waste, emissions into air, land, water) (Amahmoud, El Attar, and Meleishy 2022), see Fig. 1.

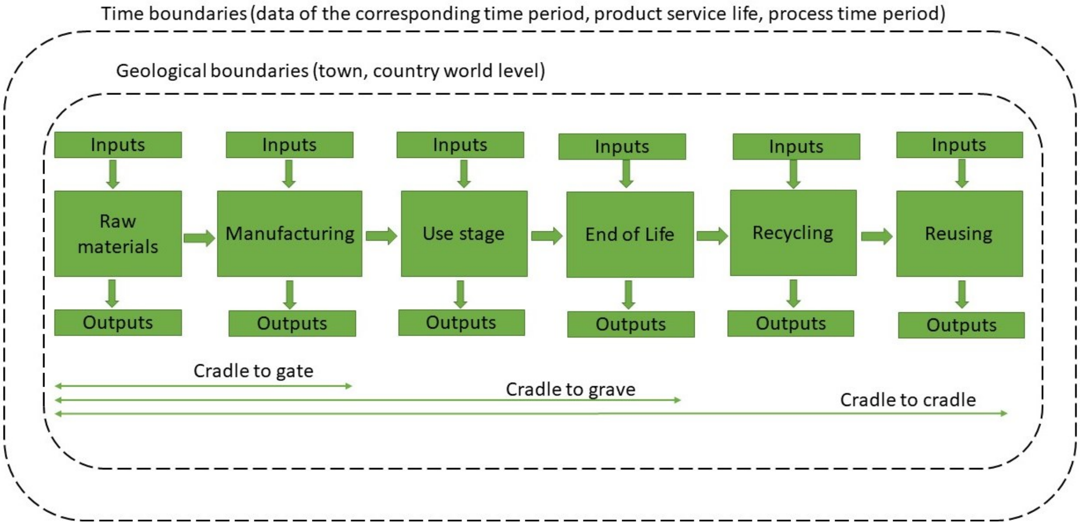

Figure 1 System boundaries in LCA (own interpretation based on (Amahmoud, El Attar, and Meleishy 2022).

1.2.3 Inventory analysis

The LCA inventory covers the determination of the quantity of all flows entering the analyzed product system, their inputs and outputs (Jolliet et al. 2016, 48). The inventory is conducted within the chosen boundaries and scope of the study (ISO 140044:2006 (E); Hauschild, Rosenbaum, and Olsen 2018, 139). Elementary flows for each process (energy, material) are entered into inventory tables and usually, are modeled using software (SimaPro, GaBi, openLCA, etc.) (Hauschild, Rosenbaum, and Olsen 2018, 139, 152-153). At this stage, it is important to collect as much high-quality primary information as possible about individual processes since they are the basis of LCI. Data quality in LCA is categorized based on its precision. Very high and high precision data include directly measured input and output flows, as well as flows modelled using site-specific data, often employing a mass balance approach. Medium and low precision data consist of information from LCA studies, reports from industry associations and national statistics, and data from LCI databases such as ecoinvent, ELCD, and GaBi databases. Very low precision data relies on expert judgment or knowledge of similar processes when specific data is lacking (Hauschild, Rosenbaum, and Olsen 2018, 141–49).

An important part of the inventory is allocation. This part is used when the system being studied produces additional products besides the main product that are not related to the specified function of that system. For example, meat production is the main process, and skin production is an additional one. It is recommended to avoid allocation by dividing a single process into subprocesses or using system expansion (ISO 140044:2006 (E)). When it is impossible to avoid allocation, LCA practitioners use physical or financial allocation (Jolliet et al. 2016, 87-95). Physical allocation is based on physical causal relationships – ratio of coproducts, common function of coproducts, cause-and-effect relationship between the coproducts. The financial allocation is used to allocate resource use or emissions among co-products based on economic causality, considering their respective financial values (Jolliet et al. 2016, 92–95).

1.2.4 Impact assessment

Environmental LCA focuses on the problem of whether a product is likely to harm the environment and, if so, to what extent. Life cycle impact assessment (LCIA) models' exposure to substances to establish precise relationships between inventory data and potential environmental damage based on these modeled pathways. For this purpose, midpoint and endpoint categories were defined (Jolliet et al. 2016, 106–8). Inventory results with similar consequences (for example, emissions of substances affecting ecotoxicity) are grouped into a midpoint category. Each midpoint has its characteristics. By multiplying the inventory flow by a factor, it is possible to estimate its contribution to this midpoint category. For example, global warming reflects the effects of greenhouse gases. Temporal changes in radiative forcing are estimated as an average and the contribution of each greenhouse gas to these changes is estimated through the global warming potential, which represents the impact of each gas compared to carbon dioxide (CO_2) emissions. Each midpoint category is then assigned to one or more endpoint categories, which are represented by a specific indicator. As the inventory progresses from the midpoint to the endpoint, there is an increase in both result uncertainty and the opportunity for better interpretation. When conducting LCA, it is possible to choose the first or second option, or to carry out both options, depending on the goal and choice of impact assessment method (Jolliet et al. 2016, 106–8). According to (ISO 140040:2006 (E); ISO 140044:2006 (E)), the LCIA contains both mandatory (Classification, Characterization) and optional steps (Normalisation, Weighting, Grouping). Impact assessment process based on (ISO 140044:2006 (E); Kočí 2013, 41–45; Jolliet et al. 2016, 105–115) presented in Fig.2.

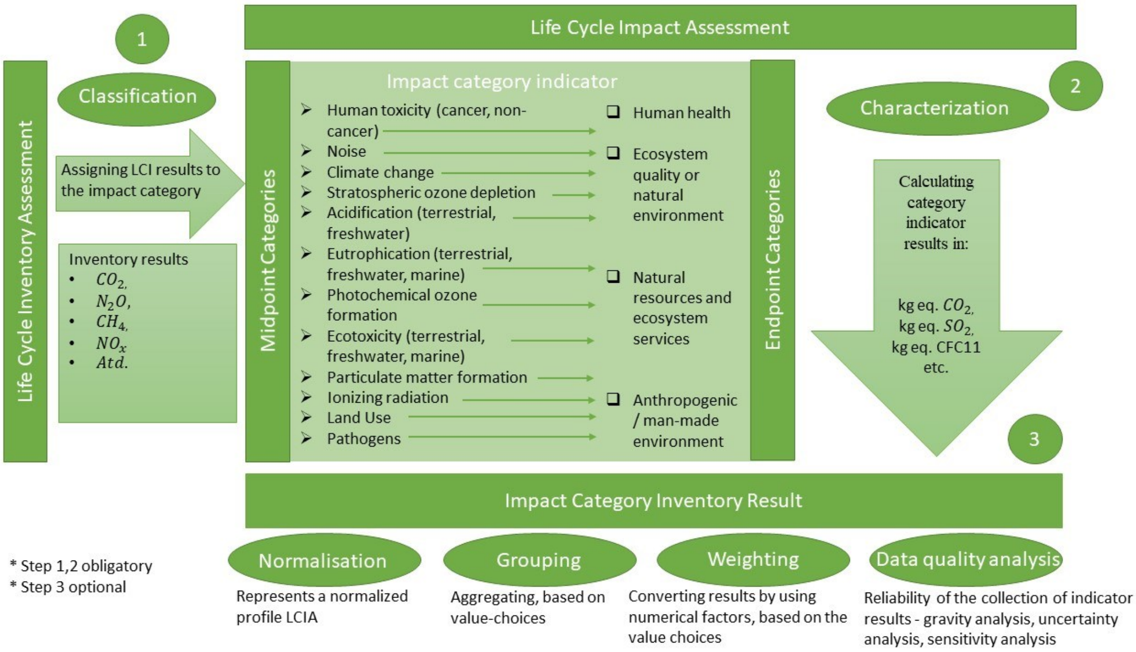

Figure 2 Life Cycle Impact Assessment process, based on (ISO 140044:2006 (E)), (Kočí 2013, 41–45), (Jolliet et al. 2016, 105–15)

Classification

At this stage, a set of average environmental impact categories is determined. For example, emissions of carbon dioxide (CO_2), methane (CH_4), particulate matter (PM), sulfur dioxide (SO_2) are associated with the corresponding midpoint categories they influence - global warming potential (CO_2, CH_4) and exposure to fine particulate matter (PM, SO_2) (Jolliet et al. 2016, 109).

Characterization

This step involves associating the LCI results with the impact categories (ISO 140044:2006 (E)). To provide each outlier's contribution to the midpoint impact category, weighting is done using the midpoint characteristic factor. Each inventory flow is then multiplied by this factor and summed together under the same midpoint impact category to which they belong to obtain midpoint score. At the classification stage, the end point categories of the product's environmental impact are also characterized by relating each midpoint category to one or another end point category. Quantitative assessment of the end point impact category is made by multiplying the each midpoint impact score of the category by the midpoint-damage characterization factor (MDF) and summed it together (Jolliet et al. 2016, 109–112).

Normalisation

The step is used in a situation where the basic units of the impact categories are difficult to interpreted. Impacts are then expressed relative to the total impact in a given category to assess their impact on a functional unit. Total damage is calculated by multiplying the annual emissions or production in a region by the midpoint or damage characterization factors and dividing this result by the total population in that region. The resulting normalized score per person allows us to assess the damage by population (Jolliet et al. 2016, 112–13).

Grouping

The process of prioritizing the results obtained by sorting them (by type of emissions, spatial scale), ranking them (assigning priorities), or establishing a hierarchy reflecting the importance of society or user (Jolliet et al. 2016, 113).

Weighting

Used when, instead of multiple ratings for a scenario, the user is interested in one overall rating for the scenario. This score is calculated by weighting the scores in each damage category based on their relative social value. Applying weights to each damage category allows them to be aggregated into an overall weighted environmental impact score (weighted in $/FU). Weights are based on social, political and ethical values and can be derived using monetization, expert surveys or policy objectives approaches (Jolliet et al. 2016, 114).

Monetization, which places weights on a monetary basis, is often based on people's willingness to pay to avoid harm (Jolliet et al. 2016), representing one method for calculating EP.

There are many LCIA methods: IMPACT2002+, ReCiPe, IMPACT World+, TRACI, LIME, CML 2001, ILCD. The choice of method directly depends on the ability to use it in the software and the variability in the selection of impact categories (Dong et al. 2021). More information presented in the Tab. 1.

Table 1 General characteristics of the well-known Impact assessment methods based on (Jolliet et al. 2016, 121–40)

LCIA methods	Year	Categories	Covered midpoint categories	Covered endpoint categories	Geography of method application
IMPACT 2002+	2003	Midpoint, and endpoint (preferably)	Global warming potentials (GWP), Ozone depletion potentials (ODP), Human Toxicity (HT), Ionizing radiation (IR), Photooxidant formation (PF), Acidification, Eutrophication, Ecotoxicity, Land use (LU), Energy use (EU), Mineral extraction (MEx), Water use (WU).	Human Health (HH), Natural biotic environment (NBE) (ecosystem), Natural abiotic resources (NAR).	Europe
ReCiPe	2009	Midpoint, endpoint	GWP, ODP, HT, PF, Acidification, Eutrophication, Ecotoxicity, LU, EU, MEx.	HH, NBE ecosystem, NAR.	Global
IMPACT World+	2013	Midpoint endpoint	GWP, Oceanic acidification, ODP, HT, Indoor and Workers Impact, IR, PF, Acidification, Eutrophication, Ecotoxicity, LU, EU, MEx, WU, Soil quality.	HH, NBE ecosystem, NAR.	Global
TRACI	2013	Midpoint	GWP, ODP, HT, PF, Acidification, Eutrophication, Ecotoxicity, EU.	HH, NBE ecosystem, NAR.	USA
LIME	2003	Midpoint endpoint	GWP, ODP, HT, PF, Acidification, Eutrophication, Ecotoxicity, LU, EU, MEx, Use the biotic resources.	HH, NBE ecosystem, NAR, Natural biotic resources, man-made biotic resources	Japan
CML (Dutch Handbook on LCA)	2002	Midpoint	GWP, ODP, HT, Accidents IR, PF, Acidification, Eutrophication, Ecotoxicity, LU, EU, Use the biotic resources.	-	Europe
ILCD (European impact assessment)	2013	Midpoint endpoint	GWP, ODP, HT, IR, PF, Acidification, Eutrophication, Ecotoxicity, LU, EU, MEx.	HH, NBE (ecosystem, NAR.	Europe, (aims global)

1.2.5 EP impact assessment method

Human actions have various effects on the environment, and lacking a single standard, it's challenging to determine which impacts are the most critical and should be addressed first to lessen the overall environmental footprint. One approach to tackle this issue is by monetizing environmental impacts, a method where the effects of releasing harmful substances or consuming natural resources are quantified in monetary terms (Arendt et al. 2020).

EPs are prices used to calculate the amount that society should be willing to pay. They are expressed in euros per kilogram of pollutant and reflect the value of emissions compared to each other and to other goods in society. These prices are based on the impact of substances on the environment, expressed through a single indicator, and represented by upper, lower, and central values at the pollutant, midpoint, and endpoint levels (Sander de Bruyn et al. 2018).

According to (Sander de Bruyn et al. 2018, p. 28) EP methodology „combines characterization models, impact pathway analyses and valuation methods to arrive at a consistent estimate of the welfare costs associated with emissions at the pollutant, midpoint and endpoint levels“ (Fig.3).

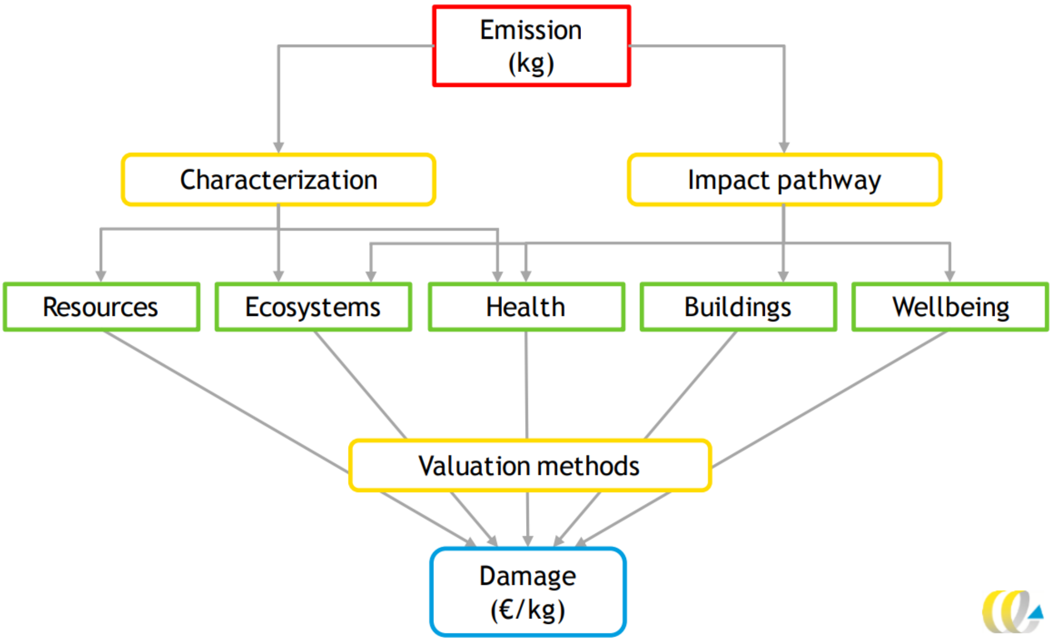

Figure 3 Characterization models, impact pathway analyses and valuation methods as a basis for the Environmental Prices Handbook (Sander de Bruyn et al. 2018).

Depending on the purpose of LCA, they could be used both as weighting factors and for estimating external costs. If the goal is weighting, a set of “weighting factors” is used, while for calculating external costs, a set of “external costs” is used. The difference is that the set of "weights" is based entirely on the hierarchical perspective of ReCiPe, while the "external costs" are based on a combination of the hierarchical and individualistic perspectives (Sander de Bruyn et al. 2018).

One important aspect of using EPs method is its applicability for assessing the environmental impacts of different products and processes. By monetizing environmental impacts, EPs method allows for easier comparison between different options, facilitating decision-making in product design, process optimization, and policy development.

However, the EP method has some limitations. The geographical scope of the method affects its applicability outside Europe, and the dependence on damage costs and abatement costs is often subject to uncertainties and assumptions. The method also requires a detailed consideration of the data sources used to obtain monetary value when comparing it with other methods and making decisions. This method relies on various factors, including social, political and ethical considerations, which can introduce subjectivity and uncertainty into the monetization process.

Despite its limitations, the EP method remains valuable for incorporating environmental impacts into decision making. It helps determine the monetary value of environmental impacts, leading to a better understanding of the costs of products and processes, and leading to more sustainable solutions (Arendt et al. 2020).

The EPs presented in this thesis reflect average values for pollution across Europe. They estimate the EP as a LCA weighting factor in monetary terms for each additional unit of pollution, enabling the derivation of midpoint characterization factors suitable for conducting single-score assessment in LCA.

1.2.6 Interpretation

Interpretation is the final stage of LCA, the purpose of which is to analyze previous results in terms of uncertainty and sensitivity of the data to the choice of methodology (Hauschild, Rosenbaum, and Olsen 2018, 324).

It includes three main points - identifying research problems, evaluating the data obtained, summarizing the results, identifying the limitations of the analysis and providing recommendations to the end users of the analysis (ISO 140044:2006 (E)).

