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Strategies and Tools for Sustainable Battery Lifecycle Management: A Multidisciplinary Approach Beyond European Regulatory Compliance

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A mia madre

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Abstract

The large-scale adoption of batteries has become a cornerstone of the energy transition, supporting the widespread deployment of electric vehicles (EVs) and renewable energy integration, improving grid stability and efficiency. However, their lifecycle presents significant environmental and strategic challenges, including the critical raw material supply chain, the high environmental impact of production, and inefficiencies in recycling processes. To address these issues and aligned with the ambitious 2030 targets set by the European Union, this research moves beyond mere regulatory compliance with traceability requirements by developing a comprehensive framework for sustainable battery lifecycle management. The proposed framework is structured around two main, synergistic and complementary tools. The first tool enables immediate predictive analysis of environmental impacts based on the selected battery design by integrating the Battery Performance and Cost Model (BatPaC) with LCA indicators. The second tool facilitates real-world battery data tracking in a fully decentralized blockchain system, incorporating automated transactions via smart contracts to ensure secure and transparent traceability. The framework is structured around the Deming cycle, fostering continuous improvement of both battery design and the associated tools. The approach has been validated through a case study on a lithium iron phosphate (LFP) EV battery, demonstrating its feasibility in guiding design choices through impact assessments and enabling secure data tracking, while ensuring regulatory compliance. This research provides a strategic contribution to the field by offering a practical solution that bridges the gap between regulatory frameworks and industrial implementation, paving the way for a more effective and responsible approach to battery lifecycle management.

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List of Abbreviations

1,4-DCB-Eq	1,4-Dichlorobenzene Equivalent
ABI	Application Binary Interface
AAS	Asset Administration Shell
Ag	Silver
AI	Artificial Intelligence
Al	Aluminium
API	Application Programming Interface
ANL	Argonne National Laboratory
ANP	Analytic Network Process
As	Arsenic
BatPaC	Battery Performance and Cost Model
BMS	Battery Management System
BM	Black Mass
BOD	Biological Oxygen Demand
Ca	Calcium
CAPEX	Capital Expanditure
Cd	Cadmium
CEAP	Circular Economy Action Plan
CF	Carbon Footprint
CFC-11-Eq	Chlorofluorocarbon-11 Equivalent
CLP	Classification, Labelling, and Packaging Regulation
CO	Critical Raw Materials Act Objective
Co	Cobalt
CO_2-Eq	Carbon Dioxide Equivalent
Co-60-Eq	Cobalt-60 Equivalent
COD	Chemical Oxygen Demand
Cu	Copper
CRM	Critical Raw Materials
CRMA	Critical Raw Materials Act
CSS	Cascading Style Sheets
DM	Data Model

DPP	Digital Product Passport
EB	Ethereum Blockchain
ECHA	European Chemicals Agency
EOFP	Photochemical Oxidant Formation for Ecosystems
ESG	Environmental, Social, and Governance
ESPR	Eco-Design for Sustainable Products Regulation
EU	European Union
EV	Electric Vehicle
EVB	Electric Vehicle Battery
EVM	Ethereum Virtual Machine
F	Fluorine
FDM	Foundational Data Model
Fe	Iron
FEP	Freshwater Eutrophication Potential
FETP	Freshwater Ecotoxicity Potential
FFP	Fossil Fuel Potential
FSI	Fragile States Index
FU	Functional Unit
GHS	UN Globally Harmonized System
GPP	Green Public Procurement
GUI	Graphical User Interface
GUIA	Graphical User Interface Desktop Application
GWP100	Global Warming Potential 100 years
HHI	Herfindahl-Hirschman Index
HTML	HyperText Markup Language
HTP	Human Toxicity Potential
HOFP	Photochemical Oxidant Formation for Human Health
HP	Hazardous Property
HSC	Hazardous Substance Classification
ICT	Information and Communication Technology
IRP	Ionising Radiation Potential
IT	Information Technology

ITI	IT Infrastructure
K	Potassium
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSDM	Life Cycle Standard Data Model
LCT	Lifecycle Thinking
Li	Lithium
LIB	Lithium-Ion Battery
LFP	Lithium Iron Phosphate
LOP	Agricultural Land Occupation Potential
MEP	Marine Eutrophication Potential
METP	Marine Ecotoxicity Potential
ML	Machine Learning
Mg	Magnesium
Mn	Manganese
N-Eq	Nitrogen Equivalent
Na	Sodium
Ni	Nickel
Ni-Cd	Nickel-Cadmium
Ni-MH	Nickel-Metal Hydride
NMC	Nickel Manganese Cobalt
NO_x-Eq	Nitrogen Oxides Equivalent
ODP	Ozone Depletion Potential
P	Phosphorus
Pb	Lead
PDCA	Plan-Do-Check-Act
PEFCR	Product Environmental Footprint Category Rules
PM2.5-Eq	Particulate Matter 2.5 Equivalent
PMFP	Particulate Matter Formation Potential
PWF	Python Web Flask
QR	Quick Response (Code)

REACH	Registration, Evaluation, Authorization and restriction of chemicals Reg.
SCS	Smart Contract Solidity
SHA-256	Secure Hash Algorithm 256-bit
Si	Silicon
Sn	Tin
SO_2-Eq	Sulfur Dioxide Equivalent
SOA	State of Art
SOC	State of Charge
SOH	State of Health
SOP	Surplus Ore Potential
SQL	Structured Query Language
STOT	Specific Target Organ Toxicity
TAP	Terrestrial Acidification Potential
TETP	Terrestrial Ecotoxicity Potential
TFEU	Treaty on the Functioning of the European Union
Ti	Titanium
TMS	Thermal Management System
UN	United Nations
UPS	Uninterruptible Power Supply
WCP	Water Consumption Potential
XML	Extensible Markup Language
Zn	Zinc
Zn/Mn	Zinc/manganese
Zn/Mn Mn-C	Zinc/manganese carbon

Chapter 1.

Introduction

The onset of the 21st century has marked a pivotal shift in global energy dynamics, with batteries emerging as central to the green transition. This evolution reflects not only advancements in technology but also a profound transformation in how energy is produced, stored, and consumed worldwide. Once conceived as auxiliary technological innovations, batteries have now become indispensable enablers of modern life—powering devices, driving the electric vehicle (EV) revolution, and supporting the integration of renewable energy sources. As their role expands, it becomes imperative to understand their far-reaching implications, particularly in terms of sustainability and resource management. In the following chapter, the approach taken to address this complex and critical issue will be outlined, starting with an overview of the growing role of batteries worldwide and, in detail, in Europe. Subsequently, the general approach adopted in this research to contribute to the sustainability objectives set by the European Union (EU) will be presented. Finally, the structure of this thesis will be explained to guide the reader through the key themes and findings discussed in this work.

1.1. The Growing Role of Batteries

Lithium-ion batteries (LIBs), first commercialized in 1991 after decades of research [1], have become the cornerstone of this transformation, dominating the global market alongside lead (Pb)–acid and nickel (Ni)-based batteries. Together, these technologies account for nearly 95% of the market [2], which is projected to grow from $85 billion in 2022 to over $400 billion by 2030, reflecting the increasing adoption of EVs and renewable energy systems, both integral to reducing carbon emissions and achieving climate neutrality. In particular, the demand for LIBs is projected to grow at an annual rate of 33% and is expected to continue dominating the market through 2030, where EV batteries will account for 91,5% of the total demand [3]. In Europe, this growing demand has spurred the establishment of key players in the battery manufacturing sector. Currently, there are seven main manufacturers of LIBs in Europe, with the top three by production capacity being LG Chem in Poland (32 GWh), Samsung SDI in Hungary (20 GWh), and Northvolt in Sweden (16 GWh). By 2030, it is estimated that 27 battery factories will be operational, spanning 18 different companies, with 8 of these facilities built through agreements with major car manufacturers such as Volkswagen, Stellantis, Nissan, Volvo, and Renault [4].

