

Life Cycle Assessment of battery with bio-based electrolyte considering EU regulations

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- Vyhodnotit LCA výsledky a navrhnout rámec sociálního posuzování životního cyklu v souladu s Nařízením o bateriích.
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ABSTRAKT

Ve snaze o čistou energii Evropa strategicky upřednostnila vývoj a výrobu baterií a uznala jejich klíčovou roli nejen v posunu k udržitelné energii, ale také jako nedílnou součást evropského průmyslu skladování energie. Vzhledem k tomu, že se očekává, že celosvětová poptávka po bateriích do roku 2030 podstoupí pozoruhodný 14násobný nárůst, vyvstává naléhavá potřeba řešit environmentální důsledky tohoto růstu. S ohledem na vyvíjející se prostředí společnosti, nový technologický vývoj, trhy a různorodé aplikace baterií učinila Evropská komise v roce 2020 významný krok tím, že navrhla nové nařízení o bateriích.

Tato práce zkoumá ekologickou udržitelnost baterií využívajících elektrolyty na biologické bázi. Využívá metodiku posouzení životního cyklu k posouzení dopadů těchto baterií na životní prostředí v průběhu jejich životního cyklu, včetně těžby zdrojů, výroby. Kromě toho vyhodnocuje soulad technologie biologických baterií s příslušnými předpisy Evropské Unie.

Výsledky zdůrazňují environmentální výkonnost baterií s biologickým elektrolytem a identifikují potenciální oblasti pro zlepšení. Tato práce také zkoumá potenciální uplatnění sociálních a ekonomických úvah při vytváření digitálního produktového pasu pro baterie, čímž se podporuje větší transparentnost a udržitelnost v řetězci výroby baterií.

Celkově tato práce přináší cenné poznatky o environmentálních a potenciálních sociálních přínosech a výzvách spojených s elektrolyty na biologické bázi pro baterie. Navrhuje rámec pro posouzení životního cyklu pro lithium-iontové biobaterie, čímž dláždí cestu pro holističtější hodnocení udržitelnosti baterií v evropském kontextu.

Klíčová slova: Lithium-iontová baterie, bakteriální celulóza, separátor baterie, udržitelnost, posouzení životního cyklu, pas baterie, předpisy pro baterie, lithium-železo-fosfátová baterie.

ABSTRACT

In the pursuit of clean energy, Europe has strategically prioritized the development and production of batteries, recognizing their crucial role not only in the transition to sustainable energy, but also as integral components in the European energy storage industry. Considering the shifting dynamics of society, new technological developments, markets, and diverse applications of batteries, the European Commission took a significant step in 2020 by proposing a new Batteries Regulation.

This thesis investigates the environmental sustainability of batteries utilizing bio-based electrolyte. It uses Life Cycle Assessment methodology in order to assess the environmental impacts of these batteries across defined system boundaries in cradle-to-gate stages of life cycle. Additionally, it evaluates the compliance of the bio-based battery technology with relevant European Union regulations.

The results highlight the environmental performance of bio-based electrolyte batteries and identify potential areas for improvement. This work also explores the potential application of environmental assessment and considerations in creating a Digital Product Passport for batteries, fostering greater transparency and sustainability in the battery production chain.

Overall, the thesis's goal is to contribute better understanding into the environmental assessment and potential challenges related to bio-based electrolytes for batteries. It proposes a system for conducting Life Cycle Assessment for lithium-ion bio-based batteries, preparing for a more complete assessment of battery sustainability in the European context.

Keywords: Lithium-ion battery, bacterial cellulose, life cycle assessment, battery separator, sustainability, battery passport, battery regulations, lithium-iron-phosphate battery.

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INTRODUCTION

The increasing demand for clean energy solutions has stimulated Europe towards prioritizing the development and production of batteries. These batteries play a crucial role not only in facilitating the transition to sustainable energy sources but also in serving as fundamental components of the continent's energy storage infrastructure. With global battery demand projected to experience a major, 14-fold increase by 2030, addressing the environmental impact of this growth trajectory becomes critical (World Economic Forum, 2019).

Recognizing the evolving social landscape, technological advancements, market dynamics, and diversified applications of batteries, the European Commission took a proactive step in 2020 by proposing a new Battery Regulations (BR). This regulation aims to ensure the sustainability of batteries across their lifecycle, starting from raw material extraction, production, use and ending with the end-of-life (EOL) management. (Al-Emran and Griffy-Brown, 2023).

As an evaluating framework, this thesis aims to use Life Cycle Assessment (LCA), a methodology which evaluates the environmental impacts of a product or service across its entire life cycle, covering stages such as raw material extraction, processing, manufacturing, use, and EOL treatment.

This thesis aims to provide a detailed exploration of the state-of-the-art in battery technology, specifically concentrating on the advancements in Lithium Iron Phosphate (LFP) and bio-based electrolyte. Additionally, it purposes to involve into the methodological frameworks of LCA, including Environmental Life Cycle Assessment (E-LCA), with the help of the relevant LCA software and databases. Furthermore, to examines the regulatory landscape within the EU, encompassing both the BR and the concept of the digital product passport (DPP).

Focus of the thesis is into the detailed description and characterization of battery technology utilizing bio-based electrolytes. It aims to present the results of the E-LCA for such batteries, focusing on the cradle-to-gate stage and highlighting the main environmental indicators. Additionally, it purposes to analyse the compliance of the assessed battery with existing European Union (EU) regulations while identifying potential areas for improvement. The carbon footprint (CF) results and the potential application of E-LCA in creating a Digital Product Passport (DPP) for batteries are also addressed in this section.

The goal of the work is to discuss the environmental benefits and challenges related with bio-based electrolytes in batteries and proposes a framework for conducting a for lithium-ion bio-based batteries. Finally, the thesis aims to conclude with a summary of the key findings and recommendations for future research endeavours.

I THEORETICAL PART

1 BATTERY TECHNOLOGY OVERVIEW

With the increasing use of fluctuating renewable energy sources such as wind and photovoltaic power plants for electricity generation, the demand for electrical storage devices like batteries for a secure power supply is increasing (Stern, 2009). A battery may seem straightforward, requiring only two electrodes and an electrolyte. However, high performance depends on managing interactions and understanding chemical reactions. Factors like cost, weight, material structure, and availability must be optimized. These challenges make designing reliable batteries a complex and time-consuming task. (Zschornak *et al.*, 2018)

1.1 Battery technology and working principle

Battery technology is essential in numerous sectors, ranging from regular user electronics to large-scale energy storage and electric vehicles (EVs). A battery is an electrochemical appliance that stores and converts chemical energy into electrical through redox reactions: oxidation at the anode and reduction at the cathode (Figure 1). This process facilitates the movement of electrons through an external circuit, which generates electrical energy.

Electrical energy is generally considered as highest quality form of energy, since it can easily be converted into other forms such as mechanical, thermal, or radiation energy. The drawback of electrical energy is the problem of its storage. Conventional capacitors provide only limited energy density, which is why storage in other forms is inevitable for most applications. Conversion to chemical energy is a very efficient way to increase energy density by orders of magnitude, but due to the dynamics of the involved chemical processes, it comes at the cost of power density. (Zschornak *et al.*, 2018).

The performance of a battery largely relies upon its design and the materials, which are used in the electrodes and electrolyte. High energy density, safety, long cycle life, and cost-effectiveness are key performance indicators for modern battery systems. LIBs have become the highly popular technology because of their high energy density and durability. However, the demand for safer, more sustainable, and cost-effective alternatives caused the exploration of new materials and chemistries, such as lithium iron phosphate (LiFePO_4 , LFP) batteries, which offer improved safety, thermal stability, and lower environmental impact (Lu and Zhu, 2024).

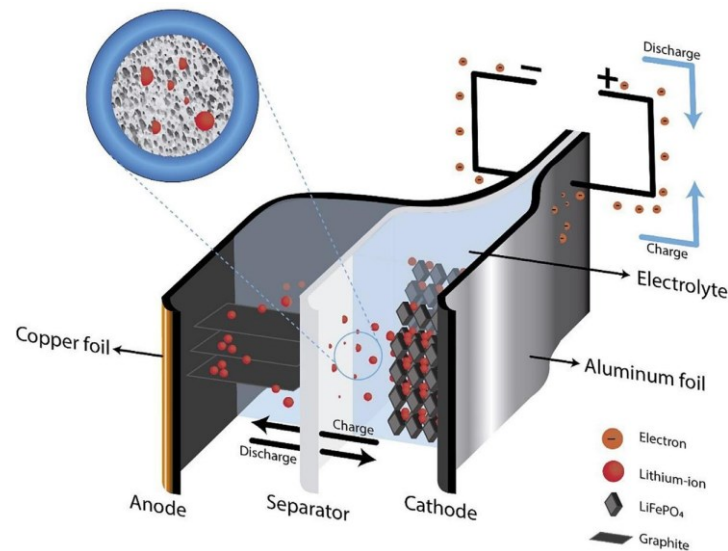


Figure 1. Lithium-ion batteries (LIBs) components, charge and discharge process and lithium-ion movement in LIBs.

(source: (Zhao et al., 2024))

Battery components.

The crucial components of LFP battery include (Fig.2):

- Cathode: Made from LiFePO_4 , this is the defining component of an LFP battery. It offers stability, safety, and a long cycle life, although it has a lower energy density compared to other lithium-ion chemistries.
- Anode: Typically made of graphite, which provides a stable structure for lithium ions to intercalate during the charging process.
- Electrolyte: The electrolyte is a lithium salt (like LiPF_6 , LiBF_4 , or LiClO_4) dissolved in an organic solvent. The electrolyte facilitates the movement of lithium ions between the anode and cathode.
- Separator: This is a porous membrane, often made from polyethylene or polypropylene, placed between the anode and cathode. It prevents the electrodes from short-circuiting while allowing lithium ions to pass through.
- Current Collectors:

Aluminium foil is used as a current collector for the cathode.

Copper foil is used as a current collector for the anode.

- Casing: The battery is enclosed in a metal or plastic casing to protect internal components from external conditions. (Chen, Li and Bae, 2024)

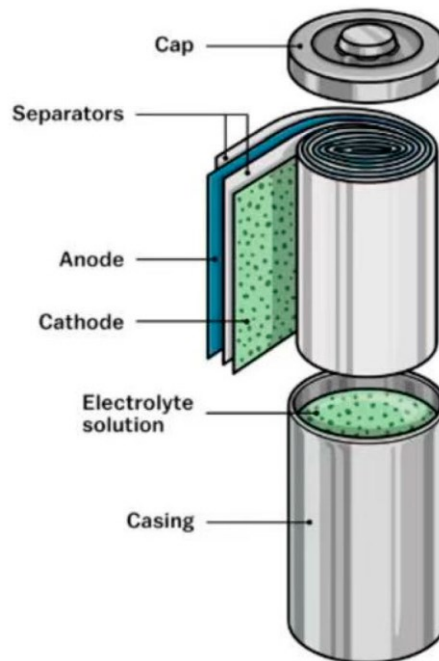


Figure 2. The structure of full-cell LFP battery (cylindrical type)

(source: (Jung and DeBrouckere, 2024), (Chen, Li and Bae, 2024))

Battery cell manufacturing processes

The fundamental process for creating composite electrodes has largely stayed the same since the advent of lithium-ion batteries in 1991. (Hawley and Li, 2019) The main elements are schematically depicted in Fig.3 This involves mixing the active material with a polymer binder and conductive carbon in a solvent to create an ink.

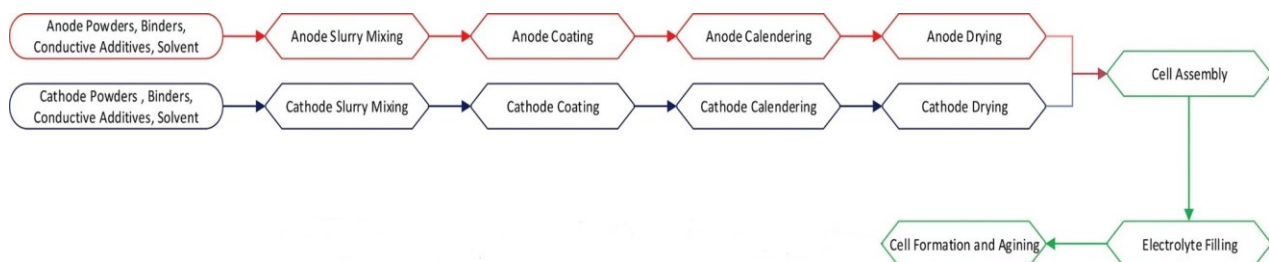


Figure 3. Scheme showing the processing steps for converting battery materials into battery cell, starting from the initial slurry mixing, electrode coating, calendering, and

drying (in red and blue for the anode and cathode, respectively), over the cell assembly and electrolyte filling until the cell formation (in green).

(created based on source: (Armand et al., 2020))

The ink is then applied to a thin aluminium or copper foil, depending on whether it's for the cathode or anode, and the solvent is carefully evaporated. The coating is subsequently compressed to the desired thickness before being cut to the appropriate size for assembly.

In Figure 4, it is shown that the battery cell manufacturing process can be divided into three categories: electrode production, cell assembly, and cell finishing. Throughout this section, we discuss lithium-ion cell manufacturing for simplicity and clarity.

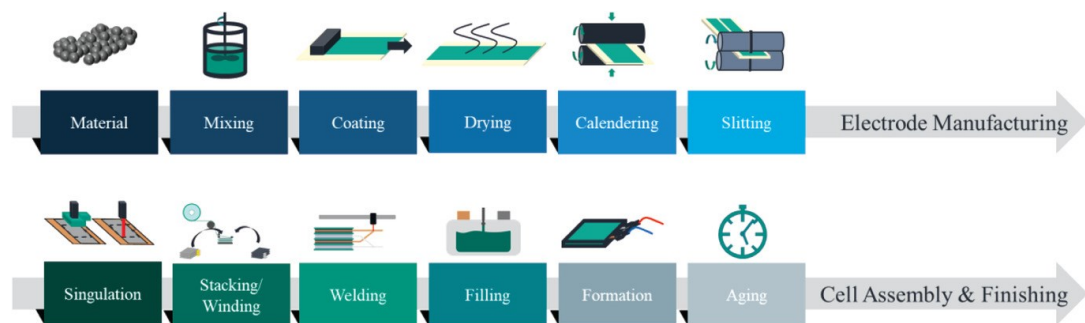


Figure 4. Visualised simplified overview of the LIB cell manufacturing process chain.