The key elements of this stage are uncertainty and sensitivity analysis (Sensitivity check) (Hauschild, Rosenbaum, and Olsen 2018, 324). Validation involves consistently monitoring the quality and variability of data at each stage of the LCA, ensuring that data are selected and assessed correctly, comparing results with other studies, checking the completeness and validity of the choice of methodology and impact assessment (Jolliet et al. 2016, 149–159). To interpret the study results, it is recommended to use special LCA software (Jolliet et al. 2016, 179).

1.3 Applications of the LCA

The applications of LCA are quite wide. The main directions are:

a) Decision making

- at the state level (environmental policy, environmental procurement),
- at the production level (development and creation of an ecological product, analysis of the production process and processing process, comparison of alternative products),
- at the consumer level (eco-design) (Tillman 2010).

b) Training - analysis of the product system in order to identify hot spots in it and search for opportunities for subsequent process modernization (Tillman 2010).

c) Communication - marketing, providing information to the public (eco-labeling, environmental product declaration, carbon foot printing) (Tillman 2010).

2 SOLID-STATE LI-ION BATTERY TECHNOLOGY

2.1 Lithium-ion battery

A battery cell is a device composed of two electrodes - anode (reducing electrode) and cathode (oxidizing electrode) - along with a liquid or solid electrolyte to ensure efficient ionic conductivity. To prevent electrical short circuits, many batteries incorporate a separator between the anode and cathode. These separators typically consist of inert, nonconductive polymer materials, allowing unimpeded exchange of electrolytes and ion transport (Petrovi´c 2021, 4–5). A battery may consist of one or more cells. Depending on the application of the battery, the cells may be cylindrical, coin, pouch or prismatic in shape (Linden and Reddy 2002, chap. 1.4). Depending on the number of possible charges, the battery can be primary (non-rechargeable) or secondary (rechargeable) (Linden and Reddy 2002, chap. 1.2). This thesis will discuss secondary lithium-ion batteries, which are used for storing electrical energy and can be recharged. Lithium-ion (Li-ion) batteries serve as energy storage systems, utilizing input reactions from both electrodes, with lithium ions acting as charge carriers. The diverse lithium-ion battery family encompasses various chemistries. Typically, the negative electrode in most lithium-ion batteries is composed of carbon (e.g., graphite) or lithium titanate ($Li_4Ti_5\,O_{12}$), and newer materials like lithium metal and Li (Si) alloys. Positive electrodes are intercalation compounds, facilitating the diffusion of Li+ ions out or back into the material. Common examples include two types – lithium transition metal phosphates - LFP (Lithium Iron Phospate); and lithium transition metal oxides such as LCO (Lithium Cobalt Oxide), NMC (Lithium Nickel Manganese Cobalt Oxide), NCA (Lithium Nickel Cobalt Aluminium Oxide), and LMO (Lithium Manganese Oxide) (Miao et al. 2019; Armand et al. 2020). The choice of electrode materials reframes the electrolyte, usually comprising a mixture of lithium salts (e.g., $LiPF_6$) and an organic solvent (e.g., diethyl carbonate) to facilitate ion transport (Miao et al. 2019).

2.1.1 Battery operating principle

The battery operates as a galvanic device, generating energy as electrons move from the negative electrode to the positive electrode. Simultaneously, Li+ ions travel from the negative electrode, through the electrolyte, to the positive electrode, maintaining electroneutrality. When functioning in charge mode, acting as an electrolytic device, the direction of electron current and Li+ ion flow is reversed. There are different types of materials for the positive and negative electrodes, the electrolyte and the separator, the variety of combinations of which causes different chemical reactions that affect the operation of the battery, the amount of energy it can store, its voltage, etc. (Miao et al. 2019).

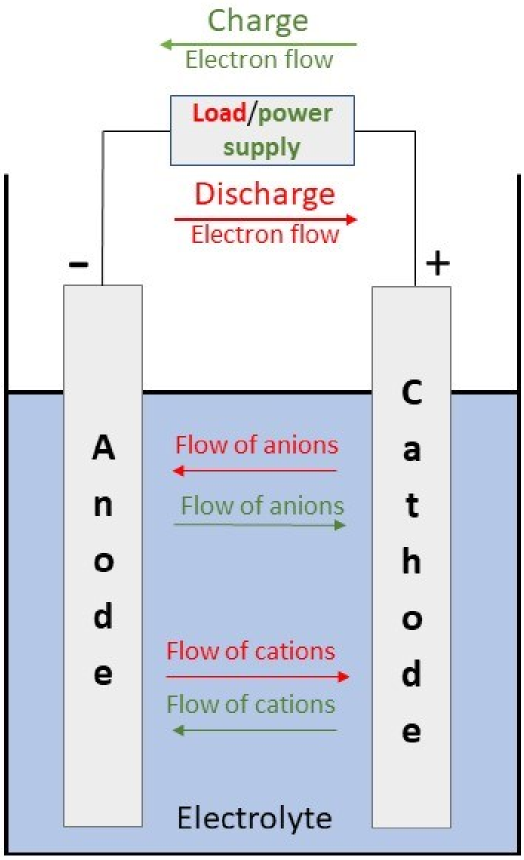

Figure 4 Operating principle of the Li -ion battery based on (Linden and Reddy 2002 chap. 1.7 - 1.8, Miao et al. 2019). Red indicates the battery discharging process, green indicates the charging process.

2.1.2 General battery metrics

For comparison and efficient operation of a battery, various parameters are used to determine its characteristics. Ideally, the parameters of the batteries under study should be measured under real operating conditions, since the indicators strongly depend on the temperature conditions, charge level, load on the battery, and correspond to the scope of application of the battery (Petrovi´c 2021, 44).

One of the main characteristics batteries are:

- Teoretical capacity, (Ah) is a parameter indicating the amount of electricity that a given battery can store (Petrovi´c 2021, 13).

• Voltage (V) – a parameter indicating the condition and charge level of the battery. The nominal voltage indicates the average voltage of the battery (Petrovi´c 2021, 23).

• Battery life cycle (end of life at 80 % capacity) is the potential number of possible charges/discharges of the battery during its operation (1 cycle = 1 charge + 1 discharge) (Borah et al., 2020; Petrovi´c 2021, 44).

• Energy density, (Wh/L or Wh/kg) is a measure that indicates the amount of energy stored by a device per mass or volume (gravimetric and volumetric energy density) (Borah et al. 2020).

• Power density, (W/kg) – a parameter indicating the maximum power generated by the battery. The parameter depends on the mass of the battery (Borah et al., 2020).

• C-rates control - an indicator showing how quickly the battery charges and discharges. And also an indicator of the maximum battery discharge rate, depending on its capacity (battery current) (Petrovi´c 2021, 28).

• Environmental impact – the possibility of recycling battery materials, the presence of toxic, critical raw materials (Petrovi´c 2021, 44).

• Operating temperature – the temperature significantly influences both the cell voltage and battery capacity by affecting the rate of electrochemical reactions. Typically, 100 % capacity is achieved at the nominal temperature of 25°C, with capacity increasing at higher temperatures and decreasing at lower temperatures (Petrovi´c 2021, 34).

2.1.3 Materials for General Battery Cell Components

1. Negative electrode active materials (Anode)

- Carbon-based electrodes and lithium titanate

Two primary types of negative electrodes commonly utilized are lithium titanate and carbon-based electrodes (grafene-based and grafite-based anodes) (Miao et al. 2019). Graphite and lithium titanate (LTO) remain viable commercial materials for Li-ion battery anodes. For graphite anodes recognized as the industry standard, only small improvements are expected. A similar situation is typical for LTO anodes used in safe segments. Although solid electrolytes can provide comparable safety performance, LTO is likely to remain the primary anode material in high-safety Li-ion batteries, at least in the short to medium term (Armand et al. 2020).

- Silicon and silicon oxide

Silicon is a standout choice for practical applications among elements forming alloys with lithium due to its exceptionally high gravimetric and volumetric capacity. It is an attractive alternative to graphite, being abundant, eco-friendly, and non-toxic, with superior capacity metrics (Armand et al. 2020).

- Li metal electrodes

Lithium-based anodes are vital for high-energy-density lithium-ion batteries (LIBs). Despite lithium metal's high theoretical capacity (3860 mAh/g) and low potential, challenges like dendrite formation, poor interfacial contact, and electrolyte sensitivity persist. Strategies involve regulating Li plating/stripping and creating composite lithium anodes with materials like graphene. Dendrite formation in lithium metal cells presents challenges, causing short circuits. Ongoing research focuses on improving safety and performance in electric vehicles using Li metal electrodes (Bubulinca et al. 2023; Miao et al. 2019).

2. Positive electrode active materials (Cathode)

– Lithium transition metal phosphates (LFP)
The main problems of LFP cathodes are their relatively poor electronic conductivity and rather low energy densities compared to the energy densities of lithium transition metal oxides materials. The maximum theoretical specific capacity of the LFP is 170 mAh/g. Despite these limitations, phosphate materials such as LFP are used in high-power applications such as hybrid electric vehicles and have achieved considerable commercial success (Armand et al. 2020).

– Lithium transition metal oxides (LCO, NMC, NCA, LMO)
LCO was the first commercially available cathode material with a theoretical specific battery capacity of 274 mAh/g. However, LCO has several problems such as thermal instability in the charged state, high cost of raw materials and limited availability of cobalt. LMO, its successor, based on manganese as the main element with a theoretical specific capacity of 148 mAh/g, was initially promising, but over time its use was limited mainly as additives in cathode mixtures. NMC and NCA cathodes offer improved energy density and longer service life compared to LCO. At the same time, NMC provides increased stability and safety, NCA provides increased energy density, which has led to the dominance of these cathode materials in the lithium-ion battery market (Armand et al. 2020).

The choice of positive electrode materials is typically determined by the desired battery performance, with considerations for factors like energy/power, cycle lifetime, safety, and cost (Miao et al. 2019; Armand et al. 2020). Most materials used in lithium-ion batteries could be applied to SSBs, with a few exceptions due to instability between electrodes and solid electrolytes. The primary distinction between SSBs and conventional LIBs lies in the electrolyte material, leading to various unique attributes of SSBs, which will be discussed later (Huang, Shao, and Han 2022).

3. Electrolytes

As mentioned earlier, the electrolyte plays a vital role in the battery by enabling the ionic conductivity necessary for the movement of Li+ ions between the electrodes while ensuring non-conductivity for electrons. Electrolytes fall into two main categories: liquid (aqueous and organic) and solid (inorganic (oxides, sulfides), polymer and hybrid electrolyte) (Miao et al. 2019; D. Wu and Wu 2023; Bubulinca et al. 2023). LIBs in use today incorporate a liquid organic solution as the electrolyte for Li-ion conduction. This solution includes lithium hexafluorophosphate ($LiPF_6$) as the conducting salt and a mixture of linear solvents (e.g., dimethyl carbonate (DMC), ethyl methyl carbonate (EMC), and diethyl carbonate (DEC)) as well as cyclic solvents (e.g., ethylene carbonate (EC)). Additionally, additives such as fluoroethylene carbonate (FEC) or vinylene carbonate (VC) is included (Armand et al. 2020). Inorganic electrolytes are composed of solid-state, inorganic, ionically conductive materials. A polymer electrolyte is solvent-free, formed by dissolving salt in a high molecular weight polymer. Polymer gel electrolyte combines a salt and solvent with a polymer. Polymer electrolytes enhance safety with low volatility. Solid gel electrolytes minimize leaks by absorbing the liquid phase within the polymer (Linden and Reddy 2002, 1094–95).

The requirements for a quality solid electrolyte are similar to traditional liquid electrolytes: low cost, high safety and compatibility with electrode materials remain crucial. Additionally, they must efficiently conduct ions while blocking the flow of electrons. Finding a solid material with these properties is challenging but essential for significant advantages over traditional liquid electrolytes. Importantly, such solid electrolytes often enable the use of metallic anodes, addressing challenges associated with dendrite formation and reactivity commonly occurring with liquid electrolytes (Borah et al. 2020).

In the past three decades, bio-based solid electrolytes, which meet the latest requirements of international environmental organizations, have attracted special attention because they are natural, non-toxic, renewable, accessible, and environmentally friendly (Rayung et al. 2020).

There are three main types of solid bio-based polymer electrolytes (Rayung et al. 2020). The first and most common is the class of polymers that are obtained directly from biomass. These include starch, cellulose and its derivatives, chitosan, gum, agar, carrageenan, pectin, guar gum, gum arabic, gelatin, natural rubber.The second type of bio-based polymers are polymers created by chemical synthesis from monomers of natural origin (polylactic acid and polyurethane based on vegetable oil). The third type - polymers produced by microorganisms or genetically modified bacteria (bacterial cellulose, gellan gum and xanthan gum) (Rayung et al. 2020). Higher cost compared to conventional petroleum-based polymers and technical problems such as hydrophilic nature and poor mechanical properties have hindered the widespread use of bio-based polymer electrolytes. For commercial applications, improvements are needed to improve ionic conductivity, mechanical strength and electrode compatibility while maintaining key characteristics. (Rayung et al. 2020).

2.2 Lithium SSB technology as a game-changer for battery technology

2.2.1 Lithium-ion battery VS Lithium SSB

At the entire cell level, there are five important key performance indicators (KPIs): safety, energy density, fast charging capability, long-term stability or lifetime, and cost (D. Wu and Wu 2023). Contemporary LIBs currently have a gravimetric energy density of <250 Wh/kg and a volumetric energy density of <650 Wh/L. The main SSBs advantage is potential improvement for higher energy density, contributing to enhanced performance (Fig.5). These enhancements are contingent on the characteristics of the anode, cathode, and electrolyte materials used, as well as the specific environment and intended application (Bubulinca et al. 2023).

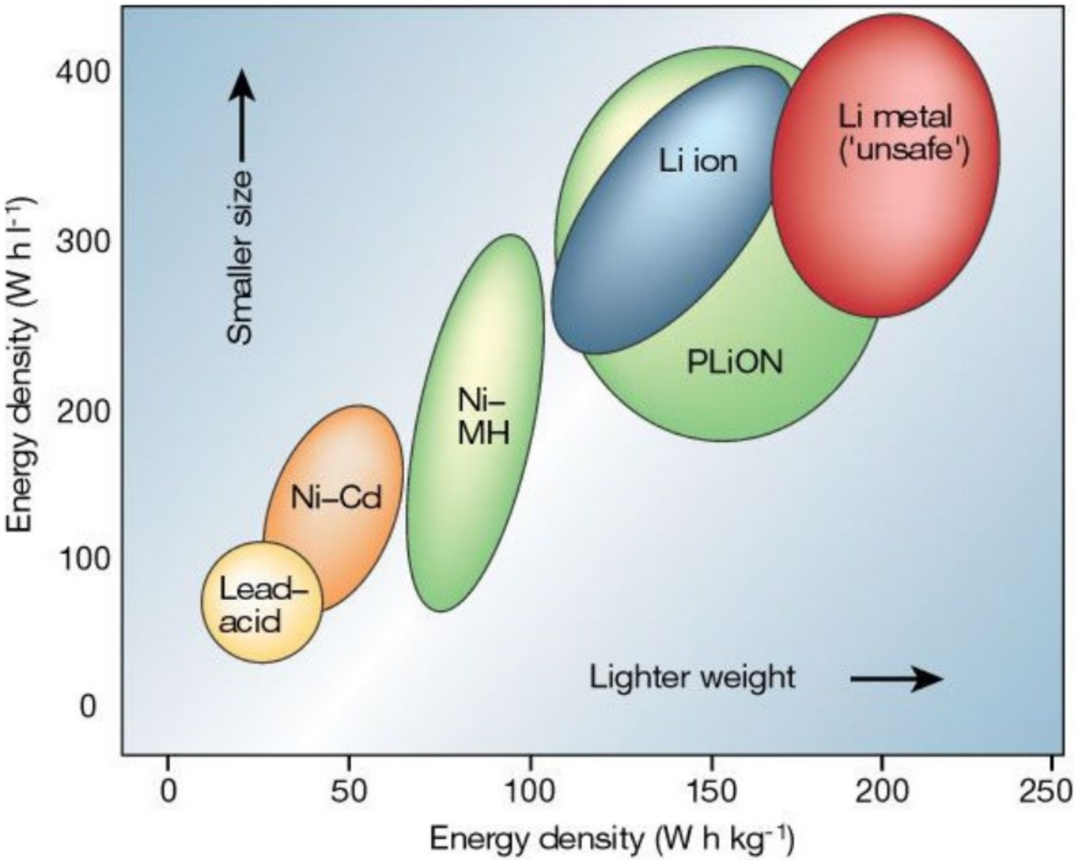

Figure 5 Battery energy storage technology for EVs is the Li-ion battery (Miao et al. 2019)

SSBs can potentially offer faster-charging rates due to the nature of solid electrolytes. Sulfide SEs hold greater promise for rapid charging compared to oxide SEs. LIBs degradation over cycles is common, affecting long-term reliability. SSBs have the potential for longer cycle life, especially with the use of solid electrolytes. The use of flexible polymer based SSBs could extend their lifetimes. Long-term stability is influenced by factors like lithium dendrite growth (D. Wu and Wu 2023). Traditional organic liquid electrolytes in rechargeable LIBs also present a safety concern due to their flammability. With the advancement of larger batteries for automotive or stationary applications, the risk of fire and explosion has become a critical issue. Replacing the flammable liquid solution with an inorganic solid electrolyte (ISE) or solid polymer electrolyte (SPE) is seen as an attractive strategy to address safety risks as well as increasing flexibility in the battery shape, facilitating widespread commercialization of large-scale batteries (Varzi et al., 2020).