However, Europe faces several critical challenges in developing a robust battery supply chain [5]. The Europe is highly dependent on imported raw materials for battery production, with key extractions concentrated in a few countries, notably China and the Democratic Republic of Congo. This concentration exposes Europe to significant geopolitical risks and global price fluctuations. Furthermore, China dominates graphite and battery production, making Europe vulnerable to export bans or sanctions [6]. Additionally, Europe currently lacks sufficient recycling capacity to address the growing volumes of end-of-life batteries. Although pioneering facilities exist in countries like France, Germany, and Belgium [7], projections indicate that internal European recycling will meet only a small fraction of the total demand for critical materials by 2030 [8]. More broadly, batteries cannot become one of the central pillars of the green revolution unless their sustainability is clearly defined and achieved. Currently, the entire lifecycle of batteries is affected by critical issues that undermine the sustainability definition outlined above [9]. Upstream processes, such as the extraction of raw materials and battery manufacturing—responsible for approximately 64% of the Carbon Footprint (CF) of the entire lifecycle—are highly polluting [10]. Downstream processes remain inefficient, with current recycling methods achieving low recovery rates for materials and circular business models being rarely adopted [11]. Additionally, from a technical standpoint, batteries require improvements in performance, safety, control, and design to facilitate their end-of-life management [12].

In response to these challenges, the EU has adopted a comprehensive regulatory approach. The Battery Regulation (EU) 2023/1542, introduced under the Circular Economy Action Plan (CEAP), represents the first European legislation to adopt a lifecycle perspective. Key aspects of this regulation include stringent recycling targets, mandatory CF declarations, and the implementation of a digital product passport (DPP) for enhanced traceability. These measures aim to ensure sustainability across the battery lifecycle, reduce environmental impacts, and foster a circular economy [13]. Complementing this regulation are initiatives such as the Critical Raw Materials Act (CRMA) [14] and the Eco-design for Sustainable Products Regulation (ESPR), which emphasize resilience, material efficiency, and the integration of eco-design principles [15]. Central to these initiatives is eco-design, as it allows for reducing the environmental impact of a product by integrating sustainability into the design phase. Eco-design promotes cradle-to-cradle thinking, optimizing all stages of the lifecycle—from design and manufacturing to end-of-life management [16]. Achieving these goals requires comprehensive and reliable data, and the most important tool in this process is Life Cycle Assessment (LCA). LCA is a standardized methodology that identifies environmental hotspots throughout the lifecycle, enabling targeted interventions to improve sustainability. By leveraging LCA during the design phase [17], manufacturers can systematically identify opportunities to reduce the energy intensity associated with the manufacturing process, which currently ranges between 60–394 kg CO_2-eq/kWh [18]. Furthermore, LCA enables the evaluation of alternative design solutions that integrate a combination of circular strategies. These strategies include extending the operational lifespan of batteries, facilitating second-life applications, and improving recycling efficiency [19].

The global battery market is in a phase of rapid expansion, becoming an increasingly influential factor in shaping global economic and energy systems. As Europe positions itself as a leader in sustainable battery production, the role of batteries in driving the green transition becomes ever more critical. Addressing current sustainability challenges while fostering innovation in eco-design and lifecycle management will ensure batteries contribute to a cleaner, more sustainable energy future.

1.2. Research Objectives

The general objective of this research is to contribute to achieving the ambitious sustainability goals set by the European Union, not only through top-down alignment with regulatory frameworks but also by adopting a bottom-up approach that extends beyond compliance . This approach is embodied in a unified framework consisting of a suite of synergistic tools and methodologies designed to empower battery manufacturers and stakeholders across the entire value chain. The framework aims not only to facilitate compliance with EU regulations but also to deliver tangible benefits for operational efficiency, innovation, and competitiveness. It addresses a critical gap: while the EU has established an intricate and robust regulatory framework, it does not currently provide adequate tools to support stakeholders in effectively achieving the ambitious targets it has set. The framework is based on the principle of continuous improvement, acknowledging the rapidly evolving nature of battery technology, market trends, and geopolitical dynamics that characterize the sector. It seeks to provide stakeholders with adaptable solutions that remain relevant in the face of such changes, ensuring a dynamic and resilient approach to sustainability. The complexity of this objective arises from the multifaceted challenges characterizing the battery lifecycle, from raw material extraction to end-of-life management. Batteries are at the heart of the green transition, yet their environmental footprint and resource requirements remain significant obstacles to their sustainable deployment. This research addresses these challenges by proposing an integrated framework that supports stakeholders in effectively navigating regulatory demands while optimizing their processes and outcomes. This framework builds on the premise that achieving sustainability in the battery lifecycle requires the integration of multiple tools and methodologies to support decision-making at various levels. Central to this approach is the development of a suite of complementary elements that enable battery manufacturers and stakeholders to adopt a lifecycle thinking (LCT) paradigm. This paradigm shifts the focus beyond internal processes, considering the entire product lifecycle—from design and production to reuse, recycling, and disposal—ensuring that environmental and economic considerations are embedded at every stage. One of the key innovations of this research lies in its holistic perspective, which integrates advanced modeling tools, such as Battery Performance and Cost Model (BatPaC) for predictive lifecycle analysis, and real-time data tracking enabled by the DPP. By doing so, the framework bridges the gap between theoretical sustainability principles and the practical needs of the industry. It offers stakeholders actionable insights to improve battery design, production efficiency, and sustainability performance, ultimately contributing to the realization of circular business models. This research also acknowledges the importance of collaboration across the value chain. By fostering transparency and facilitating data sharing, the framework ensures that all stakeholders, from designers to recyclers, have access to the information needed to align their activities with broader sustainability goals. This collaborative approach enables the identification of synergies and the resolution of inefficiencies, thus amplifying the impact of individual efforts. In practical terms, the implementation of this framework is expected to generate significant benefits. These include reduced environmental impacts, enhanced resource efficiency, and improved regulatory compliance, as well as economic advantages for companies adopting circular strategies. The ultimate goal is to demonstrate that sustainability and profitability are not mutually exclusive but can be mutually reinforcing, provided that the right tools and approaches are employed. By addressing the interconnected challenges of sustainability, compliance, and operational efficiency, this research aims to position European battery manufacturers as global leaders in sustainable innovation. The proposed unified framework, grounded in continuous improvement, represents a significant step forward in bridging the gap between the EU's ambitious regulatory objectives and the practical realities of achieving them within a complex and dynamic industrial landscape.

To address the general objective, this research is structured around three key technical objectives. The first technical objective is to establish the structural foundation of the framework, defining the methodologies, procedures, and constraints that govern its operation. This structure serves as the guiding architecture for the tools that will compose the framework, ensuring their complementarity, compatibility, and alignment with legislative, industrial, and scientific requirements. The goal is to create a coherent system where each tool operates within a well-defined set of parameters, contributing effectively to the overarching objectives of sustainability and lifecycle optimization. To achieve this, the framework incorporates a systematic approach based on the Deming cycle (Plan-Do-Check-Act), which ensures iterative improvements and adaptability over time. This cyclical methodology allows the tools and processes within the framework to evolve in response to advancements in technology, changes in regulatory requirements, and shifting market dynamics. By embedding this principle, the framework facilitates continuous enrichment of the data collected, analyzed, and organized, ensuring that stakeholders have access to increasingly robust and actionable insights. Additionally, the framework establishes constraints and standard practices that enable the seamless integration of its components, fostering interoperability and collaboration across the value chain. This structured approach ensures compliance with EU regulations, such as Battery Regulation 2023/1542, while addressing gaps in lifecycle traceability, eco-design, and end-of-life management. It also provides the flexibility needed to adapt to various battery chemistries, configurations, and industrial contexts. This foundational objective is critical for aligning the tools within the framework and ensuring they collectively address the multifaceted challenges of battery lifecycle management. By clearly defining the methodologies, procedures, and constraints, the framework is equipped to guide the development of practical solutions that enhance sustainability, operational efficiency, and regulatory compliance.