(source: (Kwade et al., 2018))

Batteries with Bio-Based Electrolyte.

The development of bio-based electrolytes represents a significant step toward creating more sustainable and environmentally friendly battery systems. Traditional electrolytes, typically composed of organic solvents, are often flammable and pose environmental hazards due to their toxicity. To mitigate these issues, researchers are exploring the use of bio-based materials for electrolytes, which could significantly reduce the environmental impact of lithium-ion batteries.

Bio-Based Electrolyte Advances:

- **Cellulose-Based Electrolytes:** Recent research has focused on the use of cellulose, a natural polymer derived from plant sources, as a component of bio-based electrolytes. Cellulose-based electrolytes offer high ionic conductivity and mechanical stability, making them a promising alternative to traditional organic solvents. Furthermore, cellulose is

biodegradable and renewable, offering significant environmental advantages (Soufi, Mesbahi and Samet, 2023).

- **Bacterial Cellulose-Supported Electrolytes:** Another innovative approach involves the use of bacterial cellulose (BC) as a support for quasi-solid electrolytes. BC is renewable, biodegradable, and provides excellent mechanical properties. Recent studies have shown that bacterial cellulose-supported electrolytes offer good ionic conductivity (Figure 5) and enhanced safety features for lithium-ion batteries (Yan et al., 2020). These electrolytes could improve the overall sustainability and safety profile of batteries, particularly in applications such as EVs and stationary energy storages.

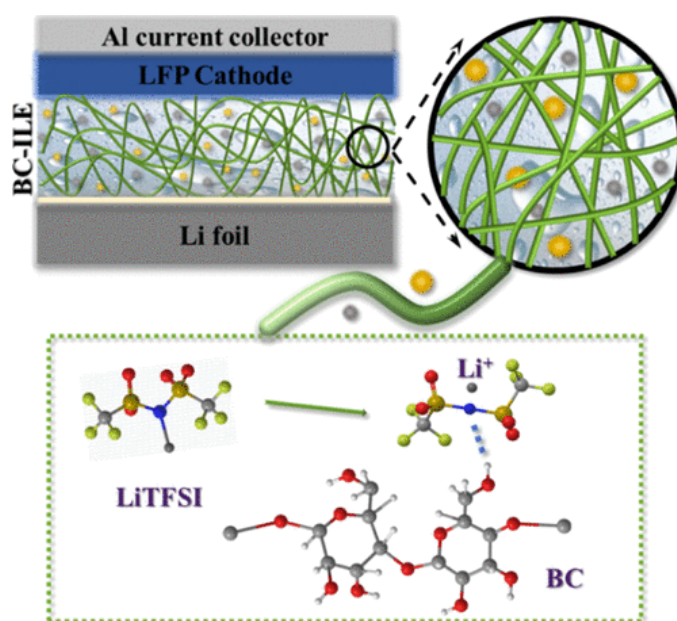


Figure 5 Schematic composition of Li/BC-ILE/LiFePO₄ battery with quasi-solid electrolyte

(source: (Yan et al., 2020))

1.2 Battery types and applications

The interaction between all the components in battery determines its energy density, power output, and life cycle.

Battery types by chemistry

The most common battery types include:

- Lead-acid batteries: primarily are used in automotive applications and backup power systems due to their low cost and reliability.
- Nickel-cadmium (NiCd) and nickel-metal hydride (NiMH) batteries: are known for their durability, these are commonly found in consumer electronics and medical devices.
- Solid-State Batteries (emerging technology): solid electrolytes are used (non-flammable)

Potentially higher energy density Improved safety

Applications: Future EVs and portable electronics Aerospace (research phase) Military applications

- Li-ion batteries widely used portable electronics, renewable energy storage systems, and in EVs because of their high energy density and long cycle life (Kwade *et al.*, 2018).

Lithium-ion batteries have revolutionized numerous applications, but the growing demand for safer, more environmentally friendly battery solutions has sparked interest in alternative technologies, such as LFP batteries and the development of bio-based electrolytes (Song and Fu, 2024).

Table 1 Common Battery Types: Chemistries, Features, Applications, and References

Battery Type	Chemistry	Key Features	Applications	Top-Cited Scientific Reference
Lithium-ion (Li-ion)	Varies (LCO, NMC, NCA, LFP, etc.)	High energy density, low self-discharge, long cycle life	Smartphones, laptops, EVs, storage	(Nitta <i>et al.</i> , 2015)
NMC	LiNiMnCoO ₂	High capacity, stable, tunable Ni/Mn/Co ratio, good lifespan	EVs (Tesla, BMW), energy storage	(Myung <i>et al.</i> , 2017)
LFP	LiFePO ₄	Excellent safety, long cycle life, thermal	Buses, grid storage, newer EVs (BYD)	(Padhi, Nanjundaswamy and Goodenough, 1997)

		stability, lower energy density		
LCO	LiCoO ₂	High energy density, widely used, high cost and cobalt dependence	Phones, tablets, cameras	(Mizushima <i>et al.</i> , 1980)
LTO	Li ₄ Ti ₅ O ₁₂	Fast charge, ultra-long lifespan, wide temperature range, low energy density	Electric buses, UPS, aerospace	(Chen <i>et al.</i> , 2017)
NiMH	Nickel- Metal Hydride	Moderate energy density, no cadmium, good for partial cycling	Hybrid vehicles, tools, medical devices	Ovshinsky & Fetcenko, J. Power Sources, 1993, DOI: 10.1016/0378-7753(93)80011- T
NiCd	Nickel- Cadmium	Rugged, low-temp tolerant, memory effect, toxic (cadmium)	Aviation, emergency lighting, older tools	(Dell <i>et al.</i> , 2001)
Lead- Acid	Pb-PbO ₂ in H ₂ SO ₄	Low cost, high power output, recyclable, heavy and bulky	Starter batteries, UPS, grid storage	(Pavlov, 2011)
Sodium- ion	Na-ion	Low-cost, abundant materials, lower energy density than Li-ion	Grid storage, future EVs (research phase)	(Hwang, Myung and Sun, 2017)
Zinc-air	Zn + O ₂ (air)	High theoretical energy density, lightweight, limited rechargeabili ty	Hearing aids, military, grid (in developme nt)	(Lee <i>et al.</i> , 2011)

Vanadium Redox Flow	V^{2+}/V^{5+} in liquid electrolytes	Scalable capacity, low energy density, long cycle life	Grid storage, renewable integration	(Skyllas-Kazacos <i>et al.</i> , 2011)
Solid-State (Emerging)	Solid electrolyte + Li-metal	Very safe, potential for higher energy density, still in development	Next-gen EVs, aerospace, military	(Janek and Zeier, 2016)

Battery types by form factor

Batteries are commonly classified not only by their chemical composition but also by their form factor, which impacts their application and energy capacity. The most prevalent battery forms include cylindrical, prismatic, pouch, and button (coin) cells (Figure 6).

- Cylindrical Batteries:

These are among the most widely used, especially in consumer electronics and power tools. They offer mechanical stability and efficient use of space within cylindrical compartments (Abdellatif M. Sadeq, 2023). A common example is the 18650 lithium-ion cylindrical cell, widely adopted in laptops and electric vehicles due to its high energy density and robustness.

- Prismatic Batteries:

With a rectangular shape, prismatic cells are designed to optimize space utilization in compact devices like smartphones and tablets. Though they tend to have lower structural integrity compared to cylindrical types, they allow more design flexibility (Skyllas-Kazacos *et al.*, 2011).

- Pouch Batteries:

These batteries use a flexible, foil-type casing, making them lighter and adaptable to irregular shapes. Pouch cells are increasingly used in EVs and portable electronics. However, they are more vulnerable to swelling and mechanical stress.

- Button or Coin Cells:

Small, round cells used in low-power applications like watches, hearing aids, and small IoT devices. They are valued for their long shelf life and compact size.

Each form factor presents trade-offs in energy density, durability, manufacturing cost, and application suitability (Kermani and Sahraei, 2017).

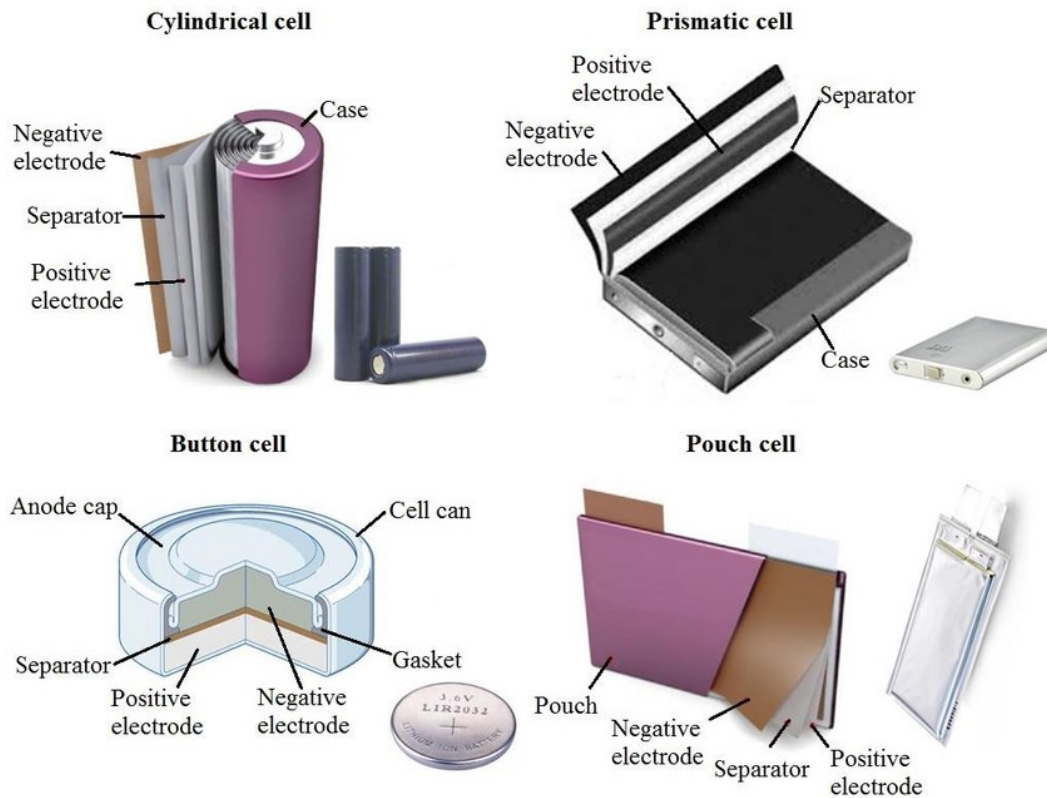


Figure 6 The most common lithium-ion cell types.

(source: (Murashko, 2016))

1.3 LFP battery technology

On the way to an efficient and complete energy shift to renewable energy sources, productive stationary energy storages can play a key role. Among all the possible power components, the most known and used are LIBs, which show great energy and power density, growing increasingly while relevantly decreasing cost. Lithium-ion battery is a special type of battery that have great potential for its power and energy to grow as well as to make less pollution by reducing carbon emissions. For that reason, it has been considered the key component toward energy sustainability development. (Kwade *et al.*, 2018), (Armand *et al.*, 2020)

As one of the types of rechargeable battery LFP battery has gained popularity in recent years. In comparison with traditional lead-acid batteries, LFP battery contains a stable and secure cathode, making it safer and more durable.

Apart from that LFP battery technology represents an important evolution in lithium-ion battery chemistry. These batteries use iron phosphate as the cathode material, which offers further explained advantages over cobalt-based lithium-ion batteries, including enhanced safety, thermal stability, and a lower environmental impact.

Key Advantages of LFP Technology:

- **Safety:** LFP batteries are less prone to overheating and thermal runaway, which makes them ideal for applications requiring high safety standards, such as stationary energy storage and EVs batteries (Lu and Zhu, 2024).
- **Longevity:** LFP batteries have longer cycle life if compare to traditional lithium-ion systems, offering greater long-term cost efficiency (Song and Fu, 2024).
- **Environmental Benefits:** The use of iron, a more abundant and less toxic material than cobalt, reduces the environmental and ethical concerns associated with mining cobalt (Song and Fu, 2024).
- **Energy Density:** Despite lower energy density comparing with cobalt-based alternatives, LFP batteries have superior safety and cost advantages make them well-suited for stationary energy storage and EV applications (Kwade *et al.*, 2018).

The production of LFP batteries has also been improving, with efforts to enhance manufacturing efficiency and reduce costs. One key development is the integration of bio-based electrolytes, which may further reduce the environmental footprint (EF) of LFP batteries (Lu and Zhu, 2024).

2 SUSTAINABILITY AND EU REGULATORY CONTEXT FOR BATTERIES

Batteries play a critical role in the global shift to clean energy, as they are key to decarbonizing the transport, energy storage, and industrial sectors. However, the sustainability of battery production and disposal, including the use of finite resources and hazardous materials, has prompted the EU to develop regulatory frameworks that prioritize sustainability throughout the entire battery lifecycle. The EU's focus on sustainability aligns with its broader Green Deal objectives, aiming to reduce greenhouse gas emissions and enhance resource efficiency. Within this regulatory landscape, batteries are subject to stringent requirements to ensure their sustainability, transparency, and circularity (European Commission, 2020).

To address the growing complexity of battery supply chains and sustainability concerns, the Digital Battery Passport (DBP) has emerged as a crucial tool. As described by (Soufi, Mesbahi and Samet, 2023) and (Berger, Schögggl and Baumgartner, 2022) the DBP provides a digital record of a battery's materials, production methods, and life cycle data. This enables stakeholders to trace the environmental impact and performance of batteries over time, from raw material extraction through to recycling or second-life applications.

Incorporating a DBP into battery production and management processes could revolutionize sustainability efforts by enabling better transparency, regulatory compliance, and circular economy models (Soufi, Mesbahi and Samet, 2023). It can also support LCA by ensuring access to real-time data about battery materials and their environmental impacts.

2.1 The EU Battery Regulation: Advancing Sustainability Across the Battery Lifecycle

The EU has established a comprehensive regulatory framework to address the sustainability and environmental impacts of batteries. One of the central pieces of legislation is the EU Battery Regulation, which was proposed in December 2020 and is expected to replace the Battery Directive 2006/66/EC. This new regulation is designed to cover the entire lifecycle of batteries, from design and production to reuse, recycling, and disposal (European Commission, 2020).