LIBs typically offer a cost advantage due to their mature technology and well-established manufacturing processes. In contrast, SSBs currently face challenges associated with higher costs, but ongoing advancements hold the potential to influence their future affordability. Polymer solid-state batteries (SSBs) have the potential to be economically competitive and cost-effective, especially with the establishment and scaling up of production lines (D. Wu and Wu 2023).

LIBs are widely integrated into portable electronics, electric vehicles, and energy storage systems. While SSBs are still in the research and development phase, efforts toward commercialization are gaining momentum. This reflects ongoing endeavors to refine battery technologies, especially in the context of lithium SSBs, which promise advancements in safety, energy density, and flexibility.

2.2.2 Promising lithium-based solid-state material components

Anodes based on metallic lithium and silicon are considered among the most promising materials for SSBs due to their high theoretical specific capacities and low operating potentials. Among cathodes, high Ni content (NMC and NCA) and LCO cathodes have higher technological potential, while LFP and Lithium Manganese Nickel Oxide (LMNO) cathodes dominate in terms of price combined with average technical characteristics (Schmaltz et al. 2023; D. Wu and Wu 2023). Garnet-type materials stand out as the most promising among solid electrolytes in oxide SE, while certain polymer SEs have found implementation in specific applications (D. Wu and Wu 2023).

More detailed characteristics of materials, their advantages and disadvantages are described in the Tab. 2 below.

Table 2 Advantages and disadvantages SSB promising materials based on (Schmaltz et al. 2023; Varzi et al. 2020; D. Wu and Wu 2023; Kim et al. 2020)

TSC – theoretical specific capacity, E_{H} – redox potencial, q_{pr} - practical capacity, Gr – gravimetric, Vol – volumetric, DoD - Depth of discharge.

Material of SSBs components	**Parameters**	**Advantages**	**Disadvantages**
Anod			
Graphite	Practical specific capacity ≈ 360 mAh/g, E_H ≈ 0.1 V versus Li+/Li	• fast charging (hight electronic conductivity) • mechanically deformable (facile lithium- ion diffusion) • high availability • safe operation • inexpensive	• compared to LIB, the energy density gain is not that great

Silicon -based	TSC = 3579 mAh/g $E_H(Si/Li_xSi)$ = 0.2 - 0.4 V vs Li^+/ Li	• high-energy anodes	• significant volume shift while cycling • interfacial contact issues
LMA (Li-metal anode)	TSC = 3862 mAh/g $E_H(Li^+/Li)$ = -3.04 V vs standard hydrogen electrolyte	• reliable and safe operation • high-energy anodes	• significant volume shift while cycling • interfacial contact issues
LMA with carbonaceous compounds	-	• keeping the anode in intimate contact with the SE during cycling	-
LTO	Specific capacity = 180 mAh/g E_H = 1.55 V versus Li+/Li	• long-term stability • candidate for high-duty SSB • high-power anodes	• low cell-level energy density
Cathode			
NMC	$E_H \approx 3.8$ V vs Li^+/ Li, TSC ≈ 275 mAh/g	• high-energy electrode	• structural instability
NCA	$E_H \approx 3.8$ V vs Li^+/ Li, TSC ≈ 275 mAh/g	• high-energy electrode	• structural instability
$LiMn_{2-x}Ni_xO_4$	$E_H \approx 4.6$ V vs Li^+/ Li	• high-voltage electrode • good cycling stability, rate capability	• limited capacity
LFP	$E_H \approx 3.3$ V vs Li^+/ Li $q_{pr} \approx 160$ mAh/g	• lower cost electrode • safe operation • thermal stability • hight cycling stability	• a practical capacity determines the limit of energy density
$LMn_xFe_{1-x}PO_4$	$E_H \approx 3.3$ V vs Li^+/ Li	• lower cost electrode	• a practical capacity determines the limit of energy density
Lithium – rich oxides (LLO)		• hight energy density	• fast cell fading
Solid electrolyte (ISE (TRL 4–6) SPE (commercial))			
Sulfide Li_3PS_4	**Energy:** Gr: 450 Wh/kg Vol: 900 Wh/L **Power:** Gr: < 500 W/kg Vol: < 1000 W/L **Cycle Life (to 80 % DOD):** 1000 **Limiting factors** • ISE stability towards high voltage cathodes • High cell impedance • Contact issue at interfaces • Dendrite growth	• extremely high ion conductivity • good solid-solid contact with the electrode interface • softer and more deformable than oxide-based system	• high reactivity with lithium metal and high- voltage cathode materials.extremely hygroscopic
Sulfide $Li_{10}GGe$ P_2S_{12} (LGPS)		• hight Li – ion conductivity at room temperature • softer and more deformable than oxide-based system	• high reactivity with lithium metal and high-voltage cathode materials
Oxide (garnet-type)		• good electrochemical stability with lithium metal • lower degradation at high voltage • Stable at high voltage and in contact with lithium metal	• relatively low ion conductivity • relatively stable in air • highly sensitive to water and CO2high resistance at the grain boundaries
Oxide (perovskite - type)		• good electrochemical stability with lithium metal • lower degradation at high voltage • high ionic conductivity	• key changes are to enlarge the channel for lithium transport

Oxide (NASICON)		• good electrochemical stability with lithium metal • lower degradation at high voltage • high ionic conductivity	• key changes are to enlarge the channel for lithium transport
Oxide (LISICON)		• good electrochemical stability with lithium metal • lower degradation at high voltage • high ionic conductivity at high temperature	• ionic conductivity gradually decreasing at low temperatures • conductivity at ambient temperature
Polymer PEO (polyethylene oxide), GPEs (gel polymer el ectrolytes)	**Energy (EVs):** Gr: 100–180 Wh/kg Vol:100 Wh/L **Power (EV):** Gr: < 200 W/kg Vol: < 200 W/L **Cycle Life (to 80 % DOD):** ca. 1300 **Limiting factors** • Operating temperature > 60 ◦C SPE stability towards high voltage cathodes • Low Li+ transference number • Stability of electrode/ electrolyte interphase	• soft • highly flexible • better processability • improved adhesion to electrodes compared to inorganic SE • better volume change compensation than with inorganic SE • potentially cost-efficient fabrication • usually, no need critical raw materials	• the glass transition or melting point of the polymer and the operating temperature affect Li+ ion transport • certain unmodified polymer SE require an external battery heater due to the weak ionic conductivity at normal temperature • usually, long charging time • require thermal stability

2.2.3 Solid-state lithium metal batteries with bio-based material electrolyte and LFP cathode

Lithium metal, with its high energy density, is one of the key promising anode materials in the battery field (Yuan et al. 2022). Based on numerous theoretical studies on the nature and behavior of lithium ions, significant progress has been made in the development of various technologies for reducing the formation of lithium dendrites, which highlights the importance of research related to electrolyte modification (use of inorganic/organic electrolytes, additive modification, etc.) and the creation of protective films for lithium (Cheng et al. 2017). The SSB technology based on organic electrolyte and LMA is already commercially used today for batteries in buses and stationary storage facilities. A battery with an energy density of 180 Wh/kg, 1300 cycles within 60°C and 80°C was patented by the French company Bolloré Group (Varzi et al. 2020).

The combination of LMA, PEO SE and LFP cathode creates a competitive technology that has a number of advantages. Despite the use of low-voltage $LiFePO_4$, lithium-metal polymer batteries are capable of providing a weight energy density of up to 300 Wh/kg. These batteries are attractive in terms of price and environmental issues. Since the cost of the LFP cathode is significantly lower than, for example, NMC or NCA, and the electrolyte is made of bio-based polymer materials PE based on PEO, it is environmentally friendly and affordable.

The main disadvantage is operation at temperatures well above room temperature (50–80 °C), which affects the mechanical stability and ionic conductivity of the battery and electrochemical instability at voltages above 4-4.1 V. Therefore, at the moment, the use of a LFP cathode is the optimal choice, since it has a voltage of 3.5V, is compatible with lithium metal polymer and is suitable for operation at elevated temperatures (Schmaltz et al. 2023; Varzi et al. 2020).

2.3 Lithium metal polymer cell manufacturing

Common SSB cell formats are prismatic or pouch cells, which are flat in shape to maintain the integrity of the SE. Each SSB cell consists of an anode, a cathode, and a solid electrolyte (conductor) with a separator (protective layer) or only electrolyte, which includes the function of both. The cathode, usually, consists of a current collector coated with a layer of paste for the positive electrode, mixed with a small amount of binder (for better conductivity). The anode consists of a Li metal foil pressing on a current collector (B.Wu et al. 2019). The electrolyte consists of a binary lithium salt with bulk polymer material (Zaman and Hatzell 2022). The battery manufacturing process typically consists of several steps: cell electrode production (mixing, coating, drying, thinning, stacking), cell assembly, and cell test (Zaman and Hatzell 2022; B. Wu et al. 2019), Fig. 6.

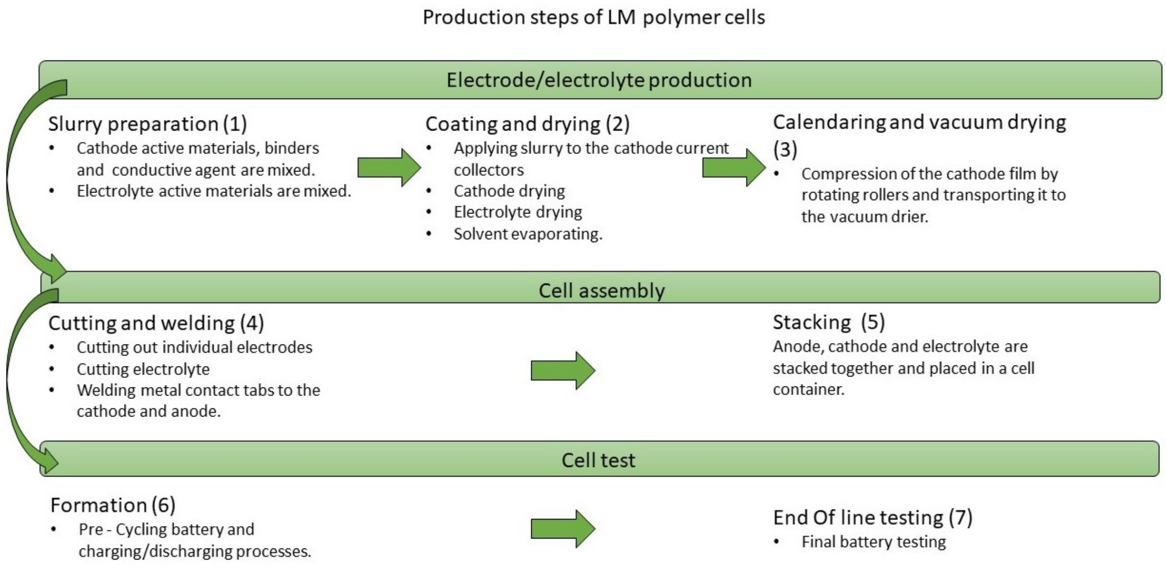

Figure 6 Production steps of lithium metal polymer cells based on (Zaman and Hatzell 2022).

3 REVIEW OF RELEVANT LCA OF SSB

A literature search in Web of Science using the keywords “solid-state battery” and “life cycle assessment” shows only eight available detailed LCA studies on SSB. The studies mostly make assumptions regarding the performance of solid-state battery technologies at various stages of their life cycle, with a primary focus on mobile applications. Details of the battery type, inventory data, functional unit, assessment boundary, and impacts categories used in these LSA studies are provided below in Tab. 3.

Table 3 Available in the literature LCA studies for the SSBs based on (Mandade et al. 2023; Popien et al. 2023)

CED- Cumulative energy demand, GWP- Global warming potential, HT-Human toxicity, PMF-Particulate matter formation, FE-Freshwater eutrophication, PF- Photochemical oxidant formation, WDP-Water depletion potential, MDP-Mineral depletion potential, POCP- Photochemical ozone formation, IR- Ionizing radiation – Human health effects, ODP-Ozone depletion potential, RDP-Resource depletion potential, AP-Acidification potential, ETP-Ecotoxicity potential, PSF- Photochemical smog formation, METP Marine ecotoxicity potential, TETP- Terrestrial ecotoxicity potential, ME- Marine eutrophication, RPE-Respiratory effects, FRS- Fossil resource scarcity, LU-Land use, MRS-Mineral resource scarcity, FDP-Fossil depletion potential, CC – Climate change, MRD – metal resource depletion, SHDB – social hotspot database.

Reference	Battery chemistry	Cell/Battery type	Data sources for inventory	FU	System boundary	Method of impact assessment/Software	Impact category	Dimensions, results
(Lastoskie and Dai 2015)	LCO, LMO, NMC, LVO, SVO, NCA, LNMO, CuMn	Model cylindrical cell for EV	Sakti3 company data, Ecoinvent 2.2 database, industrial productions method data, research literature.	1 Wh energy storage	Cradle to Gate (material, production, use stages)	ReCiPe, SimaPro v. 7.2	CED (cumulative energy demand), GWP, HT, PMF, FE, PF, WDP, MDP	Environmental assessment Solid-state lithium vanadium oxide cells have minimal impact per unit of energy compared to other types. This applies to both overall energy consumption and environmental parameters, including GWP. HH impacts and resource depletion are higher for LMO and LCO solid-state cells, but CED and GWP per unit energy are 25–65% lower for solid-state cells in different cathode chemistries.
(Keshavarzmohammadian, Cook, and Milford 2018)	Sulfur based solid-state lithium pyrite battery	Lab scale cell for EV	Laboratory data, research literature, U.S. patents, US-EI 2.2 database	Production of 80 kWh battery pack	Cradle to Gate (materials, production stages)	TRACI 1.02, SimaPro version 8.4 with the US-EI 2.2 LCI database	ODP, GWP100, PSF, AP, FE, HT, RPE, ETP, CED	Environmental assessment The 100-year estimated CED is 3300 MJ kWh−1, GWP100 is 199 kg CO2 eq. kWh−1. Impacts of CED and GWP100 related to battery production are lower than the energy consumption and emissions for a vehicle of similar size and range when considering the entire well-to-wheel process.
(Smith et al. 2021)	LFP	Model cell	Ecoinvent database, research literature, on-going Li-ion projects.	1 kg battery	Cradle to gate (material, production stages)	ReCiPe Midpoint (H) v 1.13, energy demand ILCD	CED, GWP 100, ETP, HT, METR, TETR, FE, ME, AP.	Environmental assessment LiBs generally have a lower environmental impact than SSBs across various categories. The sensitivity analysis reveals that the cycle life of SSBs needs to increase significantly, from 100 to 2800 cycles, to surpass LiBs and achieve a lower GWP impact,

								marking an improvement in this environmental category.
(Troy et al. 2016)	LCO	Original pouch cell	Ecoinvent 2.2 database, laboratory data.	1 SSB pouch cell, 43.75 mAh capacity	Cradle to Gate (material, production stages)	ILCD, GaBi6	CED, GWP, HT, PMF, FE, POCP, IP, ET, ODP, RDP, AP.	Environmental assessment Optimizing energy consumption in battery manufacturing is critical, especially in elevated temperature environments. Areas for improvement in future industrial developments are identified, with an emphasis on efficient use of resources. Comparison with commercially established technologies in early stages of LCA is not recommended.
(Vandepaer, Cloutier, and Amor 2017)	LMP	Original cell	Ecoinvent 3.1, Batt-DB database, industrial companies' data	Delivery of 1 MWh of electricity	Cradle to Gate (material, production, use, end of life stages)	IMPACT 2002+	GWP, ODP, AP, FE, HT, FDP, IR	Environmental assessment The battery manufacturing stage has the greatest environmental impact across the various batteries studied. LIBs have significant impacts on GWP and ODP, while LMP units have a more significant impact on eutrophication.
(Zhang et al. 2022)	NMC, LATP ISE	Original coin cell	Ecoinvent, GaBi prof data bases, literature	Coin cell with 100-150 mAh capacity	Cradle to Gate (material, production stages)	TRACI 2.1 (US EPA), GaBi 9.2	GWP, AP, ETP, EP, HHPA, HTP, ODP, FF, SA	Environmental assessment The production of one CR2032 ASSLIB demands 2.6 MJ of primary energy and yields 0.1 kg CO2-eq. in GWP. In comparison, it exhibits higher environmental impacts than conventional LiPF6 EC/DMC-based liquid LIBs, which need 1.1 MJ of primary energy and result in 0.05 kg CO2-eq. Large-scale fabrication can mitigate environmental impacts by reducing manufacturing energy requirements and ISE (Ionic Solid Electrolyte) thickness.
(Popien et al. 2023)	NCA, LFP, NMC 622, NMC 811, Sulfur	Model cell	Ecoinvent 3.8, SHDB, literature data, scientific literature, battery Perfomance and cost model 4.0 (BatPaC), GREET model	Production of one battery pack with a capacity of 80kWh	Cradle to Gate (material, production stages)	ReCiPi Midpoint (H) v1.13, Python-based "Brightway2" framework, SHDB	CC, HT, MRD, PSF, total battery cost, risk of child labor, risk of corruption, risk of forced labor.	Environmental, economic and social assessment ASSB-LSB was preferred in all impact categories studied. Hot spots and potential for improvement in ASSB have been identified, such as changing the composition of battery packs or using 100 % renewable energy in production.
(Schnell et al. 2020)	Sulfur based ASSB, oxide-based ASSB	Model cell	Literature values, expert interviews, supplier quotations	Unity of mass ($/kg), total amount of cells produced per year	Cradle to Gate (material, production stages)	Bottom-up cost model by Schünemann, MATLAB (version R2018 b)	Manufacturing cost for a production output of 6 GWh/year, Investment required for production facilities	Economic assessment Sulfide ASSBs can be competitive with LIBs, provided material compatibility issues are addressed and production scales up successfully. In contrast, oxide ASSBs are likely not to compete in high cost situations.