The second technical objective is the creation of a tool designed to facilitate eco-design by integrating predictive environmental analyses. A key principle in achieving this objective has been to avoid creating a tool from scratch, instead leveraging the outputs of existing design software widely available on the market. Specifically, BatPaC was selected for its simplicity—being developed in Excel by Argonne National Laboratory (ANL)—and for the depth of data it provides. This richness of data has enabled the creation of a comprehensive inventory for conducting LCA. Additionally, BatPaC offers a user-friendly approach, utilizing an input system tailored to the specific needs of users, making it accessible to a wide range of stakeholders. To enhance its functionality, additional modules have been developed to allow for immediate LCA execution, directly integrating the outputs of BatPaC into an environmental impact analysis framework. These modules streamline the process by automatically mapping BatPaC-generated data to LCA inventories, significantly reducing the time and expertise required to perform detailed assessments. This integration ensures that manufacturers can quickly evaluate the environmental footprint of different design configurations, providing actionable insights to optimize material selection, energy consumption, and overall lifecycle sustainability. The utility of these added modules lies in their ability to bridge the gap between design and environmental evaluation, allowing users to seamlessly transition from predictive modeling to comprehensive impact analysis. By enabling real-time assessments during the design phase, the tool empowers stakeholders to identify and address sustainability hotspots early in the development process, aligning their decisions with both regulatory requirements and circular economy principles. Furthermore, the enhanced tool supports iterative design improvements, facilitating dynamic feedback loops where environmental insights guide refinements in battery configurations. This capability ensures that the eco-design process is not only efficient but also adaptable to evolving technological advancements and market demands.

The third technical objective is the creation of a tool to enable real-time data collection and sharing across the battery value chain. To achieve this, a DPP has been selected as the core solution, reflecting its central role in the Battery Regulation 2023/1542 and the ESPR. However, while the concept of the DPP is outlined in these regulatory frameworks, neither its infrastructure nor its methodology is explicitly described. Therefore, this research aims to develop a complete and scalable system tailored to European supply chains, providing a solution that goes beyond the current state of the art (SOA) and integrates seamlessly into the broader framework proposed in this work. In designing the DPP, emphasis has been placed on leveraging cutting-edge technologies to address key challenges in traceability, security, accessibility, and cost-efficiency. Python and blockchain have been utilized to create a decentralized structure, enhancing data integrity and security while maintaining accessibility for stakeholders across the value chain. The implementation of smart contracts further streamlines interactions, automating processes and reducing costs associated with data management. This approach not only ensures compliance with regulatory requirements but also addresses the practical needs of European stakeholders by providing a robust, low-cost, and scalable infrastructure. The DPP serves as a critical enabler for real-time lifecycle tracking, supporting stakeholders in meeting regulatory targets and contributing to the realization of a circular economy.

1.3. Research Approach

To achieve the challenging objectives outlined, a structured research approach was established at the onset of this work. The primary goal was to organize all planned activities into a clear and coherent workflow, ensuring the production of results that are both scientifically innovative and valuable for the industrial sector. The flowchart in Figure 1 provides an overview of the activities conducted over the 3-year research period and highlights their interconnections.

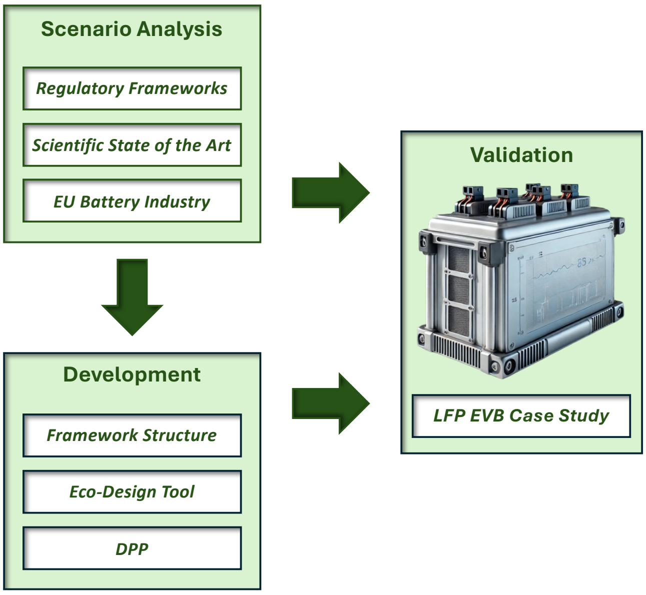

Figure 1 - Methodology

The first phase was dedicated to the *Scenario Analysis* to establish the context for this research. The initial activity focused on analyzing the normative and legislative frameworks, especially European Union (EU) regulations such as the Battery Regulation 2023/1542, ESPR, and CRMA (see details in Section 2). This was essential to identify both opportunities and limitations, ensuring the development activities were correctly aligned. Concurrently, a comprehensive review of the scientific SOA allowed for the identification of the main actors and methods in lifecycle management, eco-design, LCA, and DPPs, as well as gaps that required further exploration (see details in Section 2). Finally, an analysis of the current SOA and future projections of the European battery industry up to 2030 was conducted, leveraging available data and ad hoc forecasting studies. This analysis aimed to identify the strategic directions necessary for Europe to remain competitive in the coming years. The focus was on understanding the key drivers for growth, such as technological innovation, supply chain resilience, and sustainability initiatives, and aligning these with broader EU objectives. This phase was critical for defining the primary lifecycle phases influencing battery sustainability and for outlining the methodologies and tools needed to address them, along with potential use scenarios in industrial contexts (see details in Section 3).

The second phase involved the *Development* of methodologies and tools within the proposed framework. Continuous updates to the scientific and technological SOA ensured a high degree of innovation in the results. This phase was structured around the development of the three technical objectives described in the preceding chapter: (i) structuring the framework (Section 4); (ii) integrating BatPaC and LCA (Section 5); and (iii) designing and implementing the DPP (Section 6). Preliminary validation activities were conducted throughout this phase to verify the practical utility and integration of the tools.

The final phase was focused on the *Validation* of the proposed framework through its application in real-world case studies (see details in Section 7). The framework was validated using a lithium iron phosphate (LFP) battery case study, simulating its lifecycle from production to end-of-life. Data collected through the DPP and BatPaC modules were utilized to perform a comprehensive LCA of a LFP battery, simulating its lifecycle from production to end-of-life. This activity provided insights into the interaction between predictive modeling and real-time data tracking within the proposed framework, ensuring its alignment with sustainability objectives and industrial needs. The validation phase confirmed the feasibility and applicability of the proposed framework, demonstrating its potential to support sustainability goals while aligning with industrial requirements.

1.4. Thesis Overview

Following this introduction, the remainder of the thesis is structured as follows. *Chapter 2* provides the research background, outlining the foundational aspects of battery technology. It begins with an overview of the structure, components, and functionalities of batteries, followed by a detailed analysis of the lifecycle phases and associated challenges. Special attention is given to the regulatory landscape, with a focus on the Battery Regulation 2023/1542 and related European frameworks, highlighting gaps and opportunities. Furthermore, the SOA in eco-design, LCA, and traceability methods is reviewed, providing the basis for the proposed framework. The chapter concludes by identifying the main research gaps and framing the research questions addressed in this work. *Chapter 3* discusses the strategic pathways to meet European regulatory targets. This chapter first presents the methodological approach adopted for data collection and analysis, which forms the basis for identifying strategies. It then discusses the key strategies necessary to align the battery value chain with the EU's 2030 objectives. Specific scenarios and regulatory needs, such as managing the Black Mass (BM) issue, are explored. *Chapter 4* introduces the framework for sustainable battery lifecycle management. It details the overarching framework structure, explaining how it integrates tools and methodologies to address the challenges identified in the earlier chapters. The workflow of the framework is described, showing how data and processes interact to enable sustainability across the value chain. *Chapter 5* focuses on the integration of BatPaC with LCA indicators for the eco-design of EV batteries. It explains the predictive capabilities of BatPaC and its adaptation to incorporate LCA metrics. The chapter includes comparative analyses with LCA results from the literature that demonstrate the effectiveness of this integration in enhancing the environmental and economic assessment of battery configurations. *Chapter 6* discusses the design and implementation of the DPP. The DPP system and its main component, such as data model (DM), and IT infrastructure (ITI) are presented, along with a methodology for populating parameters that ensures compatibility with various industries, thereby granting it a universal character for enabling traceability and compliance in the battery and other key industries. *Chapter 7* applies the proposed framework to a case study involving a LFP EV battery. The chapter illustrates how the framework and its tools were implemented in an industrial context. Real-world challenges and outcomes are discussed, providing valuable insights into the practical utility of the proposed approach. Finally, *Chapter 8* presents the discussion and concluding remarks. The key findings are summarized, and the implications for industry and regulation are explored. The chapter also outlines potential future developments to further enhance the proposed framework and its applications.