The EU Battery Regulation sets ambitious targets for recycled content, collection rates, and CF, focusing on minimizing the environmental impact of batteries. It introduces

mandatory due diligence obligations for battery manufacturers to ensure ethical sourcing of raw materials, minimize energy consumption during production, and prioritize recycling and reuse at the end of life (European Commission, 2020). The regulation also promotes innovation in battery technology, aiming for more efficient and sustainable battery designs that contribute to the EU's circular economy objectives (European Commission, 2023).

The regulation emphasizes extended producer responsibility requiring battery manufacturers to ensure that their products meet sustainability criteria, including responsible material sourcing, reducing hazardous substances, and ensuring the traceability of batteries throughout their lifecycle. Furthermore, it sets specific targets for recycling efficiencies, requiring that at least 70% of the weight of lithium-ion batteries be recycled by 2030 (European Commission, 2021).

2.2 Digital Product Passport (DPP) requirements

A key component of the new EU Battery Regulation is the introduction of the Digital Product Passport (DPP), which is intended to enhance transparency and traceability of batteries across their entire lifecycle. The DPP is a digital record containing detailed information about the battery's materials, design, CF, and recycling potential. It serves as a tool for consumers, businesses, and regulators to access relevant data about a battery's sustainability performance, ethical sourcing, and compliance with environmental standards (European Commission, 2023).

The DPP requirements are part of the EU's broader strategy to promote the circular economy by ensuring that products are designed with sustainability in mind and that relevant information is easily accessible throughout the product's lifecycle (European Commission, 2021).

For batteries, the DPP will contain data on key elements such as:

- The battery's origin, including information on raw material sourcing.
- CF data to track the environmental impact of the production process.
- Information on the battery's potential for reuse, recycling, or refurbishment.
- Details on hazardous substances used and measures taken to mitigate their impact.
- Instructions for EOL management and recycling efficiency targets.

By mandating the DPP, the EU aims to support better decision-making by consumers and businesses, encouraging the adoption of more sustainable batteries and supporting the circular economy. The DPP is expected to foster innovation in battery technology, push for higher standards of environmental performance, and facilitate compliance with EU regulations (European Commission, 2023).

The DPP will also support the enforcement of regulations by providing authorities with the information needed to ensure that batteries placed on the EU market comply with sustainability and transparency standards. The DPP requirements align with other EU initiatives aims to enhance the environmental performance of products and reduce their overall EF (European Commission, 2021).

The Battery Pass Consortium in 2023 provided detailed guidelines and recommendations on the development and implementation of a digital battery passport, aligning with the EU Battery Regulation. The document is supported by the German Federal Ministry for Economic Affairs and Climate Action. The passport is designed to track information across the lifecycle of batteries, ensuring transparency, traceability, and sustainability ('Position Paper on content requirements of the EU Battery Passport', 2023).

Key components discussed include:

- **General Battery & Manufacturer Information:** Information about battery composition and manufacturer identification.
- **Carbon Footprint & Supply Chain Due Diligence:** Data collection on battery CFs and due diligence across supply chains, emphasizing primary data usage.
- **Recycled Content & Circularity:** Focuses on incorporating recycled materials and promoting efficient resource use.
- **Performance & Durability:** Establishes parameters for evaluating battery lifespan and performance through Battery Management Systems (BMS).
- **Compliance & Legal Liability:** Outlines responsibilities for ensuring data accuracy and managing potential non-compliance under the Battery Regulation. ('Position Paper on content requirements of the EU Battery Passport', 2023)

3 LIFE CYCLE ASSESSMENT (LCA) METHODOLOGICAL FRAMEWORK

LCA is a structured approach used to quantify the environmental impacts of a product, process, or service throughout its life cycle. Following the ISO 14040 and 14044 standards, this chapter expands on the four basic phases of the LCA methodology: goal and scope definition, inventory analysis, impact assessment, and interpretation of results (Fig.7)(‘ISO 14044, Environmental Management Life Cycle Assessment Requirements and Guidelines’, 2006),(‘ISO 14040:2006, Environmental management — Life cycle assessment — Principles and framework’, 2006).

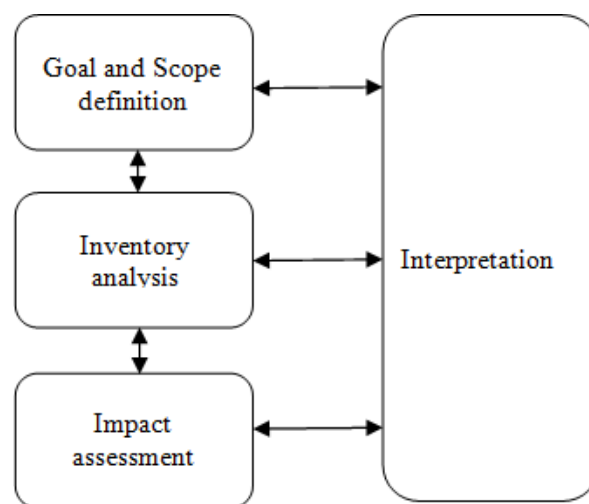


Figure 7. The four basic phases of life cycle assessment.

(source: ‘ISO 14044 Environmental Management Life Cycle Assessment Requirements and Guidelines’, 2006)

In spite of its growing popularity, LCA remains comparatively young and constantly developing application, originating from research carried out in the 1960s (Curran, 1996) and the 1970s (Royston, 1979) on energy requirements and pollution prevention (Rebitzer *et al.*, 2004).

3.1 Goal and scope definition

Defining the goal and scope are fundamental to an LCA, as it sets the purpose, system boundaries, and context for the assessment.

Purpose and Application

Recent studies emphasize that the goal of an LCA should clearly declare its intended application and audience. Whether it is for internal product development or external communication, the purpose determines the focus and depth of the study. This phase ensures that the study will meet its intended objectives (Rebitzer *et al.*, 2004).

Functional Unit and Reference Flow

The functional unit (FU) defines the quantification of the identified functions (performance characteristics based on physical units) of the product and the reference flow measure of the outputs from processes in a given product system required to fulfil the function ('ISO 14044, Environmental Management Life Cycle Assessment Requirements and Guidelines', 2006). The choice of the FU and the reference flow is crucial for enabling consistent comparisons between different products or systems. FUs must reflect the actual utility delivered to the user, especially in emerging fields such as biobased materials (Wenzel, Petersen and Hansen, 2004).

Definitions of assumptions and cut-off criteria are also included in the phase of goal and scope definition.

System Boundaries

Defining system boundaries ensures that only relevant life cycle stages and processes are included. This includes upstream and downstream processes, as well as material and energy inputs. Recent studies highlight the importance of circularity in defining these boundaries, especially in sustainable product systems (Tillman *et al.*, 1994).

3.2 Inventory analysis

Inventory analysis is the data-driven phase, where the environmental inputs and outputs are measured and recorded.

Data Collection

The transparency and quality of data collection directly influence the reliability of LCA results. Advances in digitalization have led to improved data sourcing, including real-time tracking of materials and energy flows in supply chains (Saavedra-Rubio *et al.*, 2022). It is essential to ensure high-quality, region-specific data where possible to minimize uncertainties.

Data Categorization

Data is categorized into input and output flows, which include energy use, raw materials, emissions, and waste. To bridge gaps where primary data is insufficient new methods in hybrid LCA combine process-based and input-output analysis (Majeau-Bettez, Strømman and Hertwich, 2011).

Modeling Assumptions

Transparent documentation of assumptions and data gaps is crucial. New guidelines emphasize the need for scenario analysis when data is uncertain, allowing for more robust conclusions even when precise data is unavailable (Majeau-Bettez, Strømman and Hertwich, 2011).

3.3 Impact assessment

The potential environmental impacts of the life cycle inventory result, which are elementary flows as input and output, are evaluated in the impact assessment phase. (Fig.8).

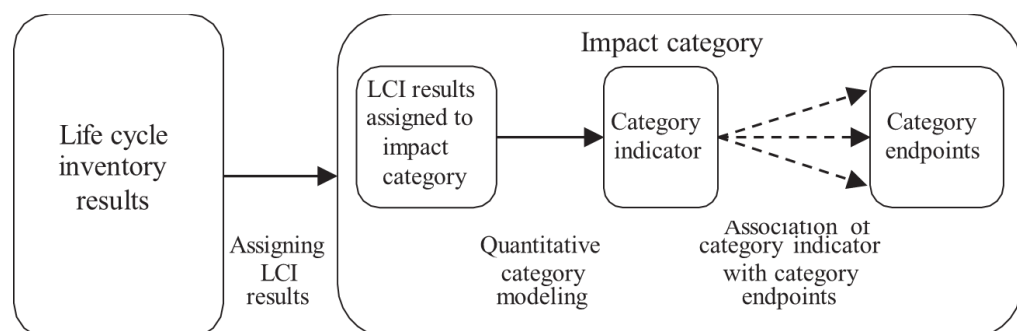


Figure 8. Impact assessment scheme.

(source: 'ISO 14044 Environmental Management Life Cycle Assessment Requirements and Guidelines', 2006)

Classification and Categorization

The elementary flows as life cycle inventory data are assigned to environmental impact categories such as climate change, human toxicity, water depletion, and resource scarcity. There is a growing focus on including social and economic dimensions in addition to environmental ones, which broadens the application of LCA to sustainability assessments (De Laurentiis et al., 2020).

Characterization Models

Characterization factors measure the effect of an elementary flow into an environmental impact based on a physical category indicator. Life cycle impact assessment (LCIA) helps interpret LCA studies by transforming emissions and resource extraction into environmental impact scores (Paul *et al.*, 2024). Characterization factors are used for this. The environmental impact per unit of stressor is indicated by characterization factors.

Two levels are used to determine indicators in ReCiPe (Fig.9.). They are:

- Midpoint level: There are eighteen midpoint indicators, which are difficult to read but have little uncertainty. Midway-level characterization factors are located somewhere along the impact pathway, prior to the cause-effect chain. Midpoint indicators focus on specific environmental problems, like acidification or the possibility of global warming.
- Endpoint level: It features three endpoint indicators that are simple to comprehend but less certain. Endpoint is a metric used to quantify damage (Paul *et al.*, 2024).

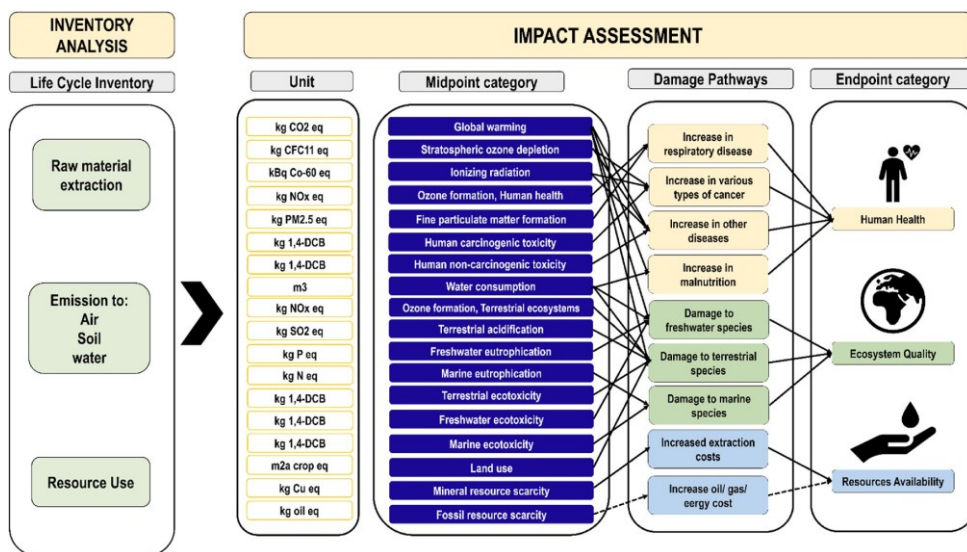


Figure 9. Relationship between ReCiPe midpoint-endpoint indicators

(source: (Paul *et al.*, 2024))

Normalization and Weighting

In some cases, impacts are normalized against a reference, such as regional per capita impacts. Weighting is often applied to express the relative importance of different impact categories. However, it is important to acknowledge the subjectivity involved in this step, as

highlighted in several comparative studies of weighting methods (Roesch, Sala and Jungbluth, 2020).

3.4 Result interpretation

The interpretation of results phase integrates the findings from the previous stages and provides actionable insights.

Identification of Key Issues

This step involves pinpointing significant contributors to the environmental impact. Studies have shown that the interpretation phase benefits from sensitivity analysis to identify which processes are critical in influencing overall results

Uncertainty and Sensitivity Analysis

Given the inherent uncertainties in any LCA, conducting uncertainty and sensitivity analyses helps to evaluate the robustness of the results. Techniques such as Monte Carlo simulations are increasingly applied to quantify uncertainties, especially in complex product systems (Bamber *et al.*, 2020).

Conclusion and Recommendations

From the interpreted results, definitive conclusions can be reached, enabling recommendations to enhance the environmental performance of products. Recent frameworks emphasize the importance of presenting results in a way that is actionable for stakeholders, including policy-makers and manufacturers.

4 TOOLS AND DATABASES FOR LCA

LCA requires accurate and comprehensive data sets, along with robust software tools to assess the environmental impacts of products or processes. Two pivotal resources in LCA practices include the ecoinvent database and the SimaPro software. This chapter outlines the roles and functionalities of these tools in modern LCA practices.

4.1 Life Cycle Inventory Database ecoinvent

The ecoinvent database version 3 is recognized as one of the most comprehensive Life Cycle Inventory (LCI) databases globally. It contains over 30,000 datasets as transparent unit-process across various sectors including energy, agriculture, chemicals, metal materials, and transportation, which are important as background data for the LCI model to be created. Founded in Switzerland, ecoinvent aims to provide transparent, high-quality and consistent LCI data to facilitate the modelling of environmental impacts across a product's lifecycle. Ecoinvent goes in correspondence with a wide range of LCA software, including SimaPro, GaBi, openLCA, and Umberto, among others. This makes it the backbone for many LCA analyses conducted worldwide. Its data is frequently updated, ensuring that users have access to the latest developments in environmental research. Moreover, ecoinvent includes a variety of system models, such as allocation at the point of substitution, cut-off, and consequential system models, offering flexibility depending on the analysis needs (Wernet *et al.*, 2016).

4.2 SimaPro Software

SimaPro, created by PRé Sustainability, is widely regarded as the go-to tool for lifecycle assessments in the industry. This software requires users to buy a license, which can be a significant expense for academic institutions and small organizations. However, its real advantage is in its robust functionality and user-friendly design. The intuitive interface makes it easy for users with various levels of expertise to navigate.