II. ANALYSIS

4 GOAL AND SCOPE

This thesis uses attribute-based LCA method with environmental impact monetarization to determine the environmental and economic impacts of a single lab-scale SSB coin cell.

The goal of the investigation is to determine the selected environmental impacts associated with a chosen CR 2032 LFP SSB with bio-based material (BBM) electrolyte produced within the TwinVECTOR project in TBU, Zlin (Czech Republic) and to monetize these impacts. The main challenge is to identify potential hot spots that will allow technology to be improved and more efficient and environmentally sustainable solutions to be developed.

The FU is defined as one SSB coin cell. The system boundaries focus on the cradle-to-gate model, including raw materials extraction and production stages. The usage and recycling phases of the SSB battery are not considered in this thesis. To carry out this assessment, material and energy flows from resource extraction to product manufacturing, as well as transport, are considered.

The production of cathode and anode materials takes place in Europe and USA. The production of cell container takes place in United Kingdom (UK). The production of electrolyte takes place in Czech Republic. This analysis used primary data obtained during laboratory battery production line at TBU in 2024. If access to primary data was limited, secondary sources of information were used. These secondary data included LCA reports, information from the ecoinvent database, and expert opinions from TBU specialists involved in laboratory-scale battery production.

Calculations for LCA were performed in the SimaPro program (9.5.0.1), using the Ecoinvent database (3.9.1). To perform the LCA, the ReCiPe 2016 impact assessment method was chosen, which is widely used in LCA analysis practice. The EP impact assessment method was used to monetize the environmental impact of the LCA. The choice of impact categories for LCA was created based on the above-mentioned review of relevant SSBs LCA: Global Warming Potencial (GWP), Ozone Depletion Potential (ODP), Terrestrial Acidification Potencial (TAP), Freshwater Eutrofication Potencial (FEP), Human Toxicity Potencial (HTP), Terestrial Ecotoxicity Potencial (TETP). In addition, the categories of Mineral Resource Scarcity (MRS) and Fossil Resource Scarcity (FRS) were included as they are important for identifying potential risks associated with the use of limited resources and the Land Use (LU) category was included due to the presence of BBM in the battery's electrolyte.

The battery study has several limitations that should be considered when interpreting the results. First, consider the maturity of battery technology, which may affect the relevance of the results. Secondly, the study was conducted at a laboratory level, which may not accurately reflect the behaviour of the battery under real-life operating conditions that are distinguishable from laboratory conditions (temperature, humidity, mechanical stress). The third limitation is data availability. Finally, limitations include the selected boundaries and impact categories. This thesis doesn`t include the energy consumption associated with formation and clean rooms. Given the above, the results need to be interpreted carefully and taken into account in future research and decision-making in the field of battery technology.

5 LIFE CYCLE INVENTORY

The production of the CR 2032 coin cell is based on TwinVector project laboratory work, and the detailed manufacturing process, included in this thesis, is illustrated in Fig. 7. The CR 2032 coin cell consists of Ø14 mm LFP cathode, Ø16 mm BBM electrolyte and Ø15 mm lithium foil, Ø14 mm Al and Ø15 mm Cu foil for current collectors. The specific capacity for the Ø20 mm size of the battery is 824.4 µAh, power of the battery is 0.0026 Wh.

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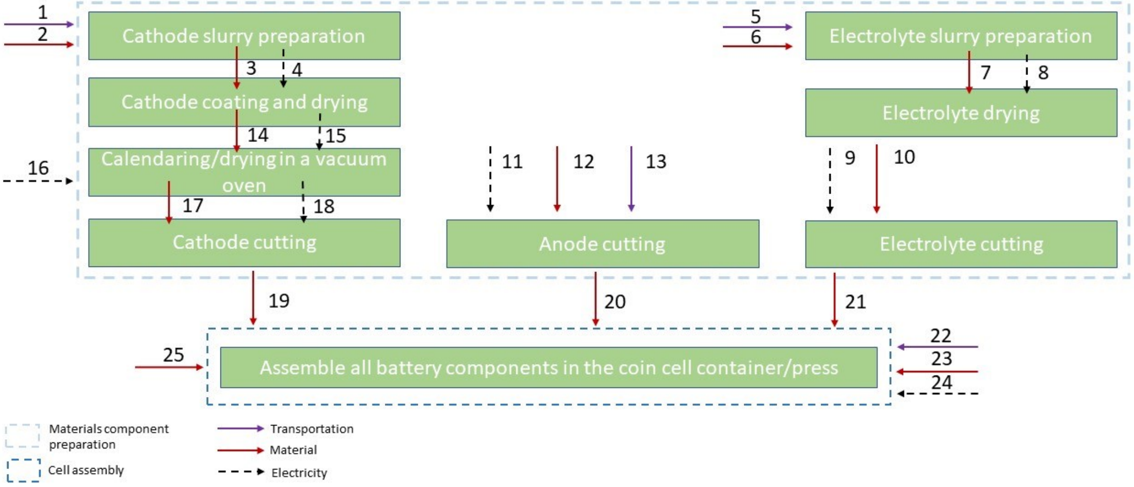

Figure 7 Flow chart for TwinVECTOR LFP coin cell laboratory battery production with BBM solid electrolyte. Diagram design based on (Erakca et al. 2023).

Table 4 Description for flow chat for LFP coin cell laboratory battery production with BBM electrolyte

Process	Discription of inputs
1	Transport for delivery cathode materials
2	Materials for cathode: positive current collector (materials, energy production, transport), positive electrode paste (materials, energy production, transport)
3	Cathode materials for manual coating
4	Energy consumption for mixing, coating and drying cathode in an oven
5	Transport for delivery electrolyte materials
6	Materials for electrolyte: materials, energy production, transport
7	Materials for electrolyte drying
8	Energy consumption for stirring; mixing and drying electrolyte in an oven
9	Manually cutting the elecrtrolyte
10	Materials for elecrtrolyte cutting

11	Manually cutting the anode
12	Materials for anode cutting
13	Transport for anode delivery
14	Materials for cathode callendaring
15	Energy consumption for cathode callendaring
16	Energy consumption for cathode drying in vacuum oven
17	Materials for cathode cutting
18	Manually cutting the cathode
19	Cathode materials for final manual assemble all battery components
20	Anode materials for final manual assemble all battery components
21	Electrolyte materials for final manual assemble all battery components
22	Transport for delivery cell container components
23	Materials for cell container (positive cap, negative cap, spring, anod and cathode spacers)
24	Electrolyte cathode filling and cell pressing in glove box
25	Materials for cathode: LiTFSI+ Propylene carbonate

5.1 Collection of input data for the selected battery type

Modeling coin cell composition

In the laboratory-scale coin cell, the four main subcomponents identified for inputs: the anode, cathode, electrolyte, and cell container. To assemble one coin cell, the following materials were utilized: 12.818 mg of LFP cathode, 0.943 mg of anode, 6.73 mg of positive current collector, 15.635 mg of negative current collector, 144.3 mg of electrolyte, and 4224 mg of cell container. The composition of materials and the mass balance are specified in Tab. 5.

Table 5 LCI for the production of the TwinVector CR 2032 LFP SSB

Parametrs	**Dataset**	**Amount,mg**	**Ratio without cell conainer**	**Ratio with cell container**
Functional Unit				
Output CR 2032 LFP SSB		180.426 (without) 4404.426 (with)	100	100
Material Requirements				

Positive electrode paste for Li-ion battery, LFP	See Table 7	12.818	7.1	0.29
Negative electrode paste for Li-ion battery, Li-Metal	See Table 14	0.943	0.52	0.02
Positive current collector for Li--ion battery, Al	See Table 13	6.73	3.73	0.15
Negative current collector for Li-ion battery Cu	See Table 15	15.635	8.67	0.35
Electrolyte for Li-ion battery , BBM	See Table 17	144.3	79.98	3.28
Cell container	See Table 22	4224	-	95.9

5.1.1 Production of the LFP cathode

According to the expert opinion from TBU's battery specialist, the following amount of material is required to produce one cathode for CR 2032: 6.73mg an aluminum current collector, 5.496 mg LFP paste, 0.1374 mg graphite, 0.5496 mg PVdF binders, 0.687 mg super P additives, 0.02748 ml NMP (N-Methyl-2-pyrrolidone) and 1.148 mg LiTFSI (lithium bis-trifluoromethanesulfonimide) salt with 4 µl propylene carbonate (PC) solvent electrolyte.

The total weight of LFP cathode: 19,548 mg (cathode paste – 65.6%, cathode current collector – 34.4%).

Preparation of the Cathode:

At the first stage, components such as LFP paste, graphite, NMP, binders, and carbon black additives are mixed and applied to the Al current collector for further drying. During the drying process, the NMP substance evaporates, which is why it wasn't accounted for in the mass balance. During the assembly stage, a small quantity of LiTFSI with PC is added to the completed cathode before stacking the battery components.

To ascertain the production details for 1 kg of the SSB LFP cathode, was conducted calculations to determine the ratio of cathode materials (Tab. 6).

$$m = p \times V \tag{1}$$

p (NMP) = 1030 kg/m^3 = 1.03 kg/l.

Mass of NMP = 0.00002748× 1.03 = 28.3 ×10^{-6} kg.

p (PC) = 1200 kg/m^3 = 1.2 kg/l.

Mass of PC = 0.000004 × 1.2 = 4.8 ×10^{-6} kg.

1 kg of cathode production is required 0.69 kg of NMP.

Table 6 Cathode materials ratio

Input	Amount	Unit	Ratio
PVdF (binders)	0.5496	mg	0.04
NMP (solvent)	28.3	mg	-
LiFePO4	5.496	mg	0.43
Graphite	0.1374	mg	0.01
Super P (carbon black)	0.687	mg	0.05
LiTFSI	1.148	mg	0.09
PC (Propylene carbonate)	4.8	mg	0.38
Total	12.818	mg	1

The PVdF organic binder (Erakca et al. 2023), LiFePO4 and (Majeau-Bettez, Hawkins, and Strømman 2011) and LiTFSI (Larrabide, Rey, and Lizundia 2022) data was used to analyze inputs.

The production details for 1 kg of the SSB LFP cathode are specified in Tab. 7.

Table 7 LCI for the production of 1 kg of the SSB LFP cathode

Products	Inputs	Outputs	Unit	
3.2 Postive electrode paste, Production		1	kg	**References**
Materials/fuels				
3.2b Organic binder PVDF	0.04		kg	Erakca et al 2022
N-methyl-2-pyrrolidone {GLO}| market for N-methyl-2-pyrrolidone | Cut-off, U	0.69		kg	TBU pilot line

3.2a Postive active material sub inventory (LiFePO4)	0.43		kg	Majeau-Bettez et al 2011
Graphite, battery grade {GLO}| market for graphite, battery grade | Cut-off, U	0.01		kg	TBU pilot line
Carbon black {GLO}| market for carbon black | Cut-off, U	0.05		kg	TBU pilot line
3.2.1 LiTFSI	0.09		kg	Rey et al 2022
Propylene carbonate {RoW}| propylene carbonate production | Cut-off, U new	0.38		kg	TBU pilot line
Transport				
Transport, freight train {RER}| market group for transport, freight train | Cut-off, U	0.129		tkm	Own calculation
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, U	0.624		tkm	Own calculation
Transport, freight, aircraft, unspecified {GLO}| market for transport, freight, aircraft, unspecified | Cut-off, U	9.23		tkm	Own calculation
Chemical factory, organics {RER}| chemical factory construction, organics | Cut-off, U	4E-10		p	Smith et al. 2021
Electricity/heat				
Electricity, low voltage {CZ}| market for electricity, low voltage | Cut-off, U	6.0772		kWh	Own calculation
Emissions to air				
1-Methyl-2-pyrrolidinone		0.69	kg	Own calculation

It is important to mention that the abbreviations in brackets in the data from the ecoinvent data base indicate the geography represented by the dataset: Global (GLO), Europe (RER), Czech (CZ), Rest of World (RoW). SimaPro utilizes a cut-off to eliminate processes with minimal contribution to the final result (Cut -off), "U" signifies that this pertains to unit processes.

5.1.1.1 Production of $LiFePO_4$

It has been suggested that lithium iron phosphate ($LiFePO_4$) was produced by hydrothermal synthesis, in which sulfate ($FeSO_4 \cdot 7H_2O$) reacts with phosphoric acid (H_3PO_4) and lithium hydroxide (LiOH) at 150–200°C for 5 hours. The resulting $LiFePO_4$ precipitate is filtered and dried at 60°C for 5 hours, with a recovery of 95%. It is assumed that by-products are released into the hydrosphere (Majeau-Bettez, Hawkins, and Strømman 2011).

The production details for 1 kg of LFP are available in Tab. 8.

Table 8 LCI for the production of 1 kg LiFePO4 (Majeau-Bettez, Hawkins, and Strømman 2011)

Products	Inputs	Outputs	Unit
3.2a Postive active material sub inventory		1	kg
Materials/fuels			
Lithium hydroxide {GLO}| market for lithium hydroxide | Cut-off, U	0.46		kg
Phosphoric acid, industrial grade, without water, in 85% solution state {GLO}| market for phosphoric acid, industrial grade, without water, in 85% solution state | Cut-off, U	0.65		kg
Iron sulfate {RER}| market for iron sulfate | Cut-off, U	1		kg
Water, deionised {Europe without Switzerland}| market for water, deionised | Cut-off, U	46		kg
Transport			
Transport, freight, lorry 16-32 metric ton, EURO3 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO3 | Cut-off, U	0.21		tkm
Transport, freight train {RER}| market group for transport, freight train | Cut-off, U	1.3		tkm
Chemical factory, organics {RER}| chemical factory construction, organics | Cut-off, U	4E-10		p
Electricity/heat			
Heat, from steam, in chemical industry {RER}| market for heat, from steam, in chemical industry | Cut-off, U	15		MJ
Emissions to water			
Lithium		0.1	kg
Iron, ion		0.019	kg
Phosphate		0.032	kg
Heat, waste		1.5	MJ

5.1.1.2 Production of LiTFSI

The LiTFSI (Larrabide, Rey, and Lizundia 2022) data was used to analyze inputs.

The production details for 1 kg of LiTFSI are available in Tab. 9.

Table 9 LCI for the production of 1 kg LiTFSI

Products	Inputs	Outputs	Unit
3.2.1 LiTFSI		1	kg
Materials/fuels			
3.2.1.1 DOL	0.084		kg
Sulfur dioxide, liquid {RER}| market for sulfur dioxide, liquid | Cut-off, U	0.718		kg
Chlorine, gaseous {RER}| market for chlorine, gaseous | Cut-off, U	0.796		kg
Hydrogen fluoride {RER}| market for hydrogen fluoride | Cut-off, U	0.568		kg
Silica sand {GLO}| market for silica sand | Cut-off, U	1.343		kg
Ammonia, anhydrous, liquid {RER}| market for ammonia, anhydrous, liquid | Cut-off, U	0.56		kg
Sodium methoxide {GLO}| market for sodium methoxide | Cut-off, U	0.224		kg
Sulfuric acid {RER}| market for sulfuric acid | Cut-off, U	0.383		kg
Lithium carbonate {GLO}| market for lithium carbonate | Cut-off, U	0.131		kg
Ethylene glycol dimethyl ether {GLO}| market for ethylene glycol dimethyl ether | Cut-off, U	0.167		kg
Electricity/heat			
Steam, in chemical industry {RER}| market for steam, in chemical industry | Cut-off, U	37.977		kg
Emissions to air			
Methane, monochloro-, R-40		4.442	kg
Methane		0.165	kg
Ammonia	low. pop.[1]	0.000177	kg
Sulfur dioxide	low. pop.	0.000227	kg
Hydrochloric acid	low. pop.	0.0001	kg
Chlorine	low. pop.	0.000252	kg
Methane	low. pop.	5.21E-05	kg
Hydrogen fluoride	low. pop.	0.00018	kg
Emissions to water			
Waste water		3.567	kg

[1] low. pop – low population density.

5.1.1.3 Production of DOL(1,3-dioxolane)

The DOL (Larrabide, Rey, and Lizundia 2022) data was used to analyze inputs.

The production details for 1 kg of DOL are available in Tab. 10.

Table 10 LCI for the production of 1 kg DOL

Products	Inputs	Outputs	Unit
3.2.1.1 DOL		1	kg
Materials/fuels			
Ethylene glycol {GLO}| market for ethylene glycol | Cut-off, U	0.874		kg
Formaldehyde {RER}| market for formaldehyde | Cut-off, U	0.423		kg
Tap water {Europe without Switzerland}| market for tap water | Cut-off, U	0.72		kg
Electricity/heat			
Heat, from steam, in chemical industry {RER}| market for heat, from steam, in chemical industry | Cut-off, U	13.6		MJ
Emissions to air			
Formaldehyde		0.127	kg
Emissions to water			
Ethylene glycol		117	kg
Formaldehyde		56.8	kg
Waste water/m3		0.053	m3

5.1.1.4 Production of PC

Due to the unavailability of current production data for PC, this material was modeled using molar calculations derived from existing ethylene carbonate chemical and the energy consumption associated with ethylene carbonate production.

The production details for 1 kg of PC are available in Tab. 11.