Chapter 2.

Research Background

This chapter provides a comprehensive review of the existing literature, forming the foundation for the development of the modules and overall structure of the proposed framework, as outlined in the technical objectives of Chapter 1. By examining key areas such as battery design, LCA, eco-design principles, and traceability mechanisms, the review identifies critical gaps and opportunities, orienting the proposed framework in this doctoral research.

2.1. Overview of Batteries: Definition, Structure, and Applications

A battery is an electrochemical energy vector that stores chemical energy and converts it into electrical energy through controlled redox reactions. This fundamental process enables batteries to serve as a versatile and reliable power source for a wide range of applications. Batteries are broadly categorized into two types: primary (non-rechargeable) and secondary (rechargeable). Primary batteries are designed for single-use applications, as their chemical reactions are irreversible. Secondary batteries, on the other hand, rely on reversible chemical processes, allowing multiple cycles of energy storage and release, which makes them ideal for applications requiring long-term energy sustainability [20].

The cell is the fundamental building block of a battery, responsible for converting chemical energy into electrical energy (Figure 2). It consists of four main components: the anode, cathode, electrolyte, and separator. The anode, typically made from lithium (Li)-rich materials or graphite, serves as the source of electrons during discharge as it undergoes oxidation. The cathode, composed of active materials such as metal oxides, accepts electrons from the external circuit during reduction. The electrolyte, which can be a liquid, gel, or solid, facilitates the movement of ions between the anode and cathode, completing the internal circuit necessary for electrochemical reactions. Lastly, the separator, a porous, non-conductive membrane, prevents direct contact between the anode and cathode to avoid short circuits while allowing ions to pass through its pores. Supporting the anode and cathode are current collectors, typically made of copper (Cu) for the anode and aluminum for the cathode, which conduct electrons to and from the external circuit, ensuring efficient energy transfer. The transformation of chemical energy into electrical energy occurs through redox reactions. During discharge, Li ions move from the anode to the cathode through the electrolyte, while electrons travel along an external circuit, generating electric current. During charging, this process is reversed, with ions and electrons returning to their original positions. A collection of cells forms a module, a structure designed to house the cells securely and optimize their performance. Modules include structural elements such as aluminum casings, electronic components for cell monitoring, insulating layers to prevent heat dissipation, and plastic materials to ensure mechanical stability. Multiple modules are assembled into a battery pack, a more complex structure that incorporates additional components to ensure safety, thermal management, and operational efficiency. Among these components, the cooling system (coolant) is essential for maintaining uniform temperature and preventing overheating. Thermal insulation reduces heat transfer between modules, while the Battery Management System (BMS) monitors and regulates key parameters such as voltage, current, and temperature to ensure safe and efficient operation. Battery packs also include protective casings, typically made of aluminum or steel, to provide structural integrity and impact resistance [21].

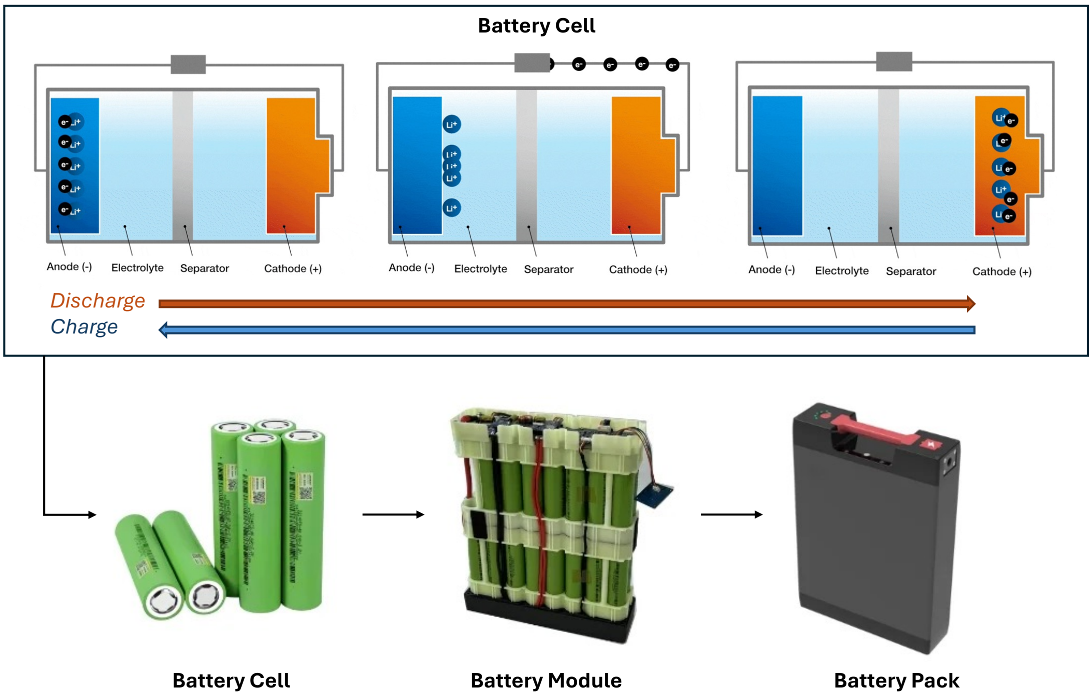

Figure 2 - Battery Composition

The performance and applicability of a battery are determined by several key characteristics and parameters, which provide a comprehensive understanding of its capabilities and limitations. These parameters are not only essential for evaluating the battery's functionality but are also integral to tools like BatPaC for design and analysis.

- *Specific Energy (Wh/kg)*: This parameter represents the energy a battery can store relative to its weight. It is a critical factor for applications requiring lightweight solutions, such as EVs and portable devices. Higher specific energy translates to longer operating times without increasing battery weight.
- *Energy Density (Wh/L)*: Energy density refers to the amount of energy stored per unit volume. It is particularly relevant for applications where space constraints are significant, such as consumer electronics and aerospace systems.
- *Specific Power (W/kg)*: This measures the battery's ability to deliver power quickly, relative to its weight. High specific power is essential for applications requiring rapid acceleration, such as EVs.
- *Cycle Life*: This parameter indicates the number of charge and discharge cycles a battery can undergo before its capacity degrades significantly. A long cycle life is critical for reducing the total cost of ownership and environmental impact in applications like grid storage and EVs.
- *State of Charge (SOC)*: SOC represents the current energy level of the battery as a percentage of its maximum capacity. It is a dynamic parameter used to monitor and manage battery performance in real-time.
- *State of Health (SOH)*: SOH evaluates the overall condition of a battery relative to its initial performance. It provides insights into capacity fade, internal resistance, and overall efficiency, serving as a critical indicator for maintenance and replacement planning.
- *C-Rate*: The C-rate defines the rate at which a battery is charged or discharged relative to its nominal capacity. For example, a 1C rate means the battery is charged or discharged in one hour, while a 2C rate implies the process is completed in half an hour. This parameter is vital for understanding a battery's performance under different operating conditions.

- Nominal Voltage: The nominal voltage is the average voltage a battery provides during normal operation. It depends on the electrochemical system and is a key factor in determining compatibility with specific devices and systems.
- Internal Resistance: Internal resistance impacts the efficiency and heat generation of a battery. Lower internal resistance allows for better energy delivery and reduces energy losses during operation.
- Self-Discharge Rate: This parameter quantifies the rate at which a battery loses charge when not in use. Low self-discharge rates are desirable for long-term energy storage applications.
- Temperature Range: The operational temperature range defines the conditions under which a battery can function effectively without degradation. It is a critical factor for applications in extreme environments, such as automotive and aerospace [22]–[24].