Being a leading LCA software SimaPro provides users with a platform to model and analyse the environmental impacts of products, processes, and services throughout the entire life cycle. In this purpose it integrates a variety of databases, including the full implementation of ecoinvent, which allows users to access reliable and scientifically-grounded LCI data (Rajić, Stanković and Milosavljević, 2024).

One of SimaPro's key strengths is its versatility. It offers two main products: SimaPro Craft, which is tailored for individual LCA experts, and SimaPro Synergy, which is designed for organizations aiming to integrate LCA into business operations on a larger scale.

The software's ability to perform detailed, comprehensive analyses makes it suitable for both academic research and industrial applications. Moreover, SimaPro has a user-friendly interface and provides tools for calculating complex environmental impact categories such as resource depletion, global warming potential, human toxicity and other. By offering access to multiple impact assessment methods, SimaPro supports accurate and customizable sustainability assessments.

SimaPro offers support for an array of impact assessment methods, including CML, ReCiPe, and TRACI, which are particularly valuable for analysing energy systems. One of its standout features is the capability to conduct multi-scenario comparisons, allowing for in-depth assessments of various energy sources like wind, solar, and nuclear power. This helps identify trade-offs among different environmental impacts. (Rajić, Stanković and Milosavljević, 2024)

Tailored for large-scale industrial applications, SimaPro excels in providing detailed product lifecycle data and tracking environmental performance.

II PRACTICAL PART

5 LCA ANALYSIS OF BIO-BASED BATTERY TECHNOLOGY

METHODOLOGICAL FRAMEWORK

Subchapter text.

5.1 Cradle-to-Gate LCA of bio-based electrolyte battery

The efficient application of electrolytes in sustainable energy storage and batteries demands materials that provide advantages in not only electrochemical performance but also in environmental sustainability. (Huang *et al.*, 2025) In this context, this master's thesis goal is to bridge the current gap between the practical characteristics of biopolymer electrolytes, which have already been known as efficient in batteries, and the environmental impact of their production process. To prepare biopolymer electrolytes covering solid electrolytes, commercially purchased BC with stable performance was taken for analysis. The assessment was made based on published results, and their ionic conductivity and electrochemical stability windows were examined. In addition, the laboratory measured the processes' electricity use.

LCA is performed to quantify the cradle-to-gate CF, acidification, eutrophication, water use, and other relevant impact metrics.

5.1.1 Goal and scope

This thesis uses E-LCA to calculate the environmental impact of a single lab-scale LFP coin cell with commercially produced BC electrolyte.

The investigation aims to determine the environmental impacts associated with a chosen LFP with bio-based electrolyte coin-cell battery production stage made within the TwinVECTOR project in TBU, Zlín (Czech Republic) and discuss the compliance of the bio-based battery technology with relevant EU regulations. The main goal is to identify potential hot spots that will allow the technology to be bettered and efficiency and environmental sustainability to be developed.

5.1.2 Functional unit

The FU was defined as 1 Wh of LFP coin-cell. The system boundaries were determined using the cradle-to-gate model, including raw materials extraction and production stages. Transportation was not considered. Material and energy flow from resource extraction to product manufacturing and transport were considered when performing this assessment.

5.1.3 System boundaries

System boundaries is decided to be chosen as cradle-to-gate, which includes the mining, production of raw materials through the manufacturing processes, but for this specific case does not include transportation, the use phase.

5.1.4 Lifecycle inventory analysis

Collection of input data in this master thesis for the selected battery type analysis was made using different sources: preliminary data provided by battery expert of TBU, laboratory data for some of selected battery step preparation, which is considered as an experimental part of the thesis, data from the scientific literature and assumptions based on the data from scientific literature.

For the analysis, primary data from the laboratory battery production line at Tomas Bata University (TBU) in 2025 was used. However, secondary data was also used, as primary data was lacking. These secondary data included LCA reports, LCA studies, and data sets from the ecoinvent database. The expert opinions of TBU specialists involved in laboratory-scale battery production were also included.

Modelling coin-cell composition

There were the four main subcomponents identified at the laboratory-scale coin cell as an input: the anode, cathode, electrolyte, and cell container. To assemble one coin cell, the following materials were utilized: cathode positive electrode paste, positive current collector (cathode), negative lithium metal (li-metal) current collector (anode), electrolyte, and cell container. The composition of materials and their ratio according to the mass balance is specified in Tab. 2.

Table 2 LCI for the production of the TwinVector LFP LIB coin-cell

Parameters	Dataset	Quantity, g	Ratio with cell container	Ratio without cell container
Output LFP LIB prototype		3.561	1	1
Material Requirements				

Positive electrode paste (cathode) for LIB, LFP	See Table 2		0.003	0.053546756
Positive current collector for LIB, Al	See Table 5		0.002	0.033070477
Negative current collector (Li-metal anode) for LIB, Cu	See Table 3		0.012	0.21101598
Electrolyte for LIB	See Table 11		0.039	0.702366788
Cell container	See Table 14		0.945	

Figure 9 presents the process of preparing the LFP cathode and li-metal anode. The LFP was prepared via a conventional slurry-casting method. The slurry was formulated with a mass ratio of 86% LFP, 8% Super P carbon Black, 5% polyvinylidene fluoride (PVDF) binder, and 1% graphite dissolved in N-methyl-2-pyrrolidone (NMP). The slurry was uniformly coated onto an aluminium current collector, and then the coated film was dried at 80°C, and then dried under vacuum at 120°C for 6 hours, calendared, and cut. For the anode, a commercial thin lithium-metal foil was cut to match the cathode geometry, ensuring balanced alignment during cell assembly.

Production of the LFP cathode

Based to the TBU battery specialist's expert opinion, the following amount of material are needed to produce one cathode for LFP/Li-metal coin-cell: 6.662 mg an aluminium current collector, 9.262 mg LFP paste, 0.539 mg graphite, 0.862 mg polyvinylidene fluoride (PVDF) binders, 0.108 mg super P additives, 0.02748 ml N-methyl-2-pyrrolidone (NMP) solvent.

The total weight of LFP cathode: 17,442 mg (cathode paste – 61,82%, cathode current collector – 38.18%).

Cathode preparation method:

In the initial phase, components such as LFP paste, NMP, graphite, binder and carbon black additives are mixed and spread on 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. Then the coated film was dried under vacuum, calendared and cut.

To ascertain the production details for 1 kg of the LFP cathode, was conducted calculations to determine the ratio of cathode materials (Tab. 3 and Tab 4).

$$m = p \times V \quad (1)$$

p (NMP) = $1030 \text{ kg/m}^3 = 1.03 \text{ kg/l}$.

Mass of NMP = $0.00002748 \times 1.03 = 28.3 \times 10^{-6} \text{ kg}$.

Table 3 Cathode materials ratio (Positive Electrode Paste)

Material	Quantity	Unit	Ratio
LiFePO ₄	9.262	mg	0.86
Graphite	0.539	mg	0.01
NMP (solvent)	28,3	mg	
Super P (carbon black)	0.108	mg	0.08
PVDF (binder)	0.862	mg	0.05
Total	10.770	mg	1

Table 4 Cathode materials ratio (Positive Current Collector, Al)

Material	Quantity, mg	Input	Unit
Aluminium, wrought alloy (positive current collector, 7 sheets)	6.652	1	kg
Sheet rolling, aluminium (positive current collector, 1 sheet)	6.652	1	kg

The PVDF organic binder (Erakca *et al.*, 2023), LiFePO₄ and (Majeau-Bettez, Hawkins and Strømman, 2011a) and (1-Butyl-1-methylpyrrolidinium bis(trifluoromethylsulfonyl)imide) (LiTFSI) (Larrabide, Rey and Lizundia, 2022) data was used to analyze inputs.

The production details for 1 kg of the LFP cathode are provided in Tab. 5.

Table 5 LCI for the production of 1 kg of the LFP cathode positive electrode paste

Material/fuels	Inputs	Outputs	Unit	References
3.2 Cathode paste (Positive Electrode Paste)		1	kg	
3.2b_AI Organic binder PVDF	0.05		kg	TBU pilot line
3.2a Positive active material sub inventory (LiFePO ₄)	0.86		kg	(Majeau-Bettez, Hawkins and Strømman, 2011b)
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	0.08		kg	TBU pilot line

Production of positive electrode current collector

Table 6 LCI for the production of 1 kg positive electrode current collector (Smith et al. 2021;(Majeau-Bettez, Hawkins and Strømman, 2011b)

Material/fuels	Inputs	Unit
3.1 Positive current collector, Production		kg
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

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), Czech (CZ), Europe (RER), 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.

Table 7 LCI for the production of 1 kg of NMP (N-methyl-2-pyrrolidone) (Kamali, 2023)

Material/fuels	Inputs	Outputs	Unit
Positive active material sub inventory		1	kg
Methylpyrrole	1.1765		kg
Bromopropane {GLO} market for bromopropane Cut-off, U (Proxy to dichloromethane (DCM); it is not available in ecoinvent database*)	0.196		kg
Activated carbon, granular {GLO} market for activated carbon, granular Cut-off, U	0.0198		kg
Platinum {GLO} market for platinum Cut-off, U	19.559		mg
Electricity/heat			
Electricity, medium voltage {RER} market group for electricity, medium voltage Cut-off, U	0.046		kWh
Final waste flows			
Chemical waste, unspecified		0.2158	kg

Production of LiFePO₄

It was assumed that, lithium iron phosphate (LiFePO₄) was produced by hydrothermal synthesis, in which sulphate (FeSO₄ · 7H₂O) reacted with phosphoric acid (H₃PO₄) and lithium hydroxide (LiOH) at 150–200°C for 5 hours. The resulting LiFePO₄ precipitate was 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, 2011b).

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

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

Material/fuels	Inputs	Outputs	Unit
Positive active material sub inventory		1	kg
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
Chemical, organic {GLO} chemical production, organic Cut-off, U	4E-10		kg
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 (I)		0.1	kg
Iron, ion		0.019	kg
Phosphate		0.032	kg
Emissions to air			
Heat, waste		1.5	MJ

Production of PVDF (binder)

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. 9.

Table 9 LCI for the production of 1 kg PVDF

Materials/fuels	Inputs	Unit
3.2b_AI Organic binder PVDF		kg
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

Production of the Li-Metal anode

Table 10 Anode materials ratio (Negative Current Collector+Li-metal anode)

Input	Quantity	Unit	Ratio
Lithium		kg	1

Copper sheet rolling		kg	1
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Production of the PEO/BC/LiTFSI/IL electrolyte/separator

Figure 10 shows the flow chart of the preparation of polyethylene oxide/bacterial cellulose (PEO/BC) electrolyte. Generally, the processes are as follows. Polyethylene oxide (PEO) and BC were mixed DI water. The mixture was freeze-dried and then vacuum-dried to remove the water. The dry PEO/BC was mixed with LiTFSI and ionic liquid (IL) electrolyte. The PEO/BC/IL-electrolyte was heated and hot pressed to get the electrolyte membrane. To prevent the short-circuit, a BC separator was prepared through the filtration of BC suspension. It was then placed between two pieces of electrolyte membranes and pressed. The electrolyte/separator was cut to the size for the coin-cell.

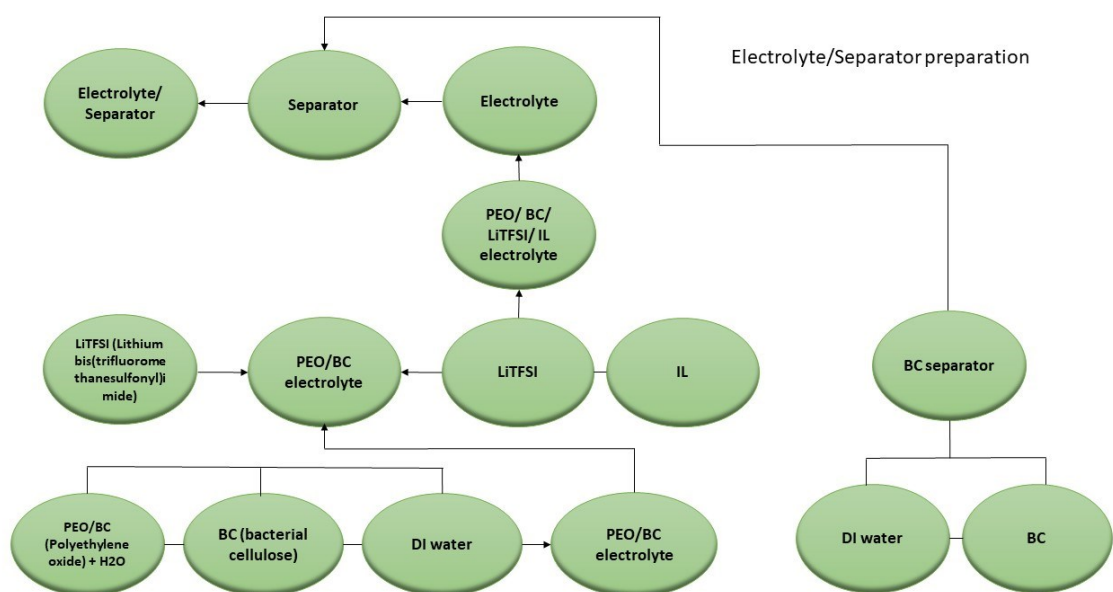


Figure 10. The preparation of polymer electrolyte/separator for coin-cell

(source: own elaboration)

Table 11 Electrolyte materials ratio (electrolyte/separator) (PEO/BC/LiTFSI/IL))

Input	Ratio	Unit
PEO/BC/LiTFSI/IL electrolyte/separator		
PEO (polyethylene oxide)	0.419	kg

BC (electrolyte)	0.047	kg
LiTFSI	0.318	kg
IL	0.216	kg
BC (separator)	0.011	kg
Total	1	kg
DI water (PEO/BC)	200	ml
Water from BC	180	ml

Production of LiTFSI

The LiTFSI (Deng *et al.*, 2017) data was used to analyze inputs.