Table 11 LCI for the production of 1 kg PC

Products	Inputs	Outputs	Unit
Propylene carbonate		1	kg
Materials/fuels			
Carbon dioxide, liquid {RER}| market for carbon dioxide, liquid | Cut-off, U	0.075094	kg	kg
Carbon dioxide, liquid {RoW}| market for carbon dioxide, liquid | Cut-off, U	0.356736	kg	kg
Chemical factory, organics {GLO}| market for chemical factory, organics | Cut-off, U	4E-10	p	p

Propylene oxide, liquid {RER}| market for propylene oxide, liquid | Cut-off, U	0.189852	kg	kg
Propylene oxide, liquid {RoW}| market for propylene oxide, liquid | Cut-off, U	0.384427	kg	kg
Electricity/heat			
Electricity, medium voltage| market for electricity, medium voltage | Cut-off, U	0.002	kWh	kWh
Heat, district or industrial, natural gas {GLO}| market group for heat, district or industrial, natural gas | Cut-off, U	0.14333	MJ	MJ
Emissions to air			
Carbon dioxide, fossil		0.005834	kg
Propylene oxide		0.000275	kg

5.1.1.5 Production of PVDF (binders)

The PVdF organic binder (Erakca et al. 2023) data was used to analyze inputs.

The production details for 1 kg of PVDF are available in Tab. 12.

Table 12 LCI for the production of 1 kg PVDF

Products	Inputs	Unit
3.2b Organic binder PVDF		kg
Materials/fuels		
Polyethylene, low density, granulate {GLO}| market for polyethylene, low density, granulate | Cut-off, U	0.5	kg
Tetrafluoroethylene {GLO}| market for tetrafluoroethylene | Cut-off, U	0.5	kg

5.1.2 Production of positive electrode current collector

Since there was no current data available on foil production process, data from the "sheet rolling" process was taken for inventory (Majeau-Bettez, Hawkins, and Strømman 2011). The production details for 1 kg of the SSB LFP positive electrode current collector are available in Tab. 13.

Table 13 LCI for the production of 1 kg positive electrode current collector (Smith et al. 2021; Majeau-Bettez, Hawkins, and Strømman 2011)

Products	Inputs	Unit
3.1 Positive current collector, Production		kg
Materials/fuels		
Aluminium, wrought alloy {GLO}| market for aluminium, wrought alloy | Cut-off, U	1	kg
Sheet rolling, aluminium {RER}| sheet rolling, aluminium | Cut-off, U	1	kg
Transport		
Transport, freight train {Europe without Switzerland}| market for transport, freight train | Cut-off, U	0.2	tkm
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, U	0.1	tkm
Infrastructure Requirements		
Metal working factory (unit)	4.6E-10	p

5.1.3 Production of the Li Metal anode

The anode materials were purchased in the UK and transported to the TBU laboratory. According to the expert opinion from TBU's battery specialist, the following amount of material is required to produce one anode for CR 2032: 15.635 mg Cu current collector and 0.943 mg Li metal foil. The total mass of anode: 16.578 mg (94.3 % current collector and 5.7 % anode Li metal foil).

Since there was no available data on foil production processes and lithium sheet rolling processes in ecoinvent 3.9, the copper sheet rolling processes were used as a proxy for anode inventory data (Smith et al. 2021).

Table 14 LCI for the production of 1 kg of the SSB anode (Smith et al. 2021)

Products	Inputs	Outputs	Unit
2.2 Negative electrode, Li-metal film		1	kg
Materials/fuels			
Lithium chloride {GLO}| market for lithium chloride | Cut-off, U	1		kg
Sheet rolling, copper {GLO}| market for sheet rolling, copper | Cut-off, U	1		kg
Transport			
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, U	0.1		tkm
Transport, freight train {Europe without Switzerland}| market for transport, freight train | Cut-off, U	0.2		tkm
Chemical factory, organics {GLO}| market for chemical factory, organics | Cut-off, U	4.6E-10		unit

5.1.4 Production of negative electrode current collector

Since there was no current data available in ecoinvent 3.9 on foil production process, the “sheet rolling” process was taken for the negative electrode current collector inventory (Majeau-Bettez, Hawkins, and Strømman 2011). The production details for 1 kg of the SSB LFP negative electrode current collector may be found in Tab. 15.

Table 15 LCI for the production of 1 kg negative electrode current collector (Majeau-Bettez, Hawkins, and Strømman 2011)

Products	Inputs	Unit
2.1 Negative current collector, Production		kg
Materials/fuels		
Copper, primary {GLO}| market for copper, cathode | Cut-off, U	1	kg
Sheet rolling, copper {GLO}| market for sheet rolling, copper | Cut-off, U	1	kg
Transport		
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, U	0.1	tkm
Transport, freight train {Europe without Switzerland}| market for transport, freight train | Cut-off, U	0.2	tkm
Infrastructure Requirements		
Metal working factory {RER}| metal working factory construction | Cut-off, U	4.6E-10	p

5.1.5 Production of the solid electrolyte

The electrolyte is developed on the TBU battery production line in the Czech Republic, Zlin. To produce a film of polymer gel electrolyte for SSB, a blank polymer electrolyte was prepared. To produce a film of polymer gel electrolyte the following amount of material is required: 0.85 g of PEO, 0.15 g bio-based material (BBM), 30 mL DMF (0.5 % of PVDF-HFP). LITFSI was mixed into the solution (ratio PEO:LiTFSI = 8:1). The solution was dried at 65 °C in the oven for 27 hours. After that, the dish was vacuum dried at 70 °C for 24 hours to remove the remaining solvent.

Determination of the mass of DMF (Dimethylformamide), PVDF-HFP and LITFSI in kg:

1. Mass of PVDF-HFP = $0.005 \times 30 = 0.15$ g.

2. p (DMF) = 0.944 g/mL at 20°C.

Mass of DMF = $29.85 \times 0.944 = 28.17$ g.

It is important to mention that during the process DMF is evaporating and not taking into account in the ratio calculation, the PVDF-HFP is stayed in electrolyte.

3. LITFSI was mixed into the solution (ratio PEO:LiTFSI = 8:1).

$$n = \frac{m}{M_w} \tag{2}$$

M_w PEO (CH_2CH_2O) = 44 g/mol, M_w (LITFSI) = 287 g/mol.

n (PEO) = 0.85 / 44 = 0.0193 mol.

m (LITFSI) = (287 ×0.0193) / 8 = 0.69 g.

To ascertain the production details for 1 kg of the SSB LFP electrolyte, was conducted calculations to determine the ratio of electrolyte materials Tab. 16.

Table 16 Electrolyte materials ratio

Input	Amount	Unit	Ratio
PEO	0.85	g	0.46
BBM	0.15	g	0.08
DMF (0.5 % of PVDF-HFP)	28.17	g	0.94
PVDF-HFP	0.15	g	0.08
LITFSI was mixed into the solution (ratio PEO:LITFSI = 8:1)	0.69	g	0.38
Total	1.84	g	1

Since PEO is not listed in the ecoinvent v3.8 database, a substitute material, polyethylene (high density, granulated), has been utilized due to its similarities (Larrabide, Rey, and Lizundia 2022). The PVdF organic binder (Erakca et al. 2023) and the LiTFSI (Larrabide, Rey, and Lizundia 2022) data were used to analyze inputs.

The production details for 1 kg of the SSB electrolyte may be found in Tab. 17.

Table 17 LCI for the production of 1 kg electrolyte

Products	Inputs	Outputs	
4.0 Electrolyte		1	kg
Materials/fuels			
PEO (polyethylene)	0.46		kg
4.1 BBM	0.08		kg
3.2.1 LiTFSI	0.38		kg
3.2b Organic binder PVDF	0.08		kg
N,N-dimethylformamide {GLO}| market for N,N-dimethylformamide | Cut-off, U	0.94		kg
Transport			
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, U	0.108		tkm
Transport, freight train {RER}| market group for transport, freight train | Cut-off, U	0.129		tkm
Electricity/heat			
Electricity, low voltage {CZ}| market for electricity, low voltage | Cut-off, U	45.394		kWh
Emissions to air			
Dimethyl formamide		0.94	kg

The mass of one electrolyte Ø16 mm is 144.3mg.

5.1.5.1 Production of BBM

To prepare the BBM, the following quantity of materials is required: BBM base (1 g), phthalic anhydride (2.76 g) and DMF (50 mL). The mixture was stirred 12 hours at 120 °C and 48 hours freeze-dried. It is important to mention that during the process DMF is evaporating and not considering in the ratio calculation.

Determination of the mass of DMF in g:

Mass of DMF = 50 × 0.944 = 47.2 g.

To ascertain the production details for 1 kg of the BBM, was conducted calculations (Tab. 18).

Table 18 BBM ratio

Input	Amount	Unit	Ratio
BBM base	1	g	0.27
Phthalic anhydride	2.76	g	0.73
DMF	47.2	g	0.93

Table 19 LCI for the production of 1 kg BBM

Products	Inputs	Outputs	
4.1 BBM		1	kg
Materials/fuels			
Phthalic anhydride {GLO}| market for phthalic anhydride | Cut-off, U	0.73		kg
N,N-dimethylformamide {GLO}| market for N,N-dimethylformamide | Cut-off, U	0.93		kg
4.1.1 BBM base	0.27		kg
Emissions to air			
Dimethyl formamide		0.93	kg

To prepare the BBM base, the following quantity of materials is required:

Table 20 LCI for the production of 1 kg BBM base

Products	Inputs	Outputs	
4.1.1 BBM base		1	kg

Avoided products			
BBM base component 3	1.22		kg
Resources			
BBM base component 4	0.446		m^3
BBM base component 5	0.088		m^2a
Materials/fuels			
BBM base component 6	11.38		kg
BBM base component 7	2		m^3
BBM base component 8	3.1		kg
4.1.1.1 BBM base component 1	4.27		kg
4.1.1.2 BBM base component 2	35		kg
Electricity/heat			
Electricity, medium voltage| market for electricity, medium voltage | Cut-off, U	0.07		kWh
Emissions to air			
Carbon dioxide		2	kg
Carbon dioxide, biogenic		-1.64	kg
Emissions to water			
BBM base component 1		0.085	kg

5.1.6 Production of CR 2032 cell container

The cell container CR 2032 for LFP SSB is mainly made from stainless-steel. It consists of a positive cap, negative cap, spring, anode spacer, cathode spacer. The total mass is 4.224g (negative cap – 0.8699g; positive cap – 0.8795 g; spring – 0.1979 g; spacer (3 pieces) – 0.7591 g x 3 = 2.2773 g). The positive cap includes stainless-steel 85 % and polypropylene material 15% (stainless-steel – 0.7495 g, polypropylene – 0.13 g). The cell container was acquired from the UK.

Table 21 Cell container ratio

Input	Amount	Unit	Ratio
Negative cap (Stainless Steel)	0.8699	g	0.21
Positive cap (Stainless Steel 85 % + polypropylene material 15%)	0.8795	g	0.21
Spring (Stainless Steel)	0.1979	g	0.05
Spacer (3 pieces) (Stainless Steel)	2.2773	g	0.53
Total	4.2246	g	

Table 22 LCI for the production of 1 kg of the SSB cell container

Products	Inputs	Unit
5.0 Cell container		kg
Materials/fuels		
Steel, chromium steel 18/8 {GLO}| market for steel, chromium steel 18/8 | Cut-off, U (spaser)	0.53	kg
Steel, chromium steel 18/8 {GLO}| market for steel, chromium steel 18/8 | Cut-off, U (negative cap)	0.21	kg
Steel, chromium steel 18/8 {GLO}| market for steel, chromium steel 18/8 | Cut-off, U (spring)	0.05	kg
5.1 Positive cap	0.21	kg
Transport		
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, U	0.265	tkm
Transport, freight, aircraft, unspecified {GLO}| market for transport, freight, aircraft, unspecified | Cut-off, U	0.667	tkm

Table 23 LCI for the production of 1 kg of the positive cap

Products	Inputs	Unit
5.1 Positive cap	1	kg
Materials/fuels		
Steel, chromium steel 18/8 {GLO}| market for steel, chromium steel 18/8 | Cut-off, U	0.85	kg
Polypropylene, granulate {GLO}| market for polypropylene, granulate | Cut-off, U	0.15	kg

5.2 Energy and transportation specifications

The battery materials were predominantly sourced from European suppliers. Specifically, the anode includes the current collector and the coin cell container, and also materials for the cathode and the electrolyte. Additionally, one supplier outside of Europe provided materials for the cathode. All necessary materials were transported to the city of Zlin, Czech Republic, using various modes of transport, including lorry a carrying capacity of 16-32 metric tons, trains and airplanes. Transportation calculations were based on the distance between the route's starting and ending points, assuming all necessary materials were purchased from manufacturers at one time in tkm (tonne-kilometre).

Energy calculations were based on proprietary energy data provided by TBU battery lab experts for pouch cell production. It was assumed, based on the opinion of the TBU battery expert, that the energy required to produce one battery on a laboratory scale is equivalent to producing 20 coin-cell batteries. Since the anode was purchased ready-made and cut manually, energy consumption was 0. Energy consumption for cathode production was calculated based on the equivalent of a pouch battery. For the processes of mixing and stirring the electrolyte, the number of electrolytes produced from one manufactured film was calculated, and the operating time and power of the equipment used were determined. The amount of electrolyte was calculated as follows: the mass of one electrolyte film produced at TBU divided by the mass of one electrolyte.

1.84 g / 0.1443 g = 12.75 g.

It is possible to prepare 12 electrolytes from one electrolyte film. The residual 0.75 g was considered as a consumable material, which was not considered in the calculation.

For the electrolyte freeze-drying process, it was calculated that 20 films could be processed per cycle, which is equivalent to 240 electrolytes per cycle.

Calculations were carried out in kilograms per cell.

Table 24 Energy consumption calculation parameters of producing CR 2032 coin cell battery

Battery component	Processes	Equipment required to carry out the processes
Cathode	Mixing and Dispersing	SFM-7 VACUUM MIXER
	Coating and Drying	Tape casting coater MSK-AFA-III
	Calendaring and drying	MSK-HRP,MR100DC
Anode	No	-
Electrolyte	Mixing (1 hours)	IKA Magnetic Stirrers RET basic
	Drying (27 hours at 65 °C at the oven)	Drying oven, UF55 53
	Vacuum drying (24 hours at 70 °C)	NRTLVacuum oven, DZF-6020
BBM	Mixing and Stirring (120 °C overnight 12 hours)	IKA Magnetic Stirrers RET basic
BBM	Freeze-drying (48 hours)	Labogene Scanvac CoolSafe Basic Freeze Dryer
Cell assembly	No	only Ar consuming

6 LIFE CYCLE IMPACT ASSESSMENT

LCIA was conducted for selected impact categories :

- Global Warming Potential, (kg $CO_2 - \text{eq to air}$) - an indicator that assesses the impact of greenhouse gas emissions, such as $CH_{2,}CH_4, SF_6, N_2O, CCl2_2F_2, CHF_3$ on climate change over a given 100-year time horizon, indicates the quantitative global warming potential, comparing their impact with that of carbon dioxide (Smith et al. 2021).
- Ozone Depletion Potential, (kg CFC (chlorofluorocarbon) 11 – eq to air) - a quantitative indicator of emissions into the air of substances that can destroy the ozone layer of the stratosphere. Calculated by comparing the pollutant to a reference substance, usually trichlorofluoromethane (CFC-11), which is assigned an ODP of 1 (Huijbregts et al. 2017).
- Terrestrial Acidification Potencial, (kg SO2-eq to air) – an indicator that assesses the potential acidification of soils (acid rain) (Huijbregts et al. 2017).
- Freshwater Eutrofication Potencial, (kg P – eq to fresh water) - an indicator that evaluates the process of accumulation of excess chemical nutrients, such as phosphorus and nitrogen, which results in disruption of the life cycle of plant and animal life and a decrease in the quality of freshwater ecosystems (Smith et al. 2021).
- Human Toxicity Potencial, (kg 1,4-DCB (dichlorobenzene) - eq to urban air) – an indicator of elevated risk for cancer and non-cancerous diseases, reflecting changes in lifetime disease incidence due to the intake of the substance (Huijbregts et al. 2017).
- Terestrial Ecotoxicity Potencial, (kg 1,4-DCB-eq to industrial soil) - an indicator that assesses ecotoxicological damage factors (pesticide emissions, use of sulphuric acid) in natural soils (Huijbregts et al. 2017).
- Land Use, (m2a crop eq) - indicate the relative loss of species attributed to different types of land use, such as annual crops, permanent crops, mosaic agriculture, forestry, urban land, and pasture (Huijbregts et al. 2017).

- Mineral Resourse Scarcity, (kg Cu-eq) - an indicator that reflects the need to increase ore production due to a decrease in ore grade as a result of primary mining (Huijbregts et al. 2017).
- Fossil Resource Scarcity, (kg oil-eq) - indicates the ratio of the higher heating value of a fossil resource to the energy content of crude oil (Huijbregts et al. 2017).

The results are assessed economically using EP impact assessments, excluding MRS and FRS categories due to their unavailability.

There are two scenarios were providing to quantify the environmental and economic impacts:

1. The overall impacts of a CR 2032 coin cell with cell container.
2. The overall impacts of a CR 2032 coin cell without cell container.

The decision to focus on two laboratory coin cell scenarios was driven by the fact that the battery container occupies a significant proportion (95%) of its components and has limited potential for improvement over the materials used inside the container. Results were provided per coin cell. Also, overall environmental impact analysis results have been expressed in kWh per cell for better comparability with other studies, both existing and future.

6.1 Quantification of the environmental impacts

6.1.1 The environmental impacts of a CR 2032 coin cell with cell container.

The inventory inputs and outputs were input into SimaPro to generate the environmental impacts of a CR 2032 coin cell.