The configuration of the battery (Figure 3) also plays a critical role in influencing these parameters, particularly when cells are arranged in series or parallel. When cells are connected in series, the overall voltage of the battery increases as the individual cell voltages are summed, while the capacity remains constant. This configuration is ideal for applications requiring higher operating voltages, such as electric motors. Conversely, when cells are connected in parallel, the capacity is increased as the individual capacities are summed, while the voltage remains the same. This setup is beneficial for applications demanding extended operating times, such as energy storage systems [25].

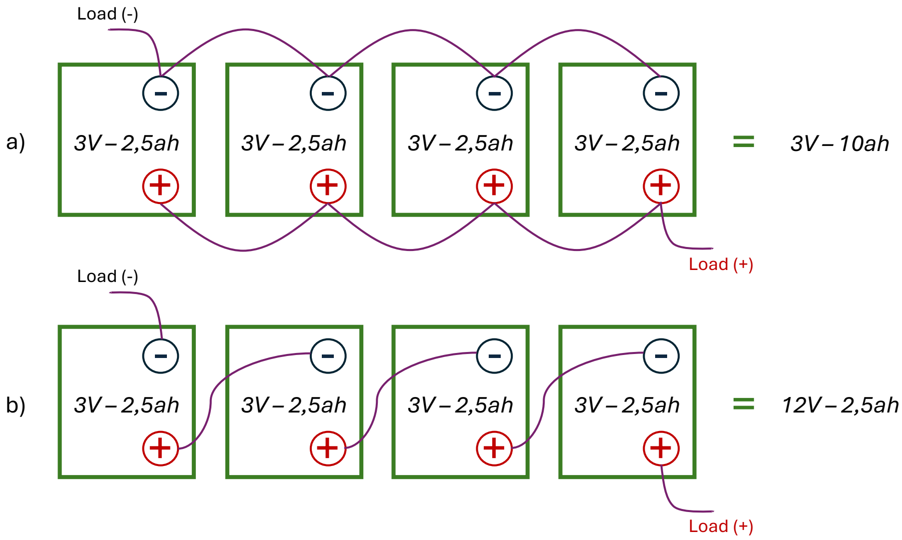

Figure 3 – Parallel (a) and Series (b) Battery Configurations

Batteries come in various types, each designed to meet specific energy storage needs, and their characteristics define their suitability for different applications. Among the most prominent are Li-ion, Pb-acid, Ni-based, metal-air, and zinc-based batteries. LIBs are among the most widely used due to their high energy density, lightweight design, and long cycle life. They can store between 150–200 Wh/kg, with some advanced configurations reaching up to 300 Wh/kg. These batteries operate efficiently across a wide temperature range (-20°C to 55°C) and are highly scalable. However, they require sophisticated BMS to ensure safety and prevent overcharge damage. Their cost is relatively high, largely due to the materials used in the cathode, such as lithium-cobalt-oxide. These features make LIBs ideal for portable electronics like smartphones and laptops, EVs, and renewable energy storage systems. Pb-acid batteries, while older in design, remain reliable and cost-effective for specific applications. Their moderate energy density and ability to deliver high discharge currents make them well-suited for automotive starter batteries and backup power systems, such as those used in telecommunications and uninterruptible power supplies (UPS). However, their shorter cycle life and lower specific energy limit their application in modern, high-demand scenarios. Ni-based batteries, including nickel-cadmium (Ni-Cd) and nickel-metal hydride (Ni-MH), are known for their durability and reliability in extreme conditions. While their energy density is lower compared to Li-ion batteries, they offer long cycle life and consistent performance. Ni-Cd batteries, however, suffer from the memory effect, a drawback mitigated in Ni-MH technology. These batteries find applications in emergency lighting, portable tools, and certain aviation systems. Metal-air batteries represent a promising frontier in energy storage, with theoretical energy densities far surpassing conventional battery technologies— Li-air systems, for example, can theoretically achieve up to 13 kWh/kg. These batteries are lightweight because they use oxygen from the atmosphere as the cathodic active material. Despite their potential, many metal-air systems remain in the experimental stage. When fully realized, they could revolutionize long-range EVs and stationary energy storage for renewable energy integration. Zinc-based batteries offer a safer and more environmentally friendly alternative, using aqueous electrolytes to minimize risk. While their energy density is lower than that of Li-ion batteries, they provide significant cost advantages and are increasingly explored for grid-scale energy storage. Primary zinc-air batteries are commonly used in small electronics such as hearing aids, while secondary versions, like rechargeable zinc-ion and zinc-air batteries, are gaining traction in backup power systems and grid energy storage applications [26].

2.2. Battery Lifecycle Phases: Processes and Challenges

The lifecycle of a battery encompasses multiple interconnected phases, each presenting unique processes and challenges that impact its overall sustainability, as highlighted in Section 1.1. Understanding these phases is essential for devising effective strategies to enhance sustainability while meeting the growing demand for energy storage solutions. The following Table 1 organizes the lifecycle into five main phases—Extraction, Manufacturing, Use, Second-Life, and Recycling—each accompanied by specific challenges and potential solutions. The challenges reflect the current limitations and inefficiencies identified through research and practice, while the proposed solutions address these issues by leveraging technological advancements, and innovative approaches.

Table 1 - Key Challenges and Proposed Solutions Across Battery Lifecycle Phases

Phase	Specific Problem	Potential Solutions
Extraction Phase	High environmental and social impacts (habitat destruction, human rights concerns)	Minimum environmental and social standards for suppliers (Responsible Sourcing) [27]–[29]
	Inefficient resource extraction methods for lithium (Li), cobalt Co), and nickel (Ni)	Adoption of advanced extraction techniques (e.g., adsorption-electrochemical methods) [27], [30]
	Over-reliance on limited geographic regions for critical materials	Investments in geothermal extraction projects for Li [30]
		Predictive models for managing Co and Ni demand and supply [31], [32]
		Improved waste management in hydrometallurgical processes [31]–[33]
Manufacturing Phase	Energy-intensive processes contributing to significant carbon emissions	Energy-efficient manufacturing processes and waste minimization [34], [35]
	Dependency on non-sustainable materials for key components	Use of eco-friendly materials (e.g., silicon (Si)-based anodes) [36], [37]
	Limited application of design principles to improve recyclability	Incorporation of eco-design principles to enhance modularity and disassembly [38]
		Renewable energy integration in production to reduce CF [39], [40]
Use Phase	Degradation due to non-optimized operational conditions (e.g., temperature, charging rates)	Battery Management Systems (BMS) to extend lifespan and optimize performance [9], [41]
	Lack of awareness and best practices in eco-friendly usage	Promoting eco-charging practices to mitigate capacity loss [41], [42]

	Poor communication and data sharing among value chain stakeholders	Enhancing collaboration with shared data platforms across stakeholders [43], [44]
Second-Life Phase	Complexity in assessing residual capacity and condition for secondary applications	Precise degradation models for accurate assessment of second-life potential [45], [46]
	High costs and inefficiencies in disassembly and refurbishing	Development of cost-effective refurbishing techniques and standards [47], [48]
	Lack of well-defined business models for repurposed batteries	Establishing circular business models for second-life usage [48], [49]
Recycling Phase	Low recovery rates for critical materials like Li	Advanced recycling technologies integrating Artificial Intelligence (AI) and machine learning (ML) [50], [51]
	Inefficiency in combining metallurgical and hydrometallurgical processes	Hybrid recycling approaches to maximize material recovery [52]
	Battery designs not optimized for recycling	Designing batteries for disassembly and efficient recycling [53], [54]

Many of the solutions proposed across the various phases of the battery lifecycle can be traced back to overarching strategies that enhance sustainability and operational efficiency. Among these, eco-design emerges as a cornerstone, emphasizing the need to integrate sustainability principles during the design phase [38]. This includes optimizing battery architecture for easier disassembly [53], improving recyclability [54], and reducing material and energy intensity [36], [37]. Another critical factor is the availability of comprehensive data and databases. Accurate and accessible data is critical for tracking materials, performance metrics, and end-of-life management [43], [44]. Unified databases enable real-time data sharing, providing stakeholders with the information needed to make informed decisions and optimize processes across the value chain. However, the availability of data alone is insufficient without the active involvement of stakeholders across the value chain. Manufacturers, suppliers, recyclers, and regulatory bodies must collaborate to address inefficiencies, ensure data integrity, and align efforts with sustainability goals. Finally, the integration of cutting-edge technologies such as AI-based predictive analytics and blockchain for secure data sharing enhances the effectiveness of these strategies [50], [51].