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

Table 12 Inventory of 1kg LiTFSI production (Deng *et al.*, 2017)

Materials/fuels	Inputs	Outputs	Unit
LiTFSI sub inventory		1	
SO ₂ (Sulfur dioxide, liquid {RER} market for sulfur dioxide, liquid Cut-off, U)	0.718		kg
Cl ₂ (Chlorine, liquid {RER} chlorine production, liquid Cut-off, U)	0.796		kg
CH ₄	0.165		kg
HF (Hydrogen fluoride {RER} market for hydrogen fluoride Cut-off, U)	0.568		kg
Silica (Silica sand {DE} silica sand production Cut-off, U)	1.343		kg

CH ₃ Cl (Methylchloride {RER} market for methylchloride Cut-off, U)	4.442		kg
NH ₃ (Ammonia, anhydrous, liquid {RoW} ammonia production, steam reforming, liquid Cut-off, U)	0.560		kg
NaOMe (Sodium methoxide {GLO} market for sodium methoxide Cut-off, U)	0.224		kg
H ₂ SO ₄ (Sulfuric acid {RoW} sulfuric acid production Cut-off, U)	0.383		kg
Li ₂ CO ₃ (Lithium carbonate {GLO} market for lithium carbonate Cut-off, U)	0.131		kg
Solvent, organic {GLO} market for solvent, organic Cut-off, U	0.251		kg
Electricity/heat			
Heat, from steam, in chemical industry {RER} market for heat, from steam, in chemical industry Cut-off, U	37.977		kg
Electricity, medium voltage {RER} market group for electricity, medium voltage Cut-off, U	42.331		MJ
Emissions to air			
Ammonia		0.000177	kg

Sulfur dioxide		0.000227	kg
Hydrochloric acid		0.0001	kg
Chlorine		0.00025	kg
Methane		0.0000521	kg
Hydrogen fluoride		0.00018	kg
Waste to treatment			
Spent solvent mixture {RoW} treatment of spent solvent mixture, hazardous waste incineration Cut-off, U		3.567	kg

Production of IL

The IL (Neale *et al.*, 2017) data was used to analyze inputs.

The production details for 1 kg of IL are available in Tab. 13.

Table 13 LCI for the production of 1 kg IL (Neale *et al.*, 2017)

Products	Inputs	Outputs	Unit
Ionic Liquid		1	
Materials/fuels			
[Pyrr14]Br	0.27		kg
LiTFSI	0.727		kg
Dichloromethane {RoW} market for dichloromethane Cut-off, U	3.18		kg
Water, deionised {RoW} market for water, deionised Cut-off, U	2.39		kg
Electricity/heat			

Electricity, medium voltage {RER} market group for electricity, medium voltage Cut-off, U	11.86		kWh
Emissions to water			
Chemically polluted water		5.57	kg

Production of [Pyrr 14]Br

The [Pyrr 14]Br (Kamali, 2023) data was used to analyze inputs.

The production details for 1 kg of [Pyrr 14]Br are available in Tab. 14.

Table 14 LCI for the production of 1 kg [Pyrr 14]Br (Kamali, 2023)

Products	Inputs	Outputs	Unit
[Pyrr 14]Br		1	
Materials/fuels			
NMP	0.62		kg
Bromopropane {GLO} market for bromopropane Cut-off, U	0.38		kg
Acetonitrile {GLO} market for acetonitrile Cut-off, U	0.881		kg
Electricity/heat			
Electricity, medium voltage {RER} market group for electricity, medium voltage Cut-off, U	5.584		kWh
Emissions to air			
Acetonitrile		0.881	kg

Production of BC

The BC (Hervy *et al.*, 2015) data was used to analyze inputs.

Table 15 Production of BC according to Hervy et al is as follows (Hervy *et al.*, 2015)

Products	Inputs	Unit
Bacterial Cellulose		
Materials/fuels		
HS medium	197.1	L
Di water	4081.3	g
Glucose	1020.3	g
Protein	1020.3	g
Yeast paste	551	g
Disodium	234.7	g
Washing water	36	L
NaOH	288	g
Water treatment	233	L
Washing electricity	10.7	MJ
Paper making (output)	653	g

Production of CR 2032 cell container

Dada based on the preliminary values given by battery expert of TBU was used to analyze inputs.

The production details for 1 kg of battery cell container are available in Tab. 16.

Table 16 Cell container ratio

Input	Ratio	Unit
Negative cap (Stainless Steel)	0.21	kg
Positive cap (Stainless Steel 85 % + polypropylene material 15%)	0.21	kg

Spring (Stainless Steel)	0.05	kg
Spacer (3 pieces) (Stainless Steel)	0.53	kg
Total	1	kg

Energy specifications

The battery materials were preliminary sourced from European suppliers. Specifically, the anode includes the current collector, the coin-cell container, materials for the cathode and the electrolyte. Additionally, one supplier outside of Europe provided materials for the cathode. However, the transportation was not taken into account during LCA modelling and not included into analysis.

Energy consumption calculations had few sources. Some of them were based on personally measured energy data at the laboratories of TBU for battery electrolyte preparation step for coin-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 21 coin-cell batteries. Since the anode was purchased ready-made and cut manually, energy consumption was assumed to be zero. 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.

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 17 Energy consumption calculation parameters of producing CR 2032 coin-cell battery

Battery component	Processes	Equipment required to carry out the processes

Cathode	No	
Anode	No	
Electrolyte	Mixing (1 hours)	IKA Magnetic Stirrers RET basic
	Sonification	
	Freeze drying (48 hours)	Drying oven, UF55 53
	Vacuum drying (24 hours at 80 °C)	NRTL Vacuum oven, DZF-6020
	Mixing/heating (2 hours at about 60 °C)	Magnetic stirrer/heater
	Heating while mixing (42 minutes at 90-120 °C)	Magnetic stirrer/heater
	Vacuum filtration of BC	
	Coating of LFP cathode	
Cell assembly	No	only Ar consuming

Modelling methodology

The E-LCA model used for environmental impact assessment (EIA) for lab scale LFP coin-cell production was built and assessed using SimaPro software. The system model was created using the ecoinvent database version 3. Cradle-to-gate system boundaries included raw material extraction, production through manufacturing including energy consumption, but does not include transportation.

5.2 Analysis of environmental impact results

In this section, the impact categories which together contribute to over the weighted aggregated single score are presented.

The total impact of the battery for 18 impact categories (without cell container) reported on Figure 10.

The results of the bio-based electrolyte with the most impact presented in Figure 11.

LCIA was conducted for selected impact categories:

- Global Warming, (kg CO₂ – eq to air) – an indicator that assesses the impact of greenhouse gas emissions, such as CH₂, CH₄, SF₆, N₂O, CCl₂F₂, CHF₃ 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)
- Stratospheric ozone depletion, (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).
- Ionizing radiation, (yr/kBq Cobalt-60 equivalents to air) accounts for the level of exposure for the global population.
- Ozone formation, Human health, (yr/kg NO_x equivalents) is an important environmental factor causing impacts on human health and ecosystem.
- Fine particulate matter formation, (PM_{2.5} for short) is mainly formed from gas to particle conversions and chemical interactions with the surrounding atmosphere, causing the particle to grow and/or change composition.
- Ozone formation, Terrestrial ecosystems, (kg NO_x eq) Cause and effect pathway from tropospheric ozone precursor emissions to damage to human health and terrestrial ecosystems.
- Terrestrial acidification, (kg SO₂-eq to air) – an indicator that assesses the potential acidification of soils (acid rain) (Huijbregts *et al.*, 2017).
- Freshwater Eutrophication, (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).
- Marine eutrophication, (kg N eq) is defined as the reaction of a marine ecosystem to an excessive availability of a limiting nutrient.

- Freshwater ecotoxicity, (kg 1,4-DCB) category indicator refers to the impact on fresh water ecosystems, as a result of emissions of toxic substances to air, water and soil.
- Marine ecotoxicity, (kg 1,4-DCB) impacts of toxic substances on marine ecosystems
- Human carcinogenic toxicity, (kg 1,4-DCB (dichlorobenzene) – eq to urban air) – an indicator of elevated risk for cancer, reflecting changes in lifetime disease incidence due to the intake of the substance (Huijbregts *et al.*, 2017).
- Human non-carcinogenic toxicity, (kg 1,4-DCB (dichlorobenzene) – eq to urban air) – an indicator of elevated risk for non-cancerous diseases, reflecting changes in lifetime disease incidence due to the intake of the substance (Huijbregts *et al.*, 2017).
- Terrestrial Ecotoxicity, (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 Recourse 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).
- Water consumption (m3 water consumed) factor for the water use is the amount of fresh water consumption.

There were two possible scenarios for providing to quantified the environmental impacts modelled:

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.

Due to the fact that the battery cell container occupies a significant proportion (about 97%) of its assembly and has limited potential for improvement over the materials used inside the container, it was decided to pay more attention on the analysis of the environmental impacts of the cell without cell container.

Also, overall environmental impact assessment (EIA) results were expressed in Wh (kWh) per cell in terms of better comparability with other studies, both existing and future.

5.2.1 Life cycle impact assessment (cradle-to-gate results)

To cradle-to-gate impact of analysed coin-cell battery is highly dependent upon energy requirements of battery cell manufacture. (Ellingsen *et al.*, 2014)

The impact category with the largest contribution to the cradle-to-gate aggregated single score is presented in Figure 11

Table 18 Environmental impact of the LFP coin-cell (without cell container)

Impact category	Unit	1.0 Cathode	1.2 Positive current collector	2.0 Anode	3.0 Electrolyte (PEO/BC/LiTFSI/IL)
Global warming	kg CO ₂ eq	5.387	4.718	13.399	37.777
Stratospheric ozone depletion	kg CFC11 eq	0.000	0.000	0.000	0.000
Ionizing radiation	kBq Co-60 eq	0.142	0.083	0.803	16.525
Ozone formation, Human health	kg NO _x eq	0.015	0.012	0.039	0.075
Fine particulate matter formation	kg PM _{2.5} eq	0.011	0.009	0.028	0.057
Ozone formation, Terrestrial ecosystems	kg NO _x eq	0.015	0.012	0.040	0.078
Terrestrial acidification	kg SO ₂ eq	0.027	0.021	0.065	0.146
Freshwater eutrophication	kg P eq	0.006	0.002	0.013	0.027
Marine eutrophication	kg N eq	0.001	0.000	0.006	0.003
Terrestrial ecotoxicity	kg 1,4-DCB	33.831	20.179	103.252	182.753
Freshwater ecotoxicity	kg 1,4-DCB	0.502	0.422	0.924	1.434
Marine ecotoxicity	kg 1,4-DCB	0.673	0.556	1.270	2.035
Human carcinogenic toxicity	kg 1,4-DCB	3.069	2.939	2.454	4.539

Human non-carcinogenic toxicity	kg 1,4-DCB	8.178	5.558	21.472	39.028
Land use	m ² a crop eq	0.164	0.082	0.406	2.301
Mineral resource scarcity	kg Cu eq	0.128	0.056	0.506	0.083
Fossil resource scarcity	kg oil eq	1.220	1.009	3.289	10.540
Water consumption	m ³	0.061	0.026	0.130	0.624

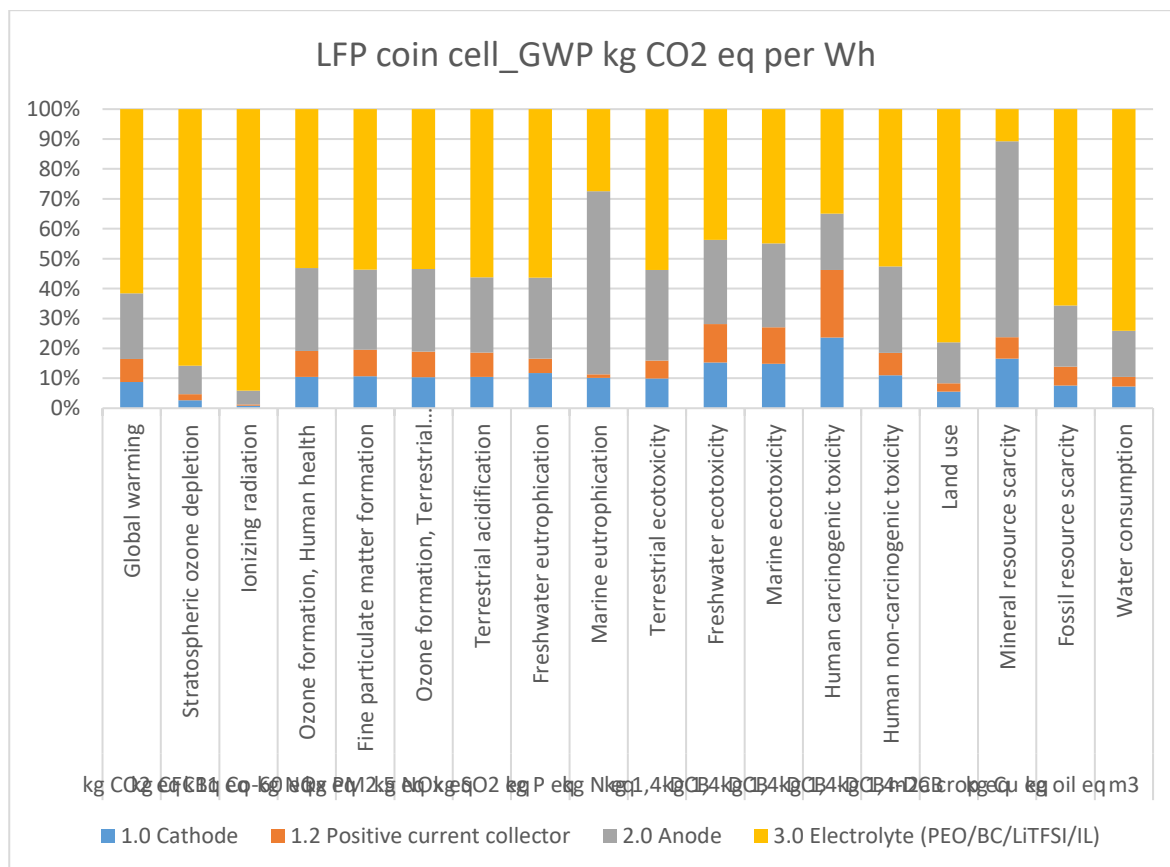


Figure 11. Midpoint impact categories for producing 1 Wh of coin cell (without cell container)