Table 25 The total environmental impact of CR 2032 coin cell battery with cell container

Impact category, units	Total impact, per cell	Total impact per kWh cell capacity	Negative current collector impact	Negative electrode impact	Positive current collector impact	Positive electrode paste impact	Electrolyte impact	Cell container impact
Global warming, kg CO2 eq	3.55E-02	1.34E+04	1.18E-04	8.54E-06	9.73E-05	4.30E-04	1.12E-02	2.36E-02

Stratospheric ozone depletion, kg CFC11 eq	5.52E-06	2.09E+00	1.33E-10	3.49E-12	2.03E-11	1.13E-07	5.40E-06	5.55E-09
Terrestrial acidification, kg SO2 eq	1.15E-04	4.36E+01	6.59E-06	6.10E-08	4.38E-07	1.12E-06	2.24E-05	8.45E-05
Freshwater eutrophication, kg P eq	1.70E-05	6.43E+00	7.12E-07	1.03E-08	3.32E-08	2.29E-07	7.75E-06	8.24E-06
Terrestrial ecotoxicity, kg 1,4-DCB	7.35E-01	2.79E+05	5.34E-02	1.88E-04	1.85E-04	1.27E-03	2.05E-02	6.60E-01
Human carcinogenic toxicity, kg 1,4-DCB	3.55E-02	1.34E+04	6.38E-05	6.99E-07	1.88E-05	2.06E-05	5.43E-04	3.48E-02
Human non-carcinogenic toxicity, kg 1,4-DCB	5.38E-02	2.04E+04	8.66E-03	3.34E-05	9.59E-05	3.76E-04	1.65E-02	2.82E-02
Land use, m2a crop	9.22E-04	3.49E+02	1.83E-05	2.70E-07	1.30E-06	6.26E-06	1.92E-04	7.04E-04
Mineral resource scarcity, kg Cu eq	1.97E-03	7.47E+02	2.63E-05	4.82E-07	1.17E-06	2.96E-06	1.76E-05	1.92E-03
Fossil resource scarcity, kg oil eq	7.61E-03	2.89E+03	2.88E-05	2.03E-06	2.05E-05	9.18E-05	1.70E-03	5.77E-03

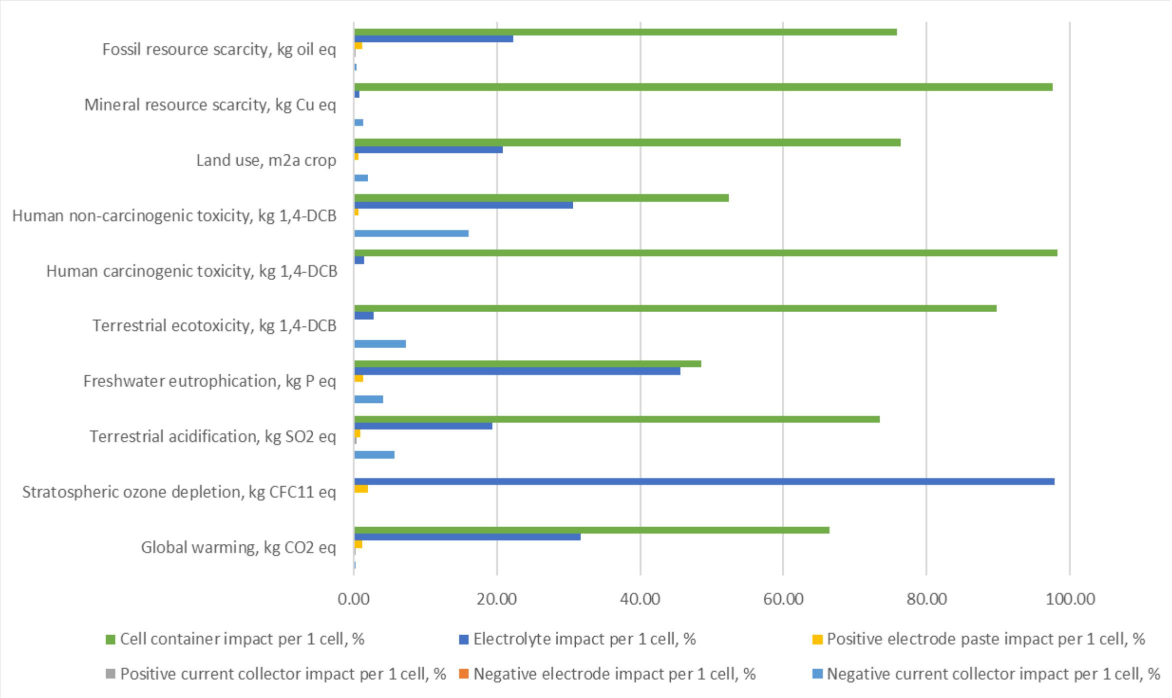

Figure 8 The total environmental impact of CR 2032 coin cell battery with cell container

Based on the results, calculations were made to determine which battery component and battery material had a more significant impact on the environment.

1. Cathode

Table 26 Environmental impact of the cathode in a coin cell battery

Impact category,%	**Aluminium**	**Sheet rolling, aluminium**	**Metal working factory**	**Organic binder PVDF**	**N-methyl-2-pyrrolidone**	**Postive active material**	**Graphite, battery grade**	**Carbon black**	**LiTFSI**	**Propylene carbonate**	**Transport, freight train, all**	**Transport, freight, lorry all**	**Transport, freight, aircraft, all**	**Chemical factory**	**Electricity, low voltage CZ**
Global warming	31.55	1.10	0.14	3.27	5.54	4.98	0.02	0.14	9.86	1.43	0.03	0.40	36.66	0.06	4.82
Stratospheric	0.06	0.00	0.00	0.87	0.01	0.01	0.00	0.00	98.99	0.01	0.00	0.00	0.02	0.00	0.01
Terrestrial	45.36	1.07	0.25	0.41	5.43	9.51	0.03	0.13	3.69	1.41	0.04	0.24	27.61	0.18	4.65
Freshwater	32.49	1.67	0.20	0.28	5.66	29.10	0.07	0.02	2.42	2.95	0.03	0.09	1.83	0.22	22.96
Terrestrial	26.38	0.68	0.24	1.01	8.64	20.64	0.01	0.10	2.85	2.99	0.04	2.79	25.63	1.42	6.58
Human carcinog	74.12	1.33	0.30	0.42	3.23	7.69	0.02	0.05	2.60	1.02	0.06	0.24	3.67	0.35	4.90
Human non-	42.88	1.44	0.27	0.94	5.94	12.96	0.04	0.06	8.34	2.09	0.03	0.43	10.24	0.81	13.55
Land use	30.28	1.66	4.69	0.45	11.05	19.50	0.06	0.20	3.27	2.29	0.13	1.34	18.66	0.57	5.85
Mineral resource	57.01	0.86	0.27	0.25	2.31	32.10	0.35	0.04	1.53	0.78	0.03	0.15	2.37	0.45	1.50
Fossil resource	27.67	1.25	0.17	0.43	8.12	5.23	0.05	0.45	2.87	2.28	0.03	0.53	46.65	0.06	4.21

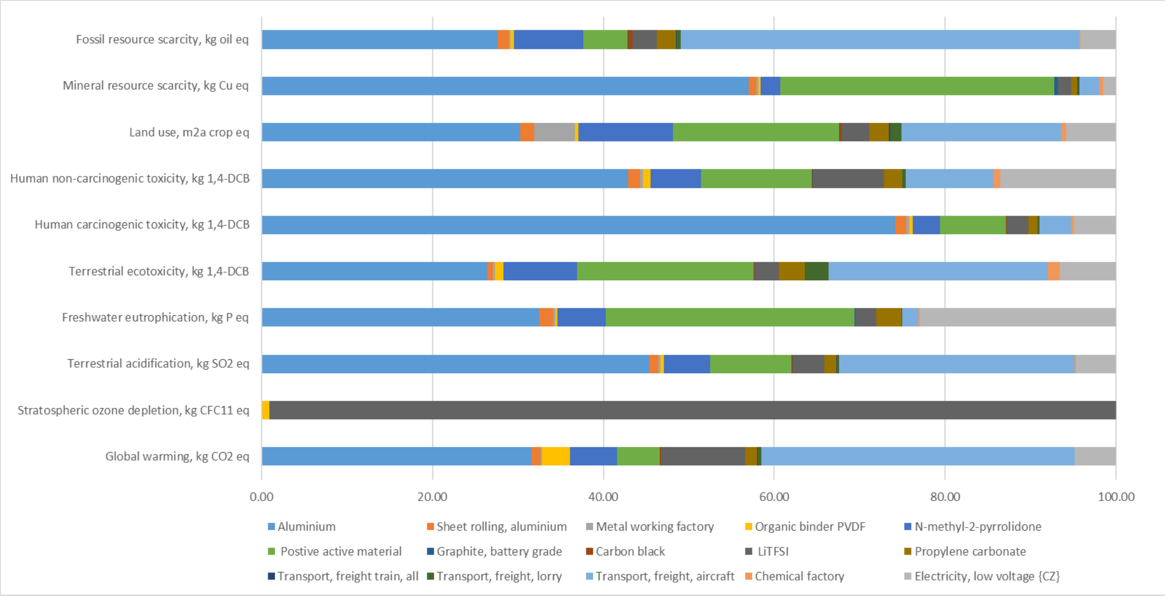

Figure 9 Environmental impact in cathode production

2. Anode

Table 27 Environmental impact of the anode in a coin cell battery

Impact category,%	Lithium chloride	Sheet rolling, copper	Chemical factory, organics	Copper	Sheet rolling, copper	Metal working factory	Transport, freight train	Transport, freight, lorry	Transport, freight, aircraft
Global warming, kg CO2 eq	6.504	0.398	0.051	83.411	6.587	0.746	0.120	0.404	1.778
Stratospheric ozone depletion, kg CFC11 eq	2.394	0.273	0.019	92.319	4.510	0.171	0.037	0.185	0.093
Terrestrial acidification, kg SO2 eq	0.720	0.240	0.008	94.880	3.964	0.081	0.010	0.015	0.082
Freshwater eutrophication, kg P eq	1.247	0.244	0.009	94.388	4.032	0.063	0.007	0.005	0.005
Terrestrial ecotoxicity, kg 1,4-DCB	0.135	0.230	0.005	95.791	3.809	0.007	0.001	0.015	0.007
Human carcinogenic toxicity, kg 1,4-DCB	0.855	0.245	0.042	94.420	4.058	0.270	0.040	0.040	0.030
Human non-carcinogenic toxicity, kg 1,4-DCB	0.167	0.233	0.006	95.711	3.856	0.016	0.001	0.005	0.005
Land use, m2a crop eq	1.232	0.262	0.035	91.838	4.341	2.062	0.045	0.112	0.075
Mineral resource scarcity, kg Cu eq	1.662	0.227	0.010	94.278	3.763	0.046	0.004	0.005	0.004

Fossil resource scarcity, kg oil eq	6.298	0.398	0.048	82.954	6.581	0.881	0.132	0.519	2.189

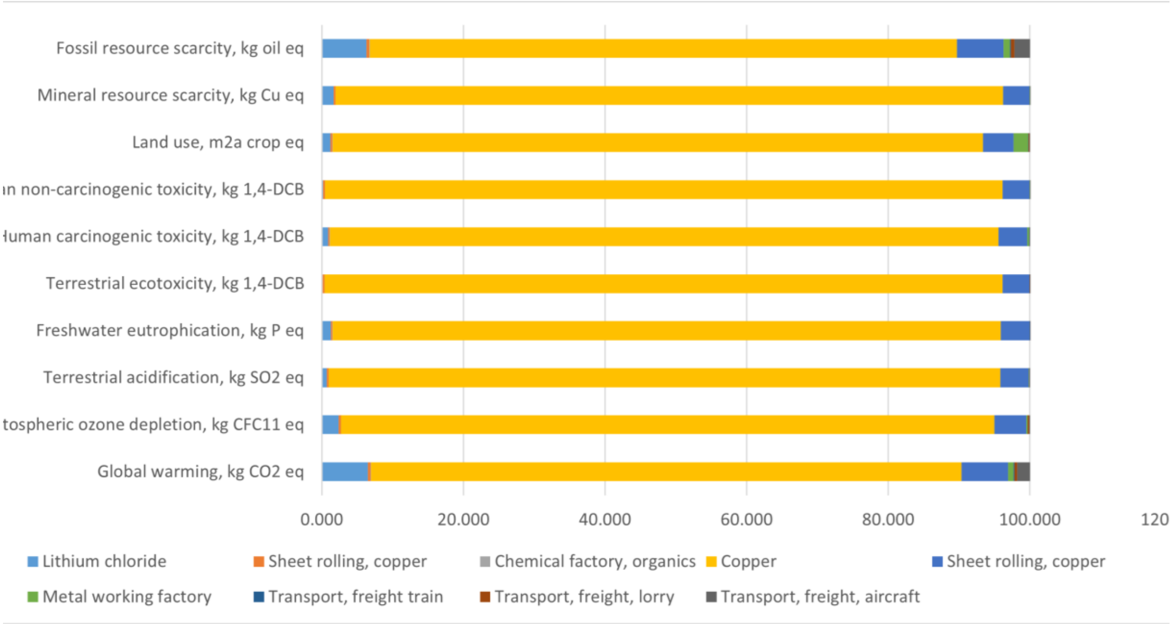

Figure 10 Environmental impact in anode production

3. Electrolyte

Table 28 Environmental impact of the anode in a coin cell battery

Impact category,%	**BBM**	**LiTFSI**	**Organic binder PVDF**	**N,N-dimethylformamide**	**Polyethylene**	**Transport, freight, lorry**	**Transport, freight train**	**Electricity, low voltage {CZ}**
Global warming, kg CO2 eq	1.61	45.83	7.19	4.48	1.17	0.03	0.01	39.69
Stratospheric ozone depletion, kg CFC11 eq	0.01	99.56	0.42	0.00	0.00	0.00	0.00	0.02
Terrestrial acidification, kg SO2 eq	2.75	27.32	1.44	6.21	1.36	0.03	0.02	60.89
Freshwater eutrophication, kg P eq	2.57	5.32	0.29	2.18	0.24	0.00	0.00	89.40
Terrestrial ecotoxicity, kg 1,4-DCB	3.51	16.44	2.77	7.84	1.11	0.23	0.01	67.18
Human carcinogenic toxicity, kg 1,4-DCB	1.76	21.03	1.59	4.55	0.97	0.03	0.03	70.04
Human non-carcinogenic toxicity, kg 1,4-DCB	1.88	19.16	1.03	2.20	0.34	0.01	0.00	55.08

Land use, m2a crop eq	49.76	10.57	0.69	4.94	0.47	0.06	0.02	33.49
Mineral resource scarcity, kg Cu eq	3.95	30.83	2.36	8.23	1.26	0.04	0.03	53.30
Fossil resource scarcity, kg oil eq	3.54	20.91	1.47	13.49	6.16	0.06	0.01	54.37

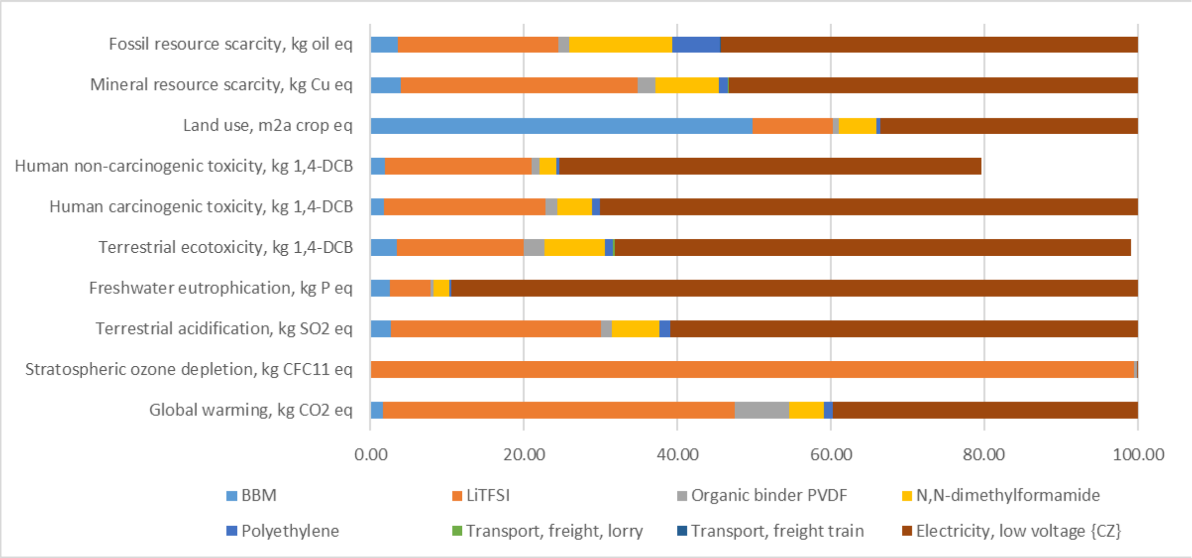

Figure 11 Environmental impact in electrolyte production

4. Coin cell container

Table 29 Environmental impact of the coin cell container

Impact category,%	**Spacer**	**Negative cap**	**Spring**	**Positive cap**	**Transport, freight, lorry**	**Transport, freight, aircraft**
Global warming, kg CO2 eq	47.97	19.01	4.53	17.50	0.91	10.09
Stratospheric ozone depletion, kg CFC11 eq	52.04	20.62	4.91	18.18	1.88	2.37
Terrestrial acidification, kg SO2 eq	50.25	19.91	4.74	17.92	0.48	6.70
Freshwater eutrophication, kg P eq	53.99	21.39	5.09	18.86	0.20	0.47
Terrestrial ecotoxicity, kg 1,4-DCB	54.08	21.43	5.10	18.31	0.51	0.57
Human carcinogenic toxicity, kg 1,4-DCB	54.66	21.66	5.16	18.44	0.03	0.06
Human non-carcinogenic toxicity, kg 1,4-DCB	53.17	21.07	5.02	18.45	0.60	1.71