These tools not only address existing inefficiencies but also provide solutions that adapt to the evolving needs of the energy storage sector, supporting a dynamic and forward-looking approach.

2.3. EU Strategies and Regulations

The European Green Deal, introduced by the European Commission in December 2019, represents a transformative strategy aimed at ensuring the sustainability of the European Union's economy while addressing pressing issues such as climate change and environmental degradation [8]. The overarching goal of this ambitious plan is to achieve climate neutrality by 2050, positioning Europe as the first continent to reach this milestone. The Green Deal represents a vast plan of reforms that covers all major areas of the economy and society, comprising concrete actions such as clean energy and emissions reduction, sustainable industry and the promotion of a circular economy, sustainable mobility and low-emission transport infrastructure, biodiversity and sustainable agriculture, and the elimination of all forms of pollution. To achieve this objective, the Green Deal outlines a series of interconnected targets spanning various sectors. These include increasing the EU's climate ambition by reducing greenhouse gas emissions by at least 55% by 2030, transitioning to renewable energy sources to ensure clean and affordable energy, and promoting sustainable practices in construction and transportation to reduce environmental footprints. A particularly critical component of the Green Deal is the initiative to mobilize industry towards a clean and circular economy. This initiative emphasizes the need for a systemic shift from linear production models, characterized by resource extraction, use, and disposal, to circular models that prioritize sustainability, material reuse, and waste minimization. This approach recognizes the significant role of industrial processes in contributing to environmental impacts and seeks to transform them into drivers of sustainability. The transition to circularity underpins the principles of resource efficiency, extended product life cycles, and enhanced waste management. Building on this vision, the CEAP was launched in March 2020 as a cornerstone of the Green Deal [55]. The CEAP identifies seven key value chains deemed critical for achieving the transition to a circular economy due to their high levels of resource consumption and waste generation. These value chains include electronics and ICT, batteries and vehicles, packaging, plastics, textiles, construction and buildings, and food, water, and nutrients. The CEAP specifically aims to establish minimum sustainability requirements for products, improve waste management systems, and promote the use of secondary raw materials. Additionally, it focuses on empowering consumers by providing clear information about product sustainability and promoting schemes such as the "right to repair." Furthermore, it emphasizes the importance of sustainable product design to enhance resource efficiency and minimize waste. The CEAP also highlights the importance of adopting digital solutions to improve traceability and efficiency in value chains, thereby fostering the transition to a circular economy. These goals are designed to facilitate the transition to a more sustainable and circular economy while fostering economic competitiveness across the EU. This framework establishes the foundation for subsequent legislative actions, such as the EU Battery Regulation, which is directly aligned with the goals of the Green Deal and CEAP.

The Battery Regulation (EU) 2023/1542, introduced in July 2023, represents the first initiative under the CEAP [13]. Replacing the Directive 2006/66/EC, it goes beyond its predecessor by adopting a regulatory framework instead of a directive and by encompassing all types of batteries, not just portable ones. This regulation is rooted in Article 114 of the Treaty on the Functioning of the European Union (TFEU), which focuses on the establishment and functioning of the internal market, rather than Article 175, which pertains to environmental protection. Therefore, the Battery Regulation sets three main objectives:

- To ensure the creation of an internal and sustainable market for batteries.
- To promote the circularity of batteries and the materials that constitute them.
- To reduce the environmental and social impacts associated with battery lifecycle management.

Additionally, this regulation is the first to set specific objectives and strategies tailored to each phase of a product's lifecycle. Table 2 provides a concise summary of the regulation's measures and objectives (BOs).

Table 2 - Battery Regulation Objectives (BOs)

Objective	Target
BO1: Responsible sourcing of raw materials	Implementation of due diligence for risk management in supply chains, ensuring socially and environmentally responsible sourcing.
BO2: Reduction of CF	By 2024: Mandatory CF declaration for batteries. Future: Compliance with specific reduction targets (details in future regulations)
BO3: Recycled content requirements for new batteries	By 2030: 12% Co, 4% Li, 4% Ni from recycled sources. By 2035: 20% Co, 10% Li, 12% Ni from recycled sources.
BO4: Performance and durability standards	Define minimum performance and durability criteria for batteries used in specific applications.
BO5: Design requirements for battery disassembly	Facilitate disassembly, reuse, and recycling.
BO6: Battery labeling and digital product passport (DPP)	By 2026: Mandatory labeling with performance, safety, and environmental impact information; by 2027: DPP with detailed data.
BO7: Battery collection targets	Portable batteries: 45% by 2023, 63% by 2027, 73% by 2030. LMT batteries: 51% by 2028, 61% by 2031. EV and industrial batteries: 100% collection obligation.
BO8: Recycling efficiency targets	By 2025: 75% for lead (Pb)-acid, 65% for Li, 80% for Ni-cadmium (Cd), 50% for other batteries. By 2030: 80% for lead-acid, 70% for Li.
BO9: Material recovery targets	By 2027: 90% for Co, Copper (Cu), Ni, Pb; 50% for Li. By 2031: 95% for Co, Cu, Ni, Pb; 80% for Li.
B10: End-of-life battery treatment	Ensure removal and proper recycling of end-of-life batteries.

Of particular interest is the adoption of the DPP, which mandates the use of a data carrier, such as a Quick Response (QR) code, and the inclusion of certain mandatory parameters. However, the regulation leaves significant flexibility in its implementation. Detailed discussions of the DPP are provided in Chapter 6, particularly in Section 6.2.

It also aligns closely with two significant regulatory frameworks: the ESPR and the CRMA. The ESPR (EU) 2024/1781, introduced on July 18, 2024 [15], replaces the Eco-Design Directive 2009/125/EC. As a key initiative of the CEAP, it establishes eco-design requirements for all physical goods (excluding food, feed, and military products) with a focus on durability and repairability, energy efficiency, hazardous substance reduction, Green Public Procurement (GPP), and a ban on the destruction of unsold goods. The ESPR also introduces the DPP as a tool for product traceability, including data on product composition, durability and repairability, environmental footprint, disposal guidelines, and energy efficiency. The DPP must be digitally accessible, with a suggested use of QR codes, and Annex 3 specifies mandatory parameters such as unique product identifiers, trade codes, compliance documentation, manuals and instructions, manufacturer and importer details, product specifications, and voluntary eco-labeling.

The CRMA (EU) 2024/1252, introduced on May 23, 2024, is another cornerstone initiative of the CEAP [14]. It aims to ensure a secure and sustainable supply of critical raw materials (CRM) essential for supporting strategic industries and advancing the EU's green transition. Detailed objectives and measures of the CRMA (COs) will be summarized in the following Table 3.

Table 3 - CRMA Objectives (COs)

Objective	Targets
CO1: Secure Supply of Strategic Raw Materials	By 2030, the EU aims to extract at least 10% of its annual consumption of strategic raw materials from within the Union.
CO2: Increase Processing Capacity	Ensure the EU processes at least 40% of its annual consumption of strategic raw materials by 2030.
CO3: Boost Recycling Capacity	Achieve a recycling capacity within the EU that meets at least 25% of its annual consumption of strategic raw materials by 2030.

CO4: Diversify Import Sources	Limit reliance on any single non-EU country to supply no more than 65% of the Union's annual consumption of any strategic raw material by 2030.
CO5: Sustainable and Strategic Projects	Promote projects that contribute to the EU's raw materials supply, ensuring they meet high environmental and social standards.
CO6: Monitor Supply Risks	Implement mechanisms to monitor and reduce supply risks, ensuring a stable supply of critical raw materials (CRMs).
CO7: Environmental Footprint	Require an environmental footprint declaration for all CRMs on the market.
CO8: Encourage Resource Efficiency	Promote technological advancements and efficiency to manage and moderate the increase in raw material consumption.