Table 19 Environmental impact of the PEO/BC/LiTFSI/IL electrolyte

Impact category	Unit	Total	3.1 PEO/BC	3.3.1 LiTFSI	3.3 LiTFSI/IL	Electricity, medium voltage {RER} market group for electricity, medium voltage Cut-off, U
Global warming	kg CO2 eq	71.985	12.973	15.148	3.912	39.952
Stratospheric ozone depletion	kg CFC11 eq	0.000	0.000	0.000	0.000	0.000
Ionizing radiation	kBq Co-60 eq	31.488	5.759	1.221	0.401	24.107
Ozone formation, Human health	kg NOx eq	0.143	0.024	0.037	0.011	0.070
Fine particulate matter formation	kg PM2.5 eq	0.108	0.018	0.026	0.007	0.057
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.148	0.026	0.039	0.011	0.073
Terrestrial acidification	kg SO2 eq	0.278	0.046	0.075	0.019	0.138
Freshwater eutrophication	kg P eq	0.051	0.010	0.004	0.001	0.037
Marine eutrophication	kg N eq	0.005	0.002	0.001	0.000	0.003
Terrestrial ecotoxicity	kg 1,4-DCB	348.237	80.494	56.788	15.434	195.520
Freshwater ecotoxicity	kg 1,4-DCB	2.732	0.613	0.267	0.078	1.773
Marine ecotoxicity	kg 1,4-DCB	3.877	0.860	0.402	0.116	2.499
Human carcinogenic toxicity	kg 1,4-DCB	8.649	2.136	1.069	0.286	5.158
Human non- carcinogenic toxicity	kg 1,4-DCB	74.367	15.519	6.540	2.136	50.172
Land use	m2a crop eq	4.385	2.657	0.159	0.052	1.516
Mineral resource scarcity	kg Cu eq	0.159	0.034	0.043	0.010	0.072
Fossil resource scarcity	kg oil eq	20.084	4.134	3.755	0.988	11.207
Water consumption	m3	1.189	0.291	0.100	0.027	0.770

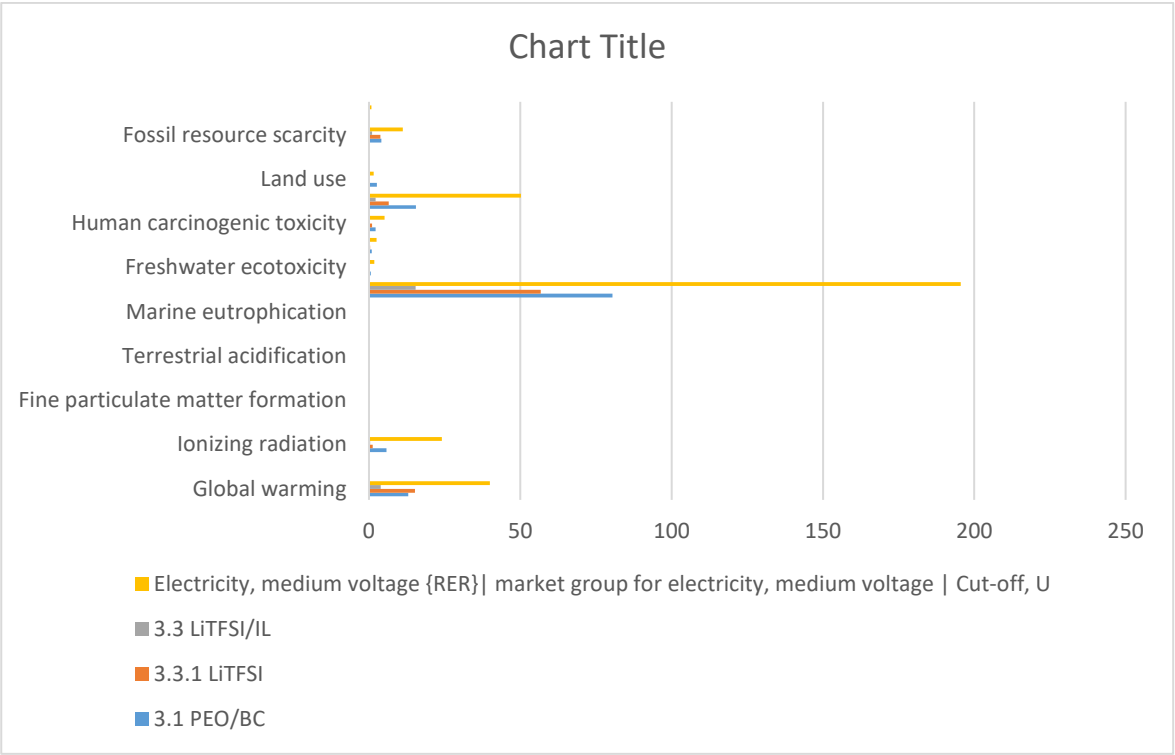


Figure 12. Midpoint impact categories for producing PEO/BC/LiTFSI/IL electrolyte

5.2.4 Conclusion and Recommendations

An inventory LFP battery with bio-based electrolyte has been compiled. In addition, the EIA associated with the production of the studied battery cell (without cell container) are assessed and analysed. (Table 11)

The most impact-intensive production chain was manufacturing of electrolyte, out of which PEO/BC production and electricity consumption contributed the most. (Figure 12)

6 COMPLIANCE WITH EU REGULATORY REQUIREMENTS

A significant element of the EU Batteries Regulation is the establishment of definitive CF requirements for all EV batteries. Representing the first requirements of this kind on a global scale, the regulations will evolve in the coming years from mandatory declaration of the battery's CF performance class to a maximum CF threshold that the batteries will need to meet to enter the EU market. These requirements will inevitably give rise to new demands for the collection and sharing of CF data across global EV battery value chains.

6.1 DPP system for batteries

The implementation of a DPP system represents a pivotal step toward enhancing the traceability, sustainability, and regulatory compliance of batteries within the EU. Under the EU Battery Regulation (Regulation (EU) 2023/1542), the DPP is mandated for all industrial and EV batteries and light means of transport (LMT) batteries above 2 kWh, including bio-based batteries where applicable (EUR-Lex, 2023). This subchapter outlines the practical considerations, technical components, and regulatory relevance of the DPP system in the context of emerging bio-based battery technologies.

6.1.1 Purpose and Scope

The main goal of the DPP is to support the circular economy by enabling data transparency across the battery life cycle.

The DPP must store and provide standardized, machine-readable information related to:

- Battery composition (including bio-based materials)
- Performance characteristics
- CF
- Durability and expected lifetime
- Origin of raw materials
- Supply chain information
- Recycling and reuse potential
- Compliance with regulatory requirements

For bio-based batteries, the DPP additionally serves to highlight their environmental advantages and the origin and share of bio-derived materials used in the battery's construction.

6.1.2 Technical Architecture

The DPP system is built on a secure, interoperable digital infrastructure, often using blockchain or distributed ledger technologies to ensure data integrity and accessibility. The core components of a battery DPP include:

- **Unique Identifier (UID):** Each battery unit is assigned a persistent digital identity via a QR code, RFID tag, or NFC chip.
- **Cloud-Based Data Repository:** The passport links to a central or federated database where stakeholders (manufacturers, recyclers, regulators, and consumers) can access relevant information.
- **Access Control Protocols:** Role-based access ensures that sensitive information is protected, while compliance-related data remains publicly available

A critical aspect of the technical design is interoperability with other product databases (e.g., SCIP under REACH, and the European Battery Alliance platform) and alignment with international standards such as IEC 62933 or ISO/IEC 21823.

6.1.3 Implementation Challenges for Bio-Based Batteries

For bio-based batteries, several challenges emerge in implementing an effective DPP system:

- **Material Classification:** Standardized definitions and classifications for bio-based materials are still evolving, which complicates the labelling and data entry processes.
- **Life-Cycle Data Collection:** The environmental impact and EOL behaviour of bio-based materials may differ significantly from conventional ones. Gathering verifiable, high-resolution life-cycle data requires collaboration with material suppliers and researchers.
- **Small-Scale Production Constraints:** Many bio-based battery projects are still in pilot or small-scale production stages, where digital infrastructure is less developed.

Despite these challenges, the DPP provides an opportunity to emphasize the low-carbon, renewable nature of bio-based battery components, potentially offering competitive advantages under EU eco-design and green procurement frameworks.

6.1.4 Regulatory Integration and Future Outlook

The EU Battery Regulation mandates that by 2027, all batteries in scope must carry a DPP. For producers of bio-based batteries, early integration of DPP systems will facilitate smoother regulatory approval and better positioning in the sustainable technology market.

In the future, DPPs are expected to expand in functionality to include dynamic data updates, automated sustainability scoring, and integration with digital twins for predictive maintenance. These advancements will benefit bio-based batteries by enabling real-time monitoring of performance and degradation, thereby supporting efforts to optimize material reuse and extend battery life.

6.2 Evaluation the compliance with EU Regulations

The European Union has established a comprehensive regulatory framework to ensure that batteries placed on the EU market meet stringent environmental, social, and technical standards throughout their life cycle. This includes not only traditional lithium-ion batteries but also emerging bio-based battery technologies, which must adhere to the same legislative principles. This subchapter provides a practical evaluation of how bio-based batteries align with the relevant EU regulatory instruments, including the new EU Battery Regulation (EUR-Lex, 2023), REACH, RoHS, and relevant directives on waste and sustainability.

6.2.1 Regulatory Landscape Overview

- The core regulatory instruments applicable to battery compliance in the EU include: Regulation (EU) 2023/1542 on batteries and waste batteries
- REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals)
- Regulation (EC No 1907/2006) RoHS (Restriction of Hazardous Substances)
- Directive (2011/65/EU) Waste Framework Directive (2008/98/EC)

The Battery Regulation introduces mandatory sustainability, safety, labelling, and circular economy provisions that cover the entire battery life cycle—from raw material sourcing and design to use and EOL treatment. Of particular relevance to bio-based batteries

are provisions related to CF declarations, recycled content, performance and durability, due diligence, and the DPP.

6.2.2 Compliance Indicators for Bio-Based Batteries

To evaluate the compliance of bio-based batteries, a set of key regulatory indicators can be applied:

Table 20 Evaluation the regulations with the compliance of bio-based batteries

Regulatory Area	Compliance Indicator	Bio-Based Battery Consideration
CF	Life-cycle greenhouse gas (GHG) emissions	Bio-based materials may reduce upstream emissions but require full LCA verification.
Material Composition	Hazardous substance content (REACH/RoHS)	Bio-based electrolytes and binders often replace toxic solvents, aiding compliance.
Recycled Content	Minimum thresholds (e.g., Co, Ni, Li by 2031)	Bio-based batteries may not contain significant critical raw materials, potentially exempting them.
Labelling & DPP	Circular Economy marking, QR code, digital passport	DPP must document origin and content of bio-based materials.
Performance & Durability	Cycle life, capacity retention	Must be tested and reported in standardized formats.
Due Diligence	Risk management in raw material sourcing	Even bio-based materials must adhere to environmental and social sourcing criteria.

Bio-based batteries may show inherent advantages—such as reduced reliance on conflict minerals or toxic chemicals—but they must be carefully documented through third-party certifications, LCA studies, and standardized reporting formats to prove compliance.

6.2.3 Case Application and Gap Analysis

In practical terms, a prototype bio-based battery was assessed against EU regulatory criteria. The LCA conducted according to ISO 14040/44 standards

Gap analysis revealed the following:

- Strengths: Low CF and biodegradable components
- Weaknesses: Limited standardization in reporting bio-based material content; insufficient recycled content (if applicable); unclear EOL collection logistics

6.2.4 Recommendations for Compliance Enhancement

To strengthen compliance with EU regulations, developers of bio-based batteries should:

Integrate regulatory compliance early in R&D by aligning product design with Battery Regulation KPIs (e.g., recyclability, durability)

- Develop transparent supplier networks to ensure traceability and due diligence for bio-based raw materials.
- Invest in standardized testing and documentation, especially for performance, safety, and material disclosures.
- Engage with EU-funded pilot projects and initiatives (e.g., Battery Passport pilots, Horizon Europe programs) to anticipate regulatory changes.

III DISCUSSION

7 ENVIRONMENTAL BENEFITS AND CHALLENGES

The text 7 of the seventh main chapter.

7.1 Environmental benefits of bio-based batteries

The global push for sustainable energy solutions has spotlighted the environmental challenges posed by conventional lithium-ion batteries, notably their reliance on finite resources and the ecological toll of mining operations. In contrast, bio-based batteries emerge as a promising alternative, leveraging renewable biological materials to mitigate environmental impacts.

- ✓ Reduced Greenhouse Gas Emissions

Bio-based batteries utilize organic components derived from renewable sources such as plants, bacteria, and other biological matter. This approach significantly lowers greenhouse gas (GHG) emissions compared to traditional fossil-based battery materials. It is found that emerging bio-based products can reduce GHG emissions by nearly 45-50% relative to their fossil-based counterparts. (Zuiderveen *et al.*, 2023)

- ✓ Sustainability Directory

Traditional battery production often depends on mining activities that can lead to environmental degradation and resource depletion. Bio-based batteries, however, draw from abundant and renewable biological resources, reducing the ecological footprint associated with material extraction. For instance, lignin, a by-product of the paper industry, has been explored as a sustainable electrode material, offering benefits such as faster charging and better performance in cold temperatures.

- ✓ Biodegradability and EOL Management

Among the significant environmental advantages of bio-based batteries lies their potential for biodegradability. Unlike conventional batteries that can persist in the environment and pose disposal challenges, bio-based batteries can be designed to break down naturally, reducing long-term environmental impact. This characteristic simplifies EOL management and aligns with circular economy principles.

- Lower Toxicity and Enhanced Safety

Bio-based batteries often avoid the use of toxic metals and hazardous chemicals common in traditional batteries. For example, sugar-based batteries utilize maltodextrin, a renewable

carbohydrate, as fuel, resulting in by-products like water and carbon dioxide, which are less harmful to the environment. This not only reduces environmental toxicity but also enhances safety by minimizing the risk of hazardous leaks and explosions.

To conclude, bio-based batteries present a compelling case for sustainable energy storage, offering environmental benefits such as reduced greenhouse gas emissions, sustainable material sourcing, biodegradability, and lower toxicity. As research and development in this field advance, bio-based batteries could play an important role in shifting to a more sustainable and environmentally friendly energy infrastructure.

7.2 Challenges in implementing sustainable battery solutions

The development of bio-based lithium iron phosphate (LFP) batteries offers promising avenues for sustainable energy storage. However, transitioning from conventional to bio-based components at the laboratory scale presents several challenges that must be addressed to realize their full potential.

7.2.1 Variability in Biomass-Derived Materials

Biomass-derived materials, such as lignin, cellulose, and chitosan, are being explored for use in battery components like binders, separators, and electrolytes. However, these materials often exhibit variability in properties due to differences in biological sources and processing methods. Ensuring consistent performance, especially in terms of electronic conductivity and mechanical stability, is a significant challenge.

7.2.2 Integration of Bio-Based Binders

Replacing traditional binders like polyvinylidene fluoride (PVDF) with bio-based alternatives requires careful consideration. For instance, using polytetrafluoroethylene (PTFE) in a semi-dry process with water-based solvents has shown promise. However, achieving uniform dispersion and adhesion remains complex, particularly when scaling up from laboratory to industrial processes.