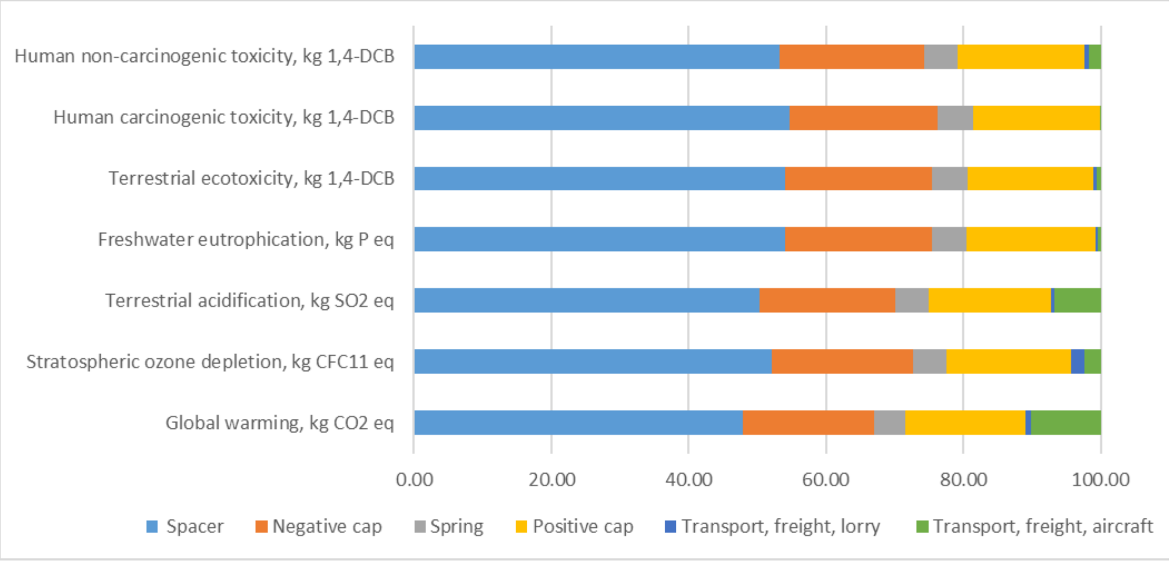

Figure 12 Environmental impact of coin cell container production

6.1.2 The environmental impacts of a CR 2032 coin cell without cell container.

The inventory inputs and outputs were input into SimaPro to generate the environmental impacts of a CR 2032 coin cell without cell container.

Table 30 The total environmental impact of CR 2032 coin cell battery without cell container, per cell

Impact category	**Total impact**	**Total impact per kWh capacity**	**Negative current collector impact**	**Negative electrode impact**	**Positive current collector impact**	**Positive electrode paste impact**	**Electrolyte impact**
Global warming, kg CO2 eq	1.19E-02	4.50E+03	1.20E-04	9.10E-06	9.91E-05	4.31E-04	1.12E-02
Stratospheric ozone depletion, kg CFC11 eq	5.50E-06	2.08E+00	1.35E-10	3.72E-12	2.07E-11	1.14E-07	5.38E-06
Terrestrial acidification, kg SO2 eq	3.06E-05	1.16E+01	6.69E-06	6.50E-08	4.46E-07	1.12E-06	2.23E-05
Freshwater eutrophication, kg P eq	8.72E-06	3.31E+00	7.23E-07	1.09E-08	3.39E-08	2.29E-07	7.72E-06
Terrestrial ecotoxicity, kg 1,4-DCB	7.63E-02	2.89E+04	5.42E-02	2.00E-04	1.88E-04	1.28E-03	2.04E-02

Human carcinogenic toxicity, kg 1,4-DCB	6.46E-04	2.45E+02	6.48E-05	7.45E-07	1.92E-05	2.07E-05	5.41E-04
Human non-carcinogenic toxicity, kg 1,4-DCB	2.57E-02	9.76E+03	8.78E-03	3.56E-05	9.77E-05	3.77E-04	1.64E-02
Land use, m2a crop	2.17E-04	8.24E+01	1.86E-05	2.88E-07	1.32E-06	6.28E-06	1.91E-04
Mineral resource scarcity, kg Cu eq	4.89E-05	1.85E+01	2.67E-05	5.14E-07	1.19E-06	2.97E-06	1.75E-05
Fossil resource scarcity, kg oil eq	1.84E-03	6.96E+02	2.93E-05	2.16E-06	2.09E-05	9.21E-05	1.69E-03

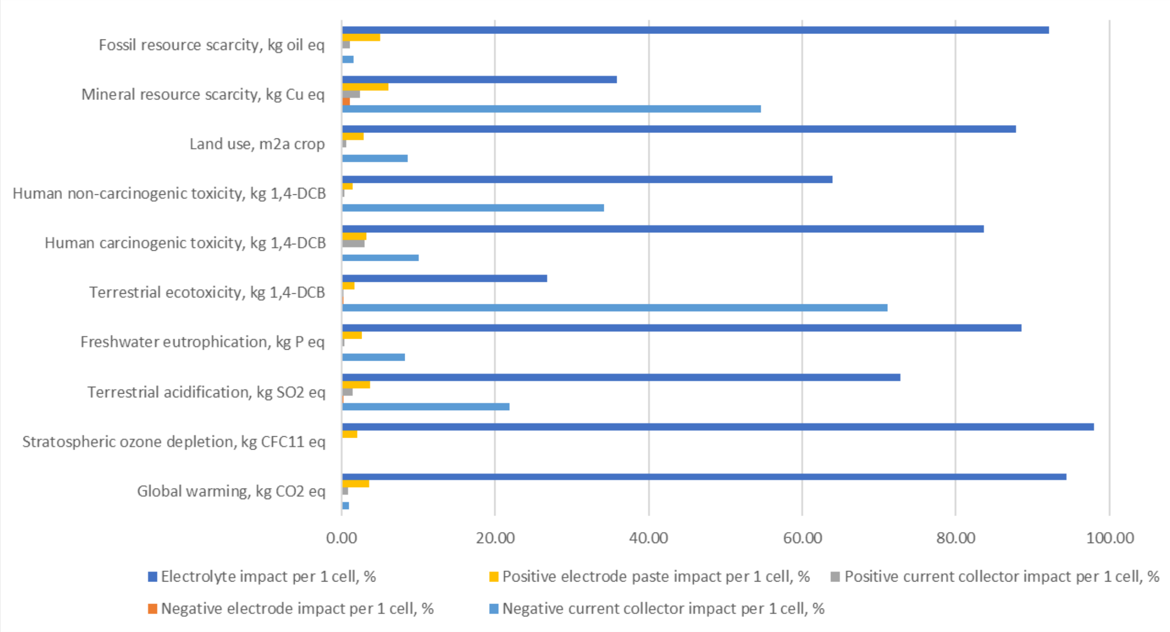

Figure 13 The total environmental impact of CR 2032 coin cell battery without cell container

6.1.3 Comparative results for both scenarios: with and without coin cell container

To explore additional opportunities for potential pathways towards further materials improvement of the coin cell battery, two scenarios were compared based on their environmental impact results.

Table 31 Comparative total environmental impacts results for both scenarios for a CR 2032 coin cell battery

Impact category, units	**Total impact per cell with cell**	**Total impact per cell without cell**
Global warming, kg CO2 eq	3.55E-02	1.19E-02
Stratospheric ozone depletion, kg	5.52E-06	5.50E-06
Terrestrial acidification, kg SO2 eq	1.15E-04	3.06E-05
Freshwater eutrophication, kg P eq	1.70E-05	8.72E-06
Terrestrial ecotoxicity, kg 1,4-DCB	7.35E-01	7.63E-02
Human carcinogenic toxicity, kg 1,4-	3.55E-02	6.46E-04
Human non-carcinogenic toxicity, kg	5.38E-02	2.57E-02
Land use, m2a crop	9.22E-04	2.17E-04
Mineral resource scarcity, kg Cu eq	1.97E-03	4.89E-05
Fossil resource scarcity, kg oil eq	7.61E-03	1.84E-03

6.2 Quantification of the economic impacts

6.2.1 The economic impacts of a CR 2032 coin cell with cell container.

Based on the first scenario LCIA results, the monetization of a CR 2032 coin cell was provided using the EP methodology.

Table 32 The economic impact results of CR 2032 battery with coin cell container

Impact category	**Unit**	**Total per cell**	**Negative current collector, per cell**	**Negative electrode, per cell**	**Positive current collector, per cell**	**Postive electrode paste, per cell**	**Electrolyte per cell**	**Cell container, per cell**
Total	**EUR2015**	**1.564E-02**	**5.681E-04**	**4.841E-06**	**3.139E-05**	**1.191E-04**	**3.631E-03**	**1.129E-02**
Climate change	EUR2015	1.928E-03	6.544E-06	4.742E-07	5.378E-06	2.290E-05	5.829E-04	1.310E-03
Ozone depletion	EUR2015	6.173E-04	1.509E-10	6.541E-11	1.236E-10	1.269E-05	6.046E-04	3.044E-08
Terrestrial acidification	EUR2015	1.058E-03	5.574E-05	5.465E-07	3.965E-06	1.054E-05	1.994E-04	7.878E-04
Freshwater eutrophication	EUR2015	2.977E-05	1.340E-06	1.155E-08	6.001E-08	3.873E-07	1.457E-05	1.341E-05
Human toxicity	EUR2015	3.556E-03	3.389E-04	1.401E-06	5.286E-06	3.034E-05	1.498E-03	1.682E-03

Terrestrial ecotoxicity	EUR2015	3.646E-05	2.176E-06	1.705E-08	2.988E-08	2.647E-07	6.162E-06	2.781E-05
Agricultural land occupation	EUR2015	6.080E-05	2.941E-07	1.293E-08	5.642E-08	3.204E-07	1.204E-05	4.807E-05

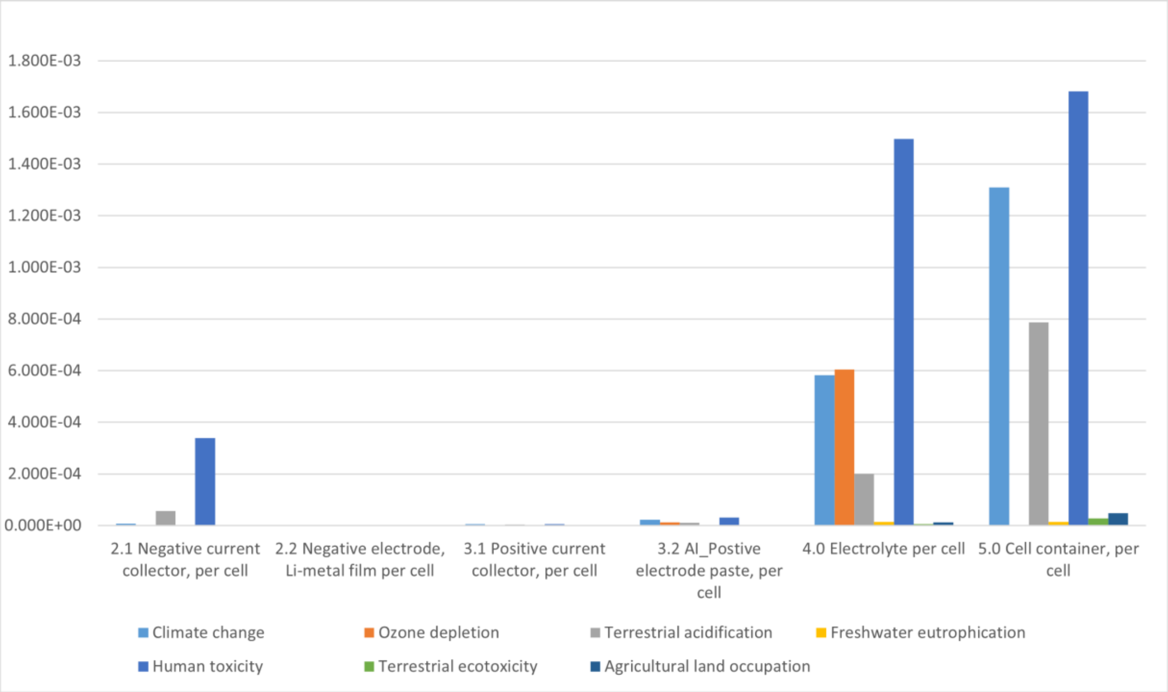

Figure 14 The economic impact results of CR 2032 battery with coin cell container, € per cell

6.2.2 The economic impacts of a CR 2032 coin cell without cell container.

Based on the second scenario LCIA results, the monetization of a CR 2032 coin cell was provided using the EP methodology.

Table 33 The economic impact results of CR 2032 battery without coin cell container

Impact category	**Unit**	**Total per cell**	**Negative current collector, per cell**	**Negative electrode, per cell**	**Positive current collector, per cell**	**Postive electrode paste, per cell**	**Electrolyte per cell**
Total	**EUR2015**	**4.349E-03**	**5.765E-04**	**5.157E-06**	**3.198E-05**	**1.195E-04**	**3.616E-03**
Climate change	EUR2015	6.162E-04	6.641E-06	5.051E-07	5.479E-06	2.296E-05	5.806E-04
Ozone depletion	EUR2015	6.149E-04	1.531E-10	6.967E-11	1.259E-10	1.273E-05	6.021E-04

Terrestrial acidification	EUR2015	2.703E-04	5.657E-05	5.822E-07	4.039E-06	1.057E-05	1.985E-04
Freshwater eutrophication	EUR2015	1.633E-05	1.360E-06	1.230E-08	6.114E-08	3.885E-07	1.451E-05
Human toxicity	EUR2015	1.873E-03	3.439E-04	1.492E-06	5.386E-06	3.043E-05	1.492E-03
Terrestrial ecotoxicity	EUR2015	8.660E-06	2.208E-06	1.817E-08	3.044E-08	2.655E-07	6.137E-06
Agricultural land occupation	EUR2015	1.269E-05	2.984E-07	1.377E-08	5.748E-08	3.214E-07	1.200E-05

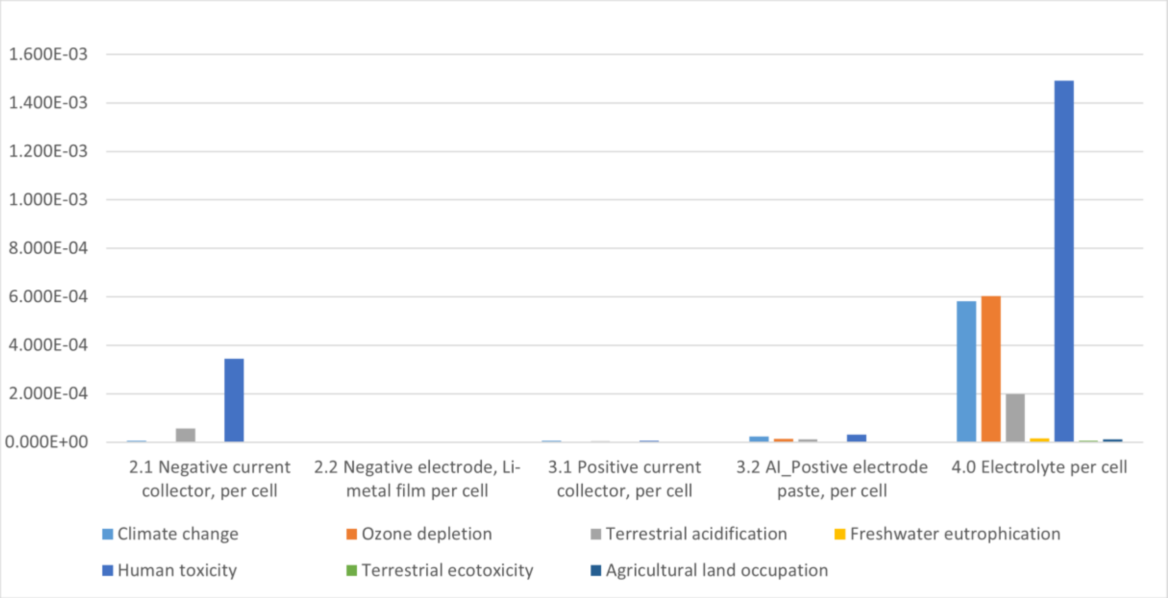

Figure 15 The economic impact results of CR 2032 battery without coin cell container

7 INTERPRETATION OF THE LCA RESULTS

7.1 Discussion of the environmental and economic impacts identified in the LCA

In the first scenario, the overall environmental impact of a CR 2032 coin cell with a BBM electrolyte was calculated across identified impact categories, as depicted in a Table 25.

Figure 8 illustrates that the different components of the CR 2032 coin cell exhibit different impacts on the LCA results. Figures 9-12 provide a more detailed insight into the contribution of each material, energy, and transportation component to the environmental impact of the battery components.

Stainless-steel production is the largest contributor to environmental impact in almost every category. This is primarily attributed to the high mass ratio of coin cell containers (95%) and stainless-steel production. The spacer component, which constitutes approximately 50% of the impact in each category, makes a notable contribution due to its substantial mass ratio.