A critical challenge relevant to the objectives of the CRMA is the management of BM, a fine, powdery byproduct of battery recycling composed of a complex mixture of valuable metals, including Li, Co, Ni, and manganese (Mn). Generated through mechanical and thermal processes during the early stages of end-of-life battery treatment, BM poses significant regulatory and economic challenges. Despite containing hazardous materials, BM is not classified as hazardous waste under current European regulations. As a result, it is often exported to countries with advanced recycling infrastructures, such as China, at low prices. This practice undermines the EU's economic and environmental goals by forfeiting valuable materials that could be recovered domestically and by hindering the CRMA's aim of reducing dependency on external supply chains for CRMs.

The detailed European context for 2030 and potential strategies for achieving its objectives will be examined further in Chapter 3.

2.4. Eco-design Frameworks

Eco-design represents a critical branch of design that embeds sustainability as a cornerstone in product development. Among its most comprehensive definitions, Charter and Tischner describe it as: "*Sustainable solutions refer to products, services, hybrids, or system alterations aimed at minimizing adverse sustainability impacts and maximizing positive effects, encompassing economic, environmental, social, and ethical dimensions, throughout and beyond the life cycle of existing products or solutions, while meeting acceptable societal demands and needs*" [56].

In the specific domain of eco-design for batteries, the development of frameworks has been notably limited due to a combination of intricate challenges. The first obstacle lies in the complexity of battery systems, which encompass a wide array of components and multiple life cycle stages, making it particularly arduous to comprehensively identify and mitigate environmental impacts [9]. Secondly, swift technological advancements in battery development necessitate regular updates to existing frameworks, ensuring their continued relevance and accuracy [57]. Thirdly, the lack of consensus on metrics and indicators for evaluating environmental impacts poses a significant barrier to standardizing frameworks, leaving decision-makers to navigate an overwhelming array of parameters [58].

Notwithstanding these impediments, the literature has witnessed the emergence of various eco-design frameworks tailored for batteries, broadly categorized into two distinct types: comprehensive and partial frameworks. Comprehensive Frameworks strive to holistically encompass environmental impacts throughout the entire battery life cycle. These frameworks employ a comprehensive set of indicators, tools, and methodologies to enhance the effectiveness and efficiency of end-of-life processes. X. Zhang et al. [59] introduced a systematic framework for eco-designing chemical products, albeit with some uncertainties in problem-solving and a limited ability to delineate the interconnections between the three pillars of sustainability. Conversely, C. Zhang et al. [57] concentrated on Battery EVs (BEVs) by employing a life cycle simulation (LCS) model and parameterized inventory within a highly intricate framework that primarily optimizes design for environmental impacts while sidelining social and economic considerations. In contrast, Zwolinski & Tichkiewitch [58] developed an agile framework grounded in standardized methods for identifying Critical Project Life Cycle Parameters (CPLCPs), encompassing diverse facets, including economic considerations. A distinct framework, projected by Sansa et al. [60] embraced all three pillars of sustainability, incorporating fuzzy Analytic Network Process (ANP)-based multi-criteria decision-making. Their approach commences with constructing product design scenarios and comprehensively analyzing internal and external contexts and stakeholders. Partial frameworks, on the other hand, concentrate on specific life cycle phases, components, or impact categories. These frameworks often target facilitating battery assembly and disassembly [61], optimizing recycling processes [62], or enabling second-use applications [63]. While effective within their defined scope, partial frameworks lack the holistic perspective necessary for addressing the interconnected sustainability challenges of the battery life cycle. Developing a comprehensive eco-design framework tailored for batteries is essential to bridge the current gaps in sustainability and regulatory compliance. Such a framework must integrate legislative constraints, industrial capabilities, market trends, value chain requirements, and the anticipated end-of-life scenarios specific to various application domains. By adopting a collaborative and data-driven approach, leveraging insights across the value chain, and aligning with technological advancements, the proposed framework ensures flexibility and precision while balancing environmental, economic, and social considerations.

This doctoral research is dedicated to designing such a framework, placing eco-design at its core and addressing the multifaceted challenges posed by the rapidly evolving battery industry. The framework seeks to empower stakeholders with actionable tools and methodologies, fostering both sustainability and competitiveness.

2.5. Integrating LCA in Battery Design: Challenges and Opportunities

A critical component of combining sustainability into battery design is the application of LCA, which has emerged as the principal tool for eco-design. The Battery Regulation underscores the necessity of incorporating LCA, particularly during the design phase, by setting specific thresholds for the CF of battery production and encouraging the adoption of greener methods and materials. To develop more sustainable battery solutions, it is crucial to first evaluate the existing design tools and their limitations in incorporating life cycle considerations.

There are numerous software tools available for battery design, each offering various capabilities tailored to different aspects of battery development. Battery Design Studio is known for its comprehensive platform that supports cell and pack design, thermal management system (TMS), and system integration, making it a versatile tool for detailed battery modeling [68]. COMSOL Multiphysics provides a flexible simulation environment that can model a wide range of battery behaviors, including electrical, thermal, chemical, and mechanical effects, particularly useful for complex, coupled physics interactions [69]. JMAG specializes in electromagnetic and thermal analysis, making it ideal for scenarios where understanding magnetic field distribution and heat generation within battery components is critical [70]. ANSYS Fluent focuses on thermal analysis and fluid flow simulations, making it particularly effective for battery TMS and cooling system design, especially in large-scale applications like EVs [71]. GT-Suite offers a multidisciplinary simulation environment that supports system-level analysis, including interactions between battery cells, cooling systems, and control systems [70]. Simulink, integrated with MATLAB, excels in modeling battery behavior under various conditions, optimizing control algorithms, and reducing the need for physical prototypes through virtual testing [72]. Lastly, BatPaC, developed by ANL, is a widely used tool designed to estimate the performance and cost of EV batteries, providing a detailed breakdown of battery components and their associated costs, which can be easily adjusted to model various battery chemistries and configurations [73]. However, none of these tools inherently provide built-in functionalities for conducting LCA, which limits their effectiveness in eco-design.

The LCA is a robust analytical methodology standardized under the ISO 14040 and ISO 14044 standards [64], [65], widely recognized in environmental management systems. This method provides a holistic framework for evaluating the environmental impacts of a product, process, or service throughout its entire life cycle—from raw material extraction through processing, use, and disposal or recycling (cradle-to-grave approach). Guided by the afore-mentioned standards, LCA research is structured around four essential phases:

- *Goal and Scope Definition:* The initial phase of an LCA involves setting clear objectives for the analysis. It is crucial to define the functional unit (FU), which quantifies the performance of the product system for use as a reference and establish precise spatial and temporal boundaries. This phase ensures that the study is aligned with its intended purpose and contextual limits.
- *Life Cycle Inventory (LCI):* This phase constitutes the core of the LCA process. The system under analysis is broken down into its constituent unit processes. An input-output analysis is then conducted for each process to capture and categorize all relevant flows within the system boundaries. This stage is critical for collecting comprehensive data that forms the basis for the subsequent impact assessment.
- *Life Cycle Impact Assessment (LCIA):* In this step, the collected data from the LCI are translated into potential environmental impacts. This transformation is achieved through the application of specific impact assessment methodologies that utilize characterization and weighting factors. These methodologies help in delineating the impact of the system in both midpoint and endpoint categories, providing a clearer picture of environmental performance.
- *Results Interpretation:* The final phase involves a thorough analysis and critical review of the results obtained from the LCIA. This step is crucial for interpreting the data in the context of the defined goals and scope. It also includes a review of the LCA process and its outcomes, fostering

a better understanding of the system's environmental impacts and identifying opportunities for improvement.