7.2.3 Electrode Fabrication Challenges

The fabrication of electrodes using bio-based materials involves challenges in achieving desired porosity, thickness, and mechanical strength. The drying process, in particular, can lead to issues like binder migration, affecting the uniformity and performance of the electrode. Optimizing drying conditions is crucial to mitigate these effects.

7.2.4 Limited Understanding of Long-Term Stability

While bio-based components offer environmental benefits, their long-term stability and performance under various operating conditions are not yet fully understood. Comprehensive studies are needed to assess degradation mechanisms and ensure reliability over the battery's lifespan.

7.2.5 Scalability and Economic Considerations

Scaling up bio-based LFP battery production from laboratory to industrial scale involves economic challenges. The cost of sourcing and processing bio-based materials can be higher compared to conventional materials. Additionally, adapting existing manufacturing infrastructure to accommodate bio-based components may require significant investment.

8 IMPLICATIONS FOR THE EU REGULATORY FRAMEWORK

The advent of bio-based battery technologies presents both opportunities and challenges within the context of the EU's regulatory framework. As the EU strives to promote sustainability, circular economy principles, and technological innovation, integrating bio-based batteries necessitates a re-evaluation of existing regulations to ensure they effectively accommodate these emerging technologies.

Alignment with Sustainability Objectives

Bio-based batteries, derived from renewable biological sources, inherently support the EU's sustainability goals by potentially reducing reliance on critical raw materials and lowering environmental impacts. Regulation (EU) 2023/1542 emphasizes the importance of minimizing adverse environmental effects throughout the battery life cycle, including aspects such as CF and ethical sourcing of raw materials.

The regulation mandates CF declarations for specific battery categories, requiring detailed LCAs to quantify greenhouse gas emissions. Bio-based batteries, with their potential for lower carbon emissions, may align well with these requirements. However, standardized methodologies for assessing the environmental impacts of bio-based materials are essential to ensure consistent and accurate reporting.

Challenges in Material Classification and Compliance

One of the primary challenges in integrating bio-based batteries into the EU regulatory framework is the classification and assessment of novel materials. The regulation necessitates comprehensive documentation of material composition, performance metrics, and safety standards. Bio-based materials, being relatively new in the battery sector, may lack established testing protocols and safety data, complicating compliance efforts.

Furthermore, the regulation imposes due diligence obligations on economic operators, requiring them to implement policies that address environmental and social risks associated with raw material sourcing. For bio-based batteries, this entails ensuring that biological feedstocks are sourced sustainably and do not contribute to deforestation, biodiversity loss, or social injustices.

Implications for the Digital Battery Passport

The introduction of the DBP is a significant development in enhancing traceability and transparency within the battery value chain. The DBP will contain information on battery composition, performance, and environmental impact, accessible to various stakeholders.

For bio-based batteries, the DBP presents an opportunity to highlight their sustainable attributes, such as the use of renewable materials and lower CFs. However, integrating bio-based components into the DBP requires the development of standardized data formats and reporting guidelines to accurately reflect their unique characteristics.

Future Regulatory Considerations

As bio-based battery technologies evolve, the EU regulatory framework must adapt to accommodate these innovations effectively. Potential areas for regulatory development include:

- Standardization of Testing Protocols: Developing standardized testing methods for bio-based materials to assess performance, safety, and environmental impact.
- Certification Schemes: Establishing certification systems to verify the sustainability and ethical sourcing of bio-based feedstocks.
- Incentive Structures: Implementing incentives for the development and adoption of bio-based batteries, such as research funding and market access support.
- Integration into Circular Economy Strategies: Ensuring that bio-based batteries are incorporated into broader circular economy initiatives, including recycling and EOL management programs.

By proactively addressing these considerations, the EU can foster an environment conducive to the growth of bio-based battery technologies, aligning regulatory frameworks with sustainability objectives and technological advancements.

8.1 Reflections towards the EU regulations

The evolution of the European Union's regulatory landscape—particularly with the enactment of Regulation (EU) 2023/1542—reflects an ambitious strategy to make batteries safer, more sustainable, and fully integrated into the circular economy. While this framework marks a decisive shift toward environmental accountability, the integration of bio-based batteries into its scope invites critical reflection on the regulation's adaptability, inclusivity, and future-readiness.

Regulatory Vision vs. Technological Diversity

EU battery regulation is, by design, technology-neutral, aiming to ensure environmental and social sustainability regardless of the chemistry or structure of the battery. However, this neutrality may unintentionally hinder the adoption of non-conventional technologies such as bio-based batteries, which often do not fit neatly into existing performance or materials classification schemes.

For instance, bio-based materials such as lignin, chitosan, or cellulose-derived components, while beneficial for sustainability, may lack representation in standardized testing or certification frameworks, potentially delaying their market entry despite their environmental promise.

A reflection here is whether tailored regulatory pathways should be introduced to accelerate the responsible development of emerging battery technologies, akin to how pharmaceuticals or medical devices are assessed under dedicated tracks within broader regulatory systems.

Compatibility with Circular Economy Objectives

The Circular Economy Action Plan (CEAP) is a cornerstone of EU policy, and the battery regulation echoes its principles through mandates on recyclability, CF, and information transparency. Bio-based batteries align well with CEAP goals by potentially enabling biodegradability, non-toxic disposal, or low-impact EOL treatment.

However, current regulatory instruments primarily evaluate batteries based on metal recovery efficiency, favouring lithium, cobalt, or nickel-containing chemistries. Since many bio-based batteries are designed with reduced or absent critical raw materials, they risk being undervalued in recyclability metrics, despite offering easier or more benign disposal.

This raises an important reflection: should “non-metal circularity” or material biodegradability be incorporated into the regulation’s recyclability metrics to acknowledge alternative sustainability routes?

Innovation Enablement vs. Compliance Burden

While the EU’s regulatory framework rightly demands rigorous transparency, traceability, and environmental reporting, there is a growing concern that early-stage or small-scale innovators—particularly in the bio-based battery sector—may struggle to meet the administrative and technical burdens without targeted support

For example, full life cycle assessments, CF declarations, and integration into the DBP require standardized datasets, third-party verification, and compliance infrastructure that small research labs or start-ups may lack. Without funded transition mechanisms, this could suppress innovation or delay deployment of sustainable alternatives.

This reflection supports calls for an EU-supported innovation exemption or sandboxing mechanism, allowing safe real-world testing of alternative battery chemistries under reduced compliance obligations, as long as core safety standards are upheld.

Towards Dynamic and Inclusive Regulation

Finally, there is a broader reflection on the future adaptability of the regulatory framework. The battery sector is advancing rapidly—chemically, structurally, and economically. As more bio-based, hybrid, and solid-state batteries emerge, the regulation must avoid a “fixed-chemistry” bias and embrace regulatory dynamism.

Periodic reviews of thresholds (e.g., CF benchmarks), updates to accepted test methods, and inclusion of new material categories in the DPP will be essential to ensure that the regulatory environment remains open to innovation without compromising on environmental and safety standards.

8.2 Future directions for sustainable battery compliance

The EU’s commitment to sustainability and circular economy principles is reshaping the battery industry. Regulation (EU) 2023/1542 introduces comprehensive measures to ensure that batteries placed on the EU market are sustainable, safe throughout their life cycle, and high-performing. As bio-based batteries emerge as a promising alternative to conventional technologies, aligning them with the evolving regulatory landscape is crucial.

Enhancing CF Transparency

A cornerstone of the new regulation is the requirement for CF declarations for EV batteries, rechargeable industrial batteries with capacities above 2 kWh, and LMT batteries. These declarations must detail the CF per kilowatt-hour over the battery's life cycle, broken down by stages such as EOL processing, manufacturing, and raw material extraction.

For bio-based batteries, which often utilize renewable and potentially lower-emission materials, this presents an opportunity to demonstrate environmental advantages. However, standardized methodologies for calculating CFs are still under development, with delegated

acts expected to establish these methods. Proactive engagement in shaping these methodologies will be essential to accurately reflect the benefits of bio-based technologies.

Integrating Recycled Content Requirements

The regulation requires batteries to contain minimum levels of recycled materials, aiming to lessen reliance on virgin resources and encourage a circular economy (Yang, Huang and Lin, 2022). By August 2031, industrial batteries must contain at least 16% cobalt, 6% lithium, and 6% nickel from recycled sources (EUR-Lex, 2023).

Bio-based batteries, while potentially less reliant on critical metals, must still navigate these requirements. Developing recycling processes tailored to bio-based materials and integrating them into existing recycling infrastructures will be vital. Additionally, clear guidelines on how bio-based components contribute to recycled content quotas will help manufacturers comply effectively.

Advancing the Digital Battery Passport

The introduction of the DBP aims to enhance traceability and transparency across the battery value chain. The DBP will store information on battery composition, performance, CF, and recycling history, accessible via a QR code (Battery Pass Consortium., 2023).

For bio-based batteries, the DBP offers a platform to highlight sustainable attributes, such as the use of renewable materials and lower environmental impacts. Ensuring that the DBP accommodates the unique characteristics of bio-based components will require collaboration between industry stakeholders and regulatory bodies to develop appropriate data standards and reporting formats.

Strengthening Due Diligence and Supply Chain Transparency

From May 2025, manufacturers must implement due diligence policies to assess and reduce an environmental risk associated with their supply chains. This includes evaluating the sourcing of raw materials, labour practices, and environmental impacts (EUR-Lex, 2023).

Bio-based battery producers must ensure that their feedstocks are sourced sustainably, without contributing to deforestation, biodiversity loss, or social injustices. Establishing robust traceability systems and engaging in third-party certifications can help demonstrate compliance and build consumer trust.

Supporting Innovation and Market Integration

To foster the development and adoption of bio-based batteries, the EU may consider implementing supportive measures, such as:

- Research and Development Funding: Allocating grants and incentives for the advancement of bio-based battery technologies.
- Standardization Initiatives: Developing testing protocols and performance standards specific to bio-based materials.
- Regulatory Sandboxes: Creating controlled environments where bio-based battery innovations can be tested and refined without the full burden of regulatory compliance.

These initiatives can help bridge the gap between innovation and regulation, ensuring that sustainable technologies are not hindered by compliance challenges (Guillaume Ragonnaud, 2025).

CONCLUSION

This thesis addressed the technological and regulatory landscape of batteries, with a special focus on the role of bio-based battery components in the context of the EU's sustainability ambitions. A key component of the work was the development and environmental assessment—via cradle-to-gate LCA—of a laboratory-scale coin-cell using BC as a bio-derived electrolyte material within a LFP configuration.

Key Findings

✓ Feasibility of Bio-Based Electrolytes:

The experimental fabrication of a bacterial cellulose-based electrolyte coin-cell battery demonstrated the technical feasibility of incorporating bio-based polymers in energy storage applications. Although performance was assessed at a laboratory scale, the result offers proof of concept for reducing dependency on fossil-based polymers and toxic solvents in battery development.

✓ LCA and EIA (Cradle-to-Gate):

The cradle-to-gate LCA revealed that raw material sourcing and laboratory-scale production processes are the primary contributors to environmental impacts. In particular, the energy-intensive steps in the preparation of BC and cell assembly accounted for a large portion of the total CF. Excluding transportation, use-phase, and EOL stages helped isolate the upstream environmental burden but also highlighted the importance of clean energy inputs and process optimization in early-stage production.

✓ Regulatory Fit and Gaps:

The current EU Battery Regulation (EU) 2023/1542 provides a solid framework for improving sustainability but is implicitly geared toward conventional battery chemistries (EUR-Lex, 2023). Because bio-based systems often fall outside critical raw material supply chains and standard recycling metrics, they are at risk of regulatory misalignment. However, provisions like CF declarations and the DBP may offer new mechanisms to reflect the low-impact potential of bio-based designs, if these tools evolve to capture non-metallic, biodegradable, or renewable components.

✓ Opportunities for Policy and Market Integration:

The exclusion of the use phase and EOL stages in this study limits claims about the full circularity of bio-based batteries. However, the findings suggest that integrating

environmental performance data from the early stages of production into EU compliance mechanisms—such as the DBP—could support more accurate, holistic assessments of emerging battery technologies. Further development of standardized sustainability criteria, recognition of non-metal material circularity, and support for pilot-scale innovation are essential next steps.

Overall Conclusion

This thesis concludes that bio-based batteries, particularly those utilizing BC electrolytes, represent a promising alternative in the transition to sustainable energy storage. Despite the current regulatory and scalability challenges, early-stage environmental assessments and policy alignment strategies indicate that these technologies could play a meaningful role in decarbonizing the battery value chain. A more inclusive and dynamic regulatory framework—paired with innovation support—will be critical to ensure that emerging sustainable materials are not only viable but also compliant and competitive within the European battery ecosystem.

BIBLIOGRAPHY

Abdellatif M. Sadeq (2023) ‘Mechanical Design of Battery Pack’. Available at: <https://doi.org/10.13140/RG.2.2.18172.92808>.

Al-Emran, M. and Griffy-Brown, C. (2023) ‘The role of technology adoption in sustainable development: Overview, opportunities, challenges, and future research agendas’, *Technology in Society*, 73, p. 102240. Available at: <https://doi.org/10.1016/j.techsoc.2023.102240>.

Armand, M. *et al.* (2020) ‘Lithium-ion batteries – Current state of the art and anticipated developments’, *Journal of Power Sources*, 479, p. 228708. Available at: <https://doi.org/10.1016/j.jpowsour.2020.228708>.

Bamber, N. *et al.* (2020) ‘Comparing sources and analysis of uncertainty in consequential and attributional life cycle assessment: review of current practice and recommendations’, *The International Journal of Life Cycle Assessment*, 25(1), pp. 168–180. Available at: <https://doi.org/10.1007/s11367-019-01663-1>.

Battery Pass Consortium. (2023) *Battery Passport Content Guidance*. Available at: <https://thebatterypass.eu/resources/>.

Berger, K., Schöggel, J.-P. and Baumgartner, R.J. (2022) ‘Digital battery passports to enable circular and sustainable value chains: Conceptualization and use cases’, *Journal of Cleaner Production*, 353, p. 131492. Available at: <https://doi.org/10.1016/j.jclepro.2022.131492>.

Chen, T., Li, M. and Bae, J. (2024) ‘Recent Advances in Lithium Iron Phosphate Battery Technology: A Comprehensive Review’, *Batteries*, 10(12), p. 424. Available at: <https://doi.org/10.3390/batteries10120424>.