The electrolyte is also significant in terms of environmental burden, with its preparation contributing to almost 99% of the ODP impact category. Furthermore, it exhibits a relatively high environmental impact in the categories of GWP, TAP, FEP, HTP, LU and FRS. Electricity consumption for solid electrolyte fabrication is the main contributor to the electrolyte production in almost all categories (due to the lab-scale production and the use of energy-intensive equipment for small material quantities), except ODP, which is almost totally dominated by LITFSI material (99.56%). The LITFSI production also contributes 45.83% to the GWP and 40.19% to the HTP, and has a substantial impact on TAP, TEP, LU, MRS, FRS impact categories. Reasons for this contribution to the environmental impact of LiTFSI production may be related to the energy intensity of the process, the use of chemicals in the synthesis and purification steps, and the emissions of pollutants and greenhouse gases such as volatile organic compounds, particulate matter, and sulfur dioxide. The electrolyte organic binders contribute about 7 % to GWP (the process for producing tetrafluoroethylene, one of the components of the organic binder, typically involves high-temperature reactions of fluorocarbon gases, resulting in significant energy consumption and emissions of greenhouse gases and pollutants). The BBM electrolyte material contributes to almost 50% of the damage in the LU category due to factors such as land conversion for feedstock cultivation, agricultural practices, and habitat alteration.

The production of the negative current collector also occupies a certain portion of impacts, accounting for 5.73% of the TAP, 7.26% of the TEP, and 16.26% of the HTP categories. A copper material, the main component of the negative current collector, is responsible for more than 82% environmental impact in all impact categories.

Lithium chloride material contributes about 6% of the GWP and FRS impacts in negative electrode production.

While the battery cell container would be the main contributor to the environmental burden in the first scenario, it is important to understand what improvements can be made to battery materials technologies such as the anode, cathode and electrolyte. In the second scenario (Fig. 13), it is evident that the majority of the environmental burden is carried by the electrolyte and the negative current collector battery components. The electrolyte components contributes over than 90% to the GWP, ODP, and FRS impact categories, and exceeds 80 % in the FEP, HT, and LU categories. Meanwhile, the negative current collector predominantly impacts the TEP and MRS categories, with 71.06% and 54.65% respectively, and constituting 21.88% in the TAP impact category.

During the stage of environmental impact monetization, utilizing LCA weighting factors (Fig. 14 and 15), the cost in euros per kilogram of emitted pollutants was computed. This metric provides an economic evaluation of the emissions attributable to the studied battery. The total cost of the CR 2032 battery is 0.0156 euros per cell, inclusive of the coin cell container cost, and 0.004 euros per cell, excluding the container. Fig. 14, 15 illustrate that the predominant portion of the emissions cost originates from battery components such as the electrolyte and coin cell container. This underscores that improvement in electrolyte production technology and adjustments in cell container not only enhanced environmental performance but also economic advantages.

Analysing the above, it is important to note that the electricity production for the anode and coin cell container wasn`t factored into the assessment because the materials were purchased already prepared. Additionally, electricity consumption for formation (materials component preparation) and clean rooms (cell assembly processes) wasn`t considered due to the lack of information.

7.2 Hotspots for improvement

7.2.1 Hotspots for improvement

This part includes environmental hotspots based on the midpoint environmental impacts results of all target impact categories.

Based on the results obtained from a detailed analysis of battery materials, electrolyte use stands out as one of the main problem areas in most environmental impact categories. To reduce this impact, the following approaches are possible: minimizing electricity usage during the laboratory battery production stage, as well as decreasing the thickness of the electrolyte to reduce material consumption per production unit.

For the battery container, a significant portion of the environmental impact, up to 50%, comes from the stainless-steel spacer used to ensure contact between battery cells components. Increasing the thickness of the anode and cathode layers may reduce the need for such a spacer, which could potentially reduce the environmental burden of the battery. However, to more accurately assess this impact, additional research is needed that takes into account changing production conditions.

In battery manufacturing, the anode manufacturing process plays a minor but significant role, especially the negative current collector, which is usually made of copper. While there are virtually no improvement methods for the for the last one, the environmental burden of the anode film could be reduced by introducing anode-free technology or reducing its thickness within the battery. Also, reducing the thickness of the cathode could lead to a slight, but still reduction in the environmental load of the battery.

7.2.2 Sensitivity analyses

The thesis results clearly indicate that enhancing the electrolyte is essential for improving the performance of LFP BBM coin cell batteries. The primary factors contributing to the environmental impact were identified as electricity consumption and the environmental effects associated with the electrolyte materials. Sensitivity analyses were conducted to assess changes in environmental impact based on changes in two main factors: the thickness of the BBM electrolyte and the energy consumption in its production. The thickness of the electrolyte could be reduced by 50% in laboratory production and by 90% in industrial production. Furthermore, it was acknowledged that the mass of the electrolyte decreases proportionally with its thickness reduction (Tab. 34).

Table 34 Sensitivity analysis calculation for BBM electrolyte thickness reduction

CR 2032 LFP solid-state battery	**Base scenario, mg**	**Ratio**	**50%, lab-scale level, mg**	**Ratio**	**90%, industrial-scale level production, mg**	**Ratio**
Material Requirements						
Positive electrode paste for Li-ion battery (kg), LFP	12.818	0.071	12.818	0.1184	12.818	0.253541
Negative electrode paste for Li-ion battery (kg), Li-Metal	0.943	0.0052	0.943	0.0087	0.943	0.018653
Positive current collector for Li--ion battery	6.73	0.0373	6.73	0.0622	6.73	0.13312
Negative current collector for Li-ion battery (kg), Cu	15.635	0.0867	15.635	0.1444	15.635	0.309261
Electrolyte for Li-ion battery (kg), BBM	144.3	0.7998	72.150	0.6664	14.430	0.285426
Total mass, mg	**180.426**	1.00	**108.276**	1.00	**50.556**	1.00

Table 35 Sensitivity analysis results for BBM electrolyte thickness reduction

Impact category, unit	**Electrolyte environmental impact per cell, base line**	**Electrolyte environmental impact per cell, 50%**	**Electrolyte environmental impact per cell, 90%**
Global warming, kg CO2 eq	1.120E-02	5.632E-03	1.138E-03
Stratospheric ozone depletion, kg CFC11 eq	5.383E-06	2.706E-06	5.469E-07
Terrestrial acidification, kg SO2 eq	2.226E-05	1.119E-05	2.262E-06
Freshwater eutrophication, kg P eq	7.722E-06	3.882E-06	7.845E-07
Terrestrial ecotoxicity, kg 1,4-DCB	2.040E-02	1.026E-02	2.073E-03
Human carcinogenic toxicity, kg 1,4-DCB	5.407E-04	2.718E-04	5.494E-05
Human non-carcinogenic toxicity, kg 1,4-DCB	1.644E-02	8.266E-03	1.671E-03
Land use, m2a crop eq	1.910E-04	9.600E-05	1.940E-05
Mineral resource scarcity, kg Cu eq	1.751E-05	8.805E-06	1.779E-06
Fossil resource scarcity, kg oil eq	1.693E-03	8.511E-04	1.720E-04

The results indicate a significant reduction in all environmental impact categories with decreasing BBM electrolyte thickness.

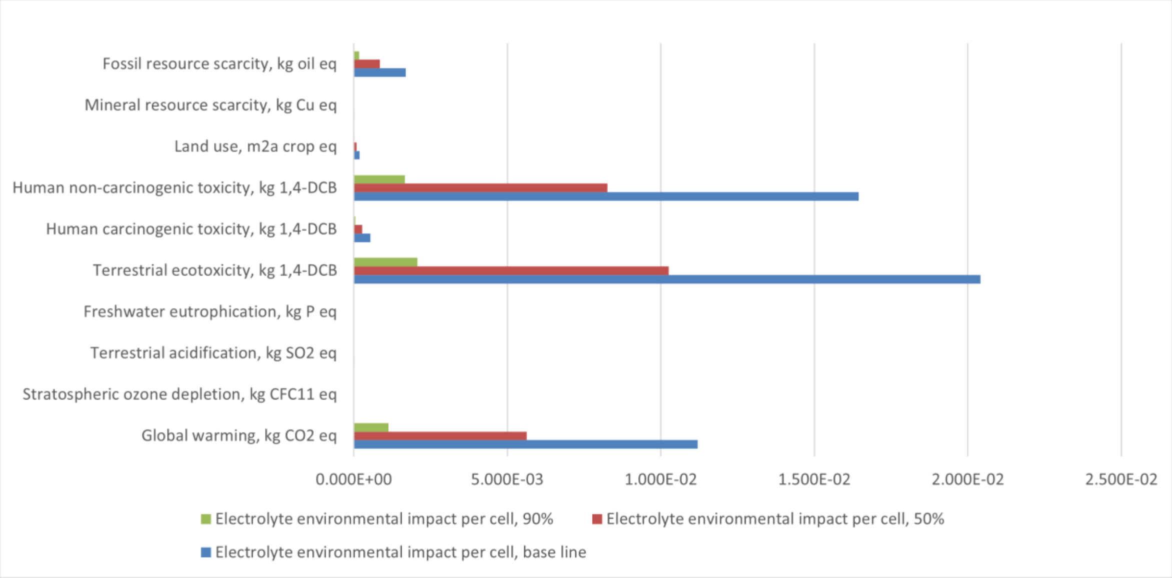

Figure 16 Sensitivity analysis results for BBM electrolyte thickness reduction

Given the high energy intensity of the laboratory battery manufacturing process, especially in the context of electrolyte production, optimization of energy consumption is also necessary to reduce its environmental impact. Switching to renewable energy sources is a promising approach to reduce negative impacts on the ecosystem. With more than 98% of Norway's electricity coming from renewable sources, the benefits of the country's hydropower-based energy supply are clear. Increased proportion of renewable energy sources in the Czech energy could significantly reduce the negative environmental impacts of electrolyte production.

Table 36 Sensitivity analysis results with energy mix variation

Impact category,%	**Electrolyte environmental impact per cell, CZ electricity mix**	**Electrolyte environmental impact per cell, NO electricity mix**	**%, Environmental impact reduction**
Global warming, kg CO2 eq	1.1203E-02	6.9858E-03	37.6
Stratospheric ozone depletion, kg CFC11 eq	5.3829E-06	5.3824E-06	0.01
Terrestrial acidification, kg SO2 eq	2.2262E-05	1.0382E-05	53.4
Freshwater eutrophication, kg P eq	7.7217E-06	1.0269E-06	86.7

Terrestrial ecotoxicity, kg 1,4-DCB	2.0402E-02	1.7689E-02	13.3
Human carcinogenic toxicity, kg 1,4-DCB	5.4071E-04	2.0219E-04	62.6
Human non-carcinogenic toxicity, kg 1,4-DCB	1.6443E-02	9.3346E-03	43.2
Land use, m2a crop eq	1.9096E-04	1.4626E-04	23.4
Mineral resource scarcity, kg Cu eq	1.7514E-05	1.4918E-05	14.8
Fossil resource scarcity, kg oil eq	1.6929E-03	8.1527E-04	51.8

The results demonstrate that using renewable energy to produce electrolytes could significantly reduce the environmental impact of electricity consumption, especially at laboratory-scale production levels, and is consistent with sustainable development goals.

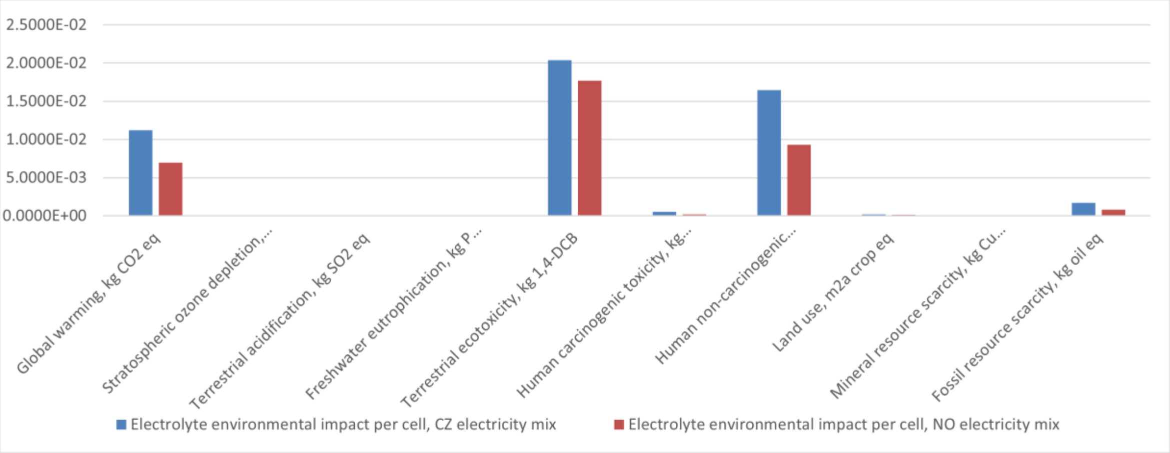

Figure 17 Sensitivity analysis results with energy mix variation

8 CONCLUSION

In the theoretical part of the thesis, special attention was paid to the LCA methodology and its importance in assessing the environmental impact of products at all stages of their life cycle. In addition, as part of the thesis, a description of SSB technology was presented, which was evaluated from the perspective of the LCA methodology. This section covered the basic principles, characteristics, and production stages of this technology.

In the analysis part, a cradle-to-gate LCA model was developed to investigate the environmental impact of the CR 2032 coin cell LFP SSB with BBM electrolyte, produced within the TwinVECTOR project in TBU, Zlin (Czech Republic), and the monetization of the environmental impact results was carried out.

The results indicate that BBM electrolyte production has significant environmental and economic impacts in all impact categories, mainly due to the high energy consumption associated with laboratory scale production and the presence of the LITFSI material in the battery electrolyte component. Proposed future transition towards higher renewable energy sources ratio in the Czech energy mix can significantly reduce the burden of the energy sector on the environment impact categories, specially in GWP, TAP, FEP, HT and FRS. Also, reducing the thickness of the electrolyte can reduce the environmental load by almost 50% in laboratory conditions and by approximately 90% in industrial production conditions.

The total environmental cost of the coin cell battery amounted to 0.0156 euros per cell. The significant portion of this impact is attributed to the coin cell container, primarily due to its mass ratio, and to the battery electrolyte, owing to its high environmental footprint.

In conclusion, this thesis underscores the significance of conducting LCA under laboratory conditions for gaining crucial environmental insights at the nascent stages of SSB advancement. While it's not designed for comparisons with mature technology, its focus lies in defining paths for enhancement and the fostering of novel technologies with environmental considerations at the forefront. The thesis adds to the existing body of literature in the field, thereby enriching the available resources for future research and enabling more comprehensive comparisons of results across studies. It's imperative that decision-makers acknowledge the thesis limitations and context when utilizing its findings, and draw upon accumulated evidence to steer the sustainable evolution of emerging technologies.

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LIST OF ABBREVIATIONS

AP-Acidification Potential

BBM – Bio-based Material

CC – Climate Change

CED- Cumulative Energy Demand

DEC - Diethyl Carbonate

DMC - Dimethyl Carbonate

DOL - 1,3-dioxolane

EC - Ethylene Carbonate

EEA - European Environment Agency

E-LCC - Environmental Life Cycle Cost

EMC - Ethyl Methyl Carbonate

EP – Environmental Price

ETP-Ecotoxicity Potential

EU - Energy Use

FEP - Freshwater Eutrophication Potential

FEC - Fluoroethylene Carbonate

FRS- Fossil Resource Scarcity

FDP - Fossil Depletion Potential

FU - Functional Unit

GWP - Global Warming Potentials

HH - Human Health

HTP - Human Toxicity Potential

IR - Ionizing Radiation

ISE - Inorganic Solid Electrolyte

ISO - International Organization for Standardization

LCA - Life Cycle Assessment

LCI - Life Cycle Inventory

LCIA – Life Cycle Impact Assessment

LCO - Lithium Cobalt Oxide

LCSA - Life Cycle Sustainability Assessment

LiTFSI - Lithium bis-trifluoromethanesulfonimide

LFP - Lithium Iron Phospate

LIB - Lithium-ion battery

LMA - Li-Metal Anode

LMO - Lithium Manganese Oxide

LMNO - Lithium Manganese Nickel Oxide

LTO - Lithium Titanate

LU - Land Use

MDF -Midpoint-damage Characterization Factor

ME- Marine eutrophication

MEx - Mineral Extraction

METP - Marine Ecotoxicity Potential

MDP-Mineral Depletion Potential

MRD – Metal Resource Depletion

MRS-Mineral Resource Scarcity

NAR - Natural Abiotic Resources

NBE - Natural Biotic Environment

NCA - Lithium Nickel Cobalt Aluminium Oxides

NMC - Lithium Nickel Manganese Cobalt Oxides

NMP - N-Methyl-2-pyrrolidone

ODP - Ozone Depletion Potentials

PC – Propylene Carbonate

PF - Photooxidant Formation

PMF - Particulate Matter Formation

POCP - Photochemical Ozone Formation

PSF - Photochemical Smog Formation

RDP - Resource Depletion Potential

RPE - Respiratory Effects

SETAC - Society for Environmental Toxicology and Chemistry

SE - Solid Electrolyte

SHDB – Social Hotspot Database

SPE – Solid Polymer Electrolyte

SSB - Solid-State Lithium-ion Batterie

TAP - Terrestrial Acidification Potencial

TETP- Terrestrial Ecotoxicity Potential

TRL - Technology Readiness Level

UNEP - United National Environmental Program

VC - Vinylene Carbonate

WDP-Water Depletion Potential

WU - Water Use

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