Chen, X. *et al.* (2017) ‘Towards stable lithium-sulfur batteries: Mechanistic insights into electrolyte decomposition on lithium metal anode’, *Energy Storage Materials*, 8, pp. 194–201. Available at: <https://doi.org/10.1016/j.ensm.2017.01.003>.

Curran, M.A. (1996) *Environmental life-cycle assessment*. New York, NY: McGraw-Hill (Environmental engineering books).

Dell, R.M. *et al.* (2001) *Understanding Batteries*. The Royal Society of Chemistry. Available at: <https://doi.org/10.1039/9781847552228>.

Deng, Y. *et al.* (2017) ‘Life cycle assessment of lithium sulfur battery for electric vehicles’, *Journal of Power Sources*, 343, pp. 284–295. Available at: <https://doi.org/10.1016/j.jpowsour.2017.01.036>.

Ellingsen, L.A. *et al.* (2014) ‘Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack’, *Journal of Industrial Ecology*, 18(1), pp. 113–124. Available at: <https://doi.org/10.1111/jiec.12072>.

Erakca, M. *et al.* (2023) ‘Closing gaps in LCA of lithium-ion batteries: LCA of lab-scale cell production with new primary data’, *Journal of Cleaner Production*, 384, p. 135510. Available at: <https://doi.org/10.1016/j.jclepro.2022.135510>.

EUR-Lex (2023) ‘Regulation (EU) 2023/1542 concerning batteries and waste batteries’. European Parliament and of the Council. Available at: <https://eur-lex.europa.eu/EN/legal-content/summary/sustainability-rules-for-batteries-and-waste-batteries.html?fromSummary=20>.

European Commission (2020) ‘European Commission’. Available at: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020PC0798>.

European Commission (2021) ‘European Commission’. Available at: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0098>.

Guillaume Ragonnaud (2025) ‘Powering the EU’s future: Strengthening the battery industry’. EPRS | European Parliamentary Research Service.

Hawley, W.B. and Li, J. (2019) ‘Electrode manufacturing for lithium-ion batteries—Analysis of current and next generation processing’, *Journal of Energy Storage*, 25, p. 100862. Available at: <https://doi.org/10.1016/j.est.2019.100862>.

Hervy, M. *et al.* (2015) ‘Life cycle assessment of nanocellulose-reinforced advanced fibre composites’, *Composites Science and Technology*, 118, pp. 154–162. Available at: <https://doi.org/10.1016/j.compscitech.2015.08.024>.

Huijbregts, M.A.J. *et al.* (2017) ‘ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level’, *The International Journal of Life Cycle Assessment*, 22(2), pp. 138–147. Available at: <https://doi.org/10.1007/s11367-016-1246-y>.

Hwang, J.-Y., Myung, S.-T. and Sun, Y.-K. (2017) ‘Sodium-ion batteries: present and future’, *Chemical Society Reviews*, 46(12), pp. 3529–3614. Available at: <https://doi.org/10.1039/C6CS00776G>.

‘ISO 14040:2006, Environmental management — Life cycle assessment — Principles and framework’ (2006). Environmental management — Life cycle assessment — Principles and framework.

‘ISO 14044, Environmental Management Life Cycle Assessment Requirements and Guidelines’ (2006). International Standards Organization: Brussels, Belgium.

Janek, J. and Zeier, W.G. (2016) ‘A solid future for battery development’, *Nature Energy*, 1(9), p. 16141. Available at: <https://doi.org/10.1038/nenergy.2016.141>.

Jung, E. and DeBrouckere, L. (2024) ‘Understanding Basics of Electric Vehicle Batteries.’

Kamali, A.K. (2023) ‘Prospective Life Cycle Assessment of Two Supercapacitor Architectures’. Available at: <https://doi.org/10.1021/acssuschemeng.3c04007>.

Kermani, G. and Sahraei, E. (2017) ‘Review: Characterization and Modeling of the Mechanical Properties of Lithium-Ion Batteries’, *Energies*, 10(11), p. 1730. Available at: <https://doi.org/10.3390/en10111730>.

Kwade, A. *et al.* (2018) ‘Current status and challenges for automotive battery production technologies’, *Nature Energy*, 3(4), pp. 290–300. Available at: <https://doi.org/10.1038/s41560-018-0130-3>.

- Larrabide, A., Rey, I. and Lizundia, E. (2022) 'Environmental Impact Assessment of Solid Polymer Electrolytes for Solid-State Lithium Batteries', *Advanced Energy and Sustainability Research*, 3(10), p. 2200079. Available at: <https://doi.org/10.1002/aesr.202200079>.
- Lee, J. *et al.* (2011) 'Metal–Air Batteries with High Energy Density: Li–Air versus Zn–Air', *Advanced Energy Materials*, 1(1), pp. 34–50. Available at: <https://doi.org/10.1002/aenm.201000010>.
- Lu, Y. and Zhu, T. (2024) 'Status and prospects of lithium iron phosphate manufacturing in the lithium battery industry', *MRS Communications*, 14(5), pp. 888–899. Available at: <https://doi.org/10.1557/s43579-024-00644-2>.
- Majeau-Bettez, G., Hawkins, T.R. and Strømman, A.H. (2011a) 'Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-In Hybrid and Battery Electric Vehicles', *Environmental Science & Technology*, 45(10), pp. 4548–4554. Available at: <https://doi.org/10.1021/es103607c>.
- Majeau-Bettez, G., Hawkins, T.R. and Strømman, A.H. (2011b) 'Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-In Hybrid and Battery Electric Vehicles', *Environmental Science & Technology*, 45(10), pp. 4548–4554. Available at: <https://doi.org/10.1021/es103607c>.
- Majeau-Bettez, G., Strømman, A.H. and Hertwich, E.G. (2011) 'Evaluation of Process- and Input–Output-based Life Cycle Inventory Data with Regard to Truncation and Aggregation Issues', *Environmental Science & Technology*, 45(23), pp. 10170–10177. Available at: <https://doi.org/10.1021/es201308x>.
- Mizushima, K. *et al.* (1980) 'Li_xCoO₂ (0 < x < 1): A new cathode material for batteries of high energy density', *Materials Research Bulletin*, 15(6), pp. 783–789. Available at: [https://doi.org/10.1016/0025-5408\(80\)90012-4](https://doi.org/10.1016/0025-5408(80)90012-4).
- Murashko, K. (2016) 'Thermal modelling of commercial lithium-ion batteries'. Unpublished. Available at: <https://doi.org/10.13140/RG.2.1.3930.0723>.
- Myung, S.-T. *et al.* (2017) 'Nickel-Rich Layered Cathode Materials for Automotive Lithium-Ion Batteries: Achievements and Perspectives', *ACS Energy Letters*, 2(1), pp. 196–223. Available at: <https://doi.org/10.1021/acseenergylett.6b00594>.
- Neale, A.R. *et al.* (2017) 'Physical–Chemical Characterization of Binary Mixtures of 1-Butyl-1-methylpyrrolidinium Bis{(trifluoromethyl)sulfonyl}imide and Aliphatic Nitrile Solvents as Potential Electrolytes for Electrochemical Energy Storage Applications', *Journal of Chemical & Engineering Data*, 62(1), pp. 376–390. Available at: <https://doi.org/10.1021/acs.jced.6b00718>.
- Nitta, N. *et al.* (2015) 'Li-ion battery materials: present and future', *Materials Today*, 18(5), pp. 252–264. Available at: <https://doi.org/10.1016/j.mattod.2014.10.040>.
- Padhi, A.K., Nanjundaswamy, K.S. and Goodenough, J.B. (1997) 'Phospho-olivines as Positive-Electrode Materials for Rechargeable Lithium Batteries', *Journal of The Electrochemical Society*, 144(4), pp. 1188–1194. Available at: <https://doi.org/10.1149/1.1837571>.

Paul, D. *et al.* (2024) 'Life cycle assessment of lithium-based batteries: Review of sustainability dimensions', *Renewable and Sustainable Energy Reviews*, 206, p. 114860. Available at: <https://doi.org/10.1016/j.rser.2024.114860>.

Pavlov (2011) *Lead-Acid Batteries: Science and Technology*. Elsevier. Available at: <https://doi.org/10.1016/C2009-0-16975-1>.

'Position Paper on content requirements of the EU Battery Passport' (2023).

Rajić, M., Stanković, Z. and Milosavljević, P. (2024) 'Life Cycle Impact Assessment: A review of tools for sustainable energy management', in *SimTerm Proceedings 2024 - zbornik radova. SimTerm Proceedings 2024, Niš, Serbia, October 22-25.2024.*, University of Niš, Faculty of Mechanical Engineering, Niš, pp. 450–463. Available at: <https://doi.org/10.5937/SimTerm24450R>.

Rebitzer, G. *et al.* (2004) 'Life cycle assessment', *Environment International*, 30(5), pp. 701–720. Available at: <https://doi.org/10.1016/j.envint.2003.11.005>.

Roesch, A., Sala, S. and Jungbluth, N. (2020) 'Normalization and weighting: the open challenge in LCA', *The International Journal of Life Cycle Assessment*, 25(9), pp. 1859–1865. Available at: <https://doi.org/10.1007/s11367-020-01790-0>.

Royston, M.G. (1979) *Pollution Prevention Pays*. Kent: Elsevier Science.

Saavedra-Rubio, K. *et al.* (2022) 'Stepwise guidance for data collection in the life cycle inventory (LCI) phase: Building technology-related LCI blocks', *Journal of Cleaner Production*, 366, p. 132903. Available at: <https://doi.org/10.1016/j.jclepro.2022.132903>.

Skyllas-Kazacos, M. *et al.* (2011) 'Progress in Flow Battery Research and Development', *Journal of The Electrochemical Society*, 158(8), p. R55. Available at: <https://doi.org/10.1149/1.3599565>.

Smith, L. *et al.* (2021) 'The Role of Cycle Life on the Environmental Impact of $\text{Li}_{6.4}\text{La}_3\text{Zr}_{1.4}\text{Ta}_{0.6}\text{O}_{12}$ based Solid-State Batteries', *Advanced Sustainable Systems*, 5(2), p. 2000241. Available at: <https://doi.org/10.1002/adsu.202000241>.

Song, Y. and Fu, Z. (2024) 'Mini-Review on the Preparation of Iron Phosphate for Batteries', *Energy & Fuels*, 38(19), pp. 18194–18207. Available at: <https://doi.org/10.1021/acs.energyfuels.4c02533>.

Soufi, C., Mesbahi, T. and Samet, A. (2023) 'Digital Battery Passport as an Enabler of Environmental Impact Assessment in Electric Vehicle Applications', in *2023 IEEE Vehicle Power and Propulsion Conference (VPPC). 2023 IEEE Vehicle Power and Propulsion Conference (VPPC)*, Milan, Italy: IEEE, pp. 1–6. Available at: <https://doi.org/10.1109/VPPC60535.2023.10403389>.

Sterner, M. (2009) 'Limiting global warming by transforming energy systems Bioenergy and renewable power methane in integrated 100% renewable energy systems'. Available at: <https://doi.org/10.17170/KOBRA-202210176997>.

Tillman, A.-M. *et al.* (1994) ‘Choice of system boundaries in life cycle assessment’, *Journal of Cleaner Production*, 2(1), pp. 21–29. Available at: [https://doi.org/10.1016/0959-6526\(94\)90021-3](https://doi.org/10.1016/0959-6526(94)90021-3).

Wenzel, H., Petersen, C. and Hansen, K. (2004) *The Product, Functional Unit and Reference Flows in LCA*.

Wernet, G. *et al.* (2016) ‘The ecoinvent database version 3 (part I): overview and methodology’, *The International Journal of Life Cycle Assessment*, 21(9), pp. 1218–1230. Available at: <https://doi.org/10.1007/s11367-016-1087-8>.

World Economic Forum (2019) *A Vision for a Sustainable Battery Value Chain in 2030 Unlocking the Full Potential to Power Sustainable Development and Climate Change Mitigation*.

Yan, M. *et al.* (2020) ‘Biodegradable Bacterial Cellulose-Supported Quasi-Solid Electrolyte for Lithium Batteries’, *ACS Applied Materials & Interfaces*, 12(12), pp. 13950–13958. Available at: <https://doi.org/10.1021/acsami.0c00621>.

Yang, Z., Huang, H. and Lin, F. (2022) ‘Sustainable Electric Vehicle Batteries for a Sustainable World: Perspectives on Battery Cathodes, Environment, Supply Chain, Manufacturing, Life Cycle, and Policy’, *Advanced Energy Materials*, 12(26), p. 2200383. Available at: <https://doi.org/10.1002/aenm.202200383>.

Zhao, T. *et al.* (2024) ‘An overview on the life cycle of lithium iron phosphate: synthesis, modification, application, and recycling’, *Chemical Engineering Journal*, 485, p. 149923. Available at: <https://doi.org/10.1016/j.cej.2024.149923>.

Zschornak, M. *et al.* (2018) ‘Fundamental principles of battery design’, *Physical Sciences Reviews*, 3(11). Available at: <https://doi.org/10.1515/psr-2017-0111>.

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LIST OF ABBREVIATIONS

BC	Bacterial Cellulose
CF	Carbon footprint
CZ	Czech Republic (in SimaPro)
DBP	Digital Battery Passport
DPP	Digital Product Passport
EIA	Environmental impact assessment
E-LCA	Environmental Life Cycle Assessment
EOL	End-of-life
EU	European Union
EV	Electric vehicle
FU	Functional Unit
GLO	Global (in SimaPro)
GWP	Global warming potential
kg CO ₂ eq	Kilograms of carbon dioxide equivalents
kWh	Kilowatt hour
LIBs	Lithium-ion batteries
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCSA	Life Cycle Sustainability Assessment
LiFePO ₄ , LFP	Lithium Iron Phosphate
NMC	Nickel Manganese Cobalt
NMP	N-methyl-2-pyrrolidone
RER	Europe (in SimaPro)
RoW	Rest of the world
SDGs	Sustainable Development Goals

SHDB	Social Hotspot Database
S-LCA	Social Life Cycle Assessment
C-BC	Commercial bacterial cellulose
L-BC	Laboratory produced bacterial cellulose
Li-metal	Lithium metal
LFP, LiFePO ₄	Lithium iron phosphate
LiTFSI	Lithium bis (trifluoromethane)sulfonylimide
TBU	Tomas Bata University
PEO	Polyethylene oxide
PEO/BC	Polyethylene oxide/Bacterial Cellulose
PVDF	Polyvinylidene fluoride
IL	Ionic liquid
DI	Deionized Water
Wh	Watt hour