Each of these phases is interconnected, forming a comprehensive framework that supports the detailed analysis of environmental impacts associated with any given product system. The LCA methodology faces significant challenges in the context of batteries due to the absence of standardization. For instance, Dolganova et al. [66] demonstrated that altering the FU in comparative analyses of batteries can yield vastly different results, increasing uncertainty in decision-making processes. In this regard, the Product Environmental Footprint Category Rules (PEFCR) for High Specific Energy Rechargeable Batteries for Mobile Applications provides the only EU-specific LCA standardization attempt for batteries. Published in February 2018 and valid until December 31, 2020, the PEFCR defined rules applicable to e-mobility batteries, Information and Communication Technology (ICT) devices (such as tablets, phones, and laptops), and cordless power tools. The FU was established as 1 kWh of total energy delivered over the battery's service life. This document also specified life cycle stages, mandatory impact categories, and reference flows, but its validity has since expired [67].

To address the inconsistencies, a solution must be embedded directly within design software that already possesses data which, if properly organized, could constitute an LCI. By integrating tools that analyze battery design solutions using a standardized FU, these systems could generate instantaneous LCAs, providing valuable insights during the design phase. A preliminary attempt was made by ANL with the development of EverBatt. This Excel-based tool, built on the BatPaC model, is designed to evaluate the environmental and economic impacts of battery recycling [74]. While it offers useful insights into the trade-offs between using recycled versus virgin materials, it does not provide a comprehensive LCA across all stages of the battery's life. Its focus on the recycling process and reliance on predefined environmental impact categories limits its applicability for battery eco-design purposes. Unlike a true cradle-to-grave. LCA, EverBatt's analysis is confined to specific modules, which may result in a fragmented understanding of the overall environmental impacts.

Moreover, the tool's customization options for LCA are restricted, making it less flexible for tailored environmental assessments compared to a fully integrated LCA tool.

Unlike the other design tools, which are based on proprietary software platforms, BatPaC is developed in Excel, making it more accessible for experimentation and customization, which is particularly advantageous for this study's integration with LCA methodologies. In this study a new tool with a more holistic approach, which leverages BatPaC-generated parameters to enable a complete and customizable LCA supporting comprehensive eco-design strategies, is presented.

2.6. Traceability in the Value Chain

Data plays a critical role in the battery value chain, serving as the foundation for informed decision-making and the continuous improvement of product quality, efficiency, and sustainability along the entire lifecycle. The availability and accessibility of accurate, timely data ensure transparency, enhance collaboration among stakeholders, and support compliance with regulatory requirements. By fostering traceability, stakeholders in the value chain can identify inefficiencies, mitigate risks, and develop targeted strategies to optimize performance and sustainability outcomes.

DPPs have the potential to overcome key barriers to circular product lifecycle information flows, in particular the batteries that are the first to be regulated by EU, such as those identified by Kurilova-Palisaitiene: lack of awareness, underdeveloped shared value systems, and limited data sharing due to competitive concerns [75]. The DPP is composed of two fundamental components, DM and ITI, that have different roles within the four main functions of the DPP: Data Collection, Curation, Sharing, and Utilization [76] (Table 4). The DM establishes a coherent structure for organizing and validating collected data. It ensures interoperability across systems and prepares the data for detailed analyses and reporting, enabling stakeholders to extract meaningful insights efficiently. The ITI leverages advanced technologies, such as IoT, to collect real-time data, stores it securely in cloud environments, and facilitates secure transfer through technologies like APIs and blockchain systems. It also provides user-friendly tools for data analysis and access, enabling seamless integration into decision-making processes.

Table 4 - The role of the Data Model (DM) and IT Infrastructure (ITI)

Component	Data Collection	Data Curation	Data Sharing	Data Utilization
DM	Defines a coherent structure for data.	Organizes and validates collected data.	Ensures interoperability across systems.	Prepares data for analyses and reporting.
ITI	Employs IoT to collect real-time data.	Stores data securely in cloud environments.	Uses APIs and blockchain for secure transfer.	Provides tools for intuitive access and analysis.

Currently, there are over 80 documented DPP initiatives [77], ranging from product-specific solutions like "EasyBat", which focuses on 6 battery parameters [78], to complex systems like "atma.io" and "CircThread", whose cover multiple sectors and their entire lifecycles [79]. However, many of these initiatives face challenges related to scalability, interoperability, and the adoption of decentralized technologies. These initiatives often adopt sector-specific or partially cover the lifecycle, while others remain at a conceptual stage. Moreover, none of the models fully leverage data to make them LCA-ready, which is essential for ensuring a comprehensive evaluation of environmental impacts.

In the realm of industrial applications, cases such as Madaster in the construction sector and OpenSC in the food industry serve as exemplars of DM efficacy within their specific domains. Nevertheless, these DMs demonstrate a disproportionate emphasis on certain aspects: Madaster predominantly addresses material characteristics [80], whereas OpenSC is focused on product origin and sustainability [81]. This represents a departure from a holistic lifecycle methodology, wherein equal consideration of all lifecycle stages is imperative. In the battery sector, the Global Battery Alliance's development of its own DPP leverages digital twin technology and processes data from various stakeholders in the value chain. While this data is standardized and analyzed to assess environmental, social, and governance (ESG) performance metrics for batteries [82], the DPP's current framework manifests substantial complexities. This includes intricate procedures for uploading data to the cloud, coupled with a latency in data processing. Furthermore, the DPP diverges from the stipulations of the EU Battery Regulation, implementing autonomous methodologies for result analysis, which encompasses factors such as greenhouse gas emissions, thereby deviating from both the EU regulatory framework and traditional LCA methodologies. The DPP predominantly prioritizes user information, delivering data in a standardized format rather than providing a bespoke approach to various value chain actors, thus lacking a personalized focus and a holistic lifecycle perspective. The heterogeneity of these tools highlights the lack of a standardized, universal, and adaptable DM. None of these models currently adopt a comprehensive lifecycle approach that could fully exploit inputs from the DMs to generate an LCI. This could significantly reduce the time and costs of LCA studies, improving their quality and marking a major step toward effectively integrating sustainability into product design and management. The structure proposed by Mandolini et al. [83], identified as "Life Cycle Standard Data Model" (LCSDM), demonstrates significant adaptability for various products and intricate scenarios. The LCSDM, conceptualized as a tree structure and technology-neutral framework, focuses on data standardization and LCT. However, the LCSDM, in its broad application, may not sufficiently accommodate the unique complexities and regulatory demands of diverse product categories. Indeed, a fundamental gap can be identified across various solutions, marked by the absence of a system capable of generating a DM from a given product. The adoption of a systematic approach, enabling developers to identify product parameters and develop an appropriate DM for different product categories, becomes imperative when considering the complexity and diverse regulatory requirements across sectors. Consequently, in the research, specifically within the module dedicated to the DPP, a product-specific decision-making framework is being proposed for the development of the DM for batteries. This framework is designed to address the shortcomings highlighted in this section, ensuring a tailored approach to meet the unique requirements of battery systems while leveraging the principles of DPP development.

Regarding ITI for DPPs, several approaches have been explored. Wiesner et al. [84] demonstrated how integrating the Asset Administration Shell (AAS) at the batch level could help connect older, legacy infrastructures with modern systems. Similarly, Koppelaar et al. [85] proposed an ITI AAS-based for the management of CRMs while Plociennik et al. [86] exploited AAS for managing post-end-of-life electronic waste and automated data acquisition. Further, Hulea et al. [87] tested a dual blockchain infrastructure for DPP management, utilizing cheqd.io for decentralized identification (DID) and implementing smart contracts on Hyperledger Fabric. Meanwhile, Nowacki et al. [88] proposed a multisectoral DPP framework incorporating IoT, Distributed Ledger Technologies (DLT) such as IOTA, and smart contracts. Despite progress, key challenges remain. Technologies like blockchain and the AAS face limitations in interoperability across different sectors and systems, as well as scalability issues due to growing data volumes and integration complexity. Blockchain, in particular, struggles with high costs and energy demands [89], while the AAS encounters challenges in managing extensive data and integrating seamlessly into legacy systems and proprietary technologies. Finally, ensuring user-friendly access to DPP data for stakeholders remains a significant hurdle, as current models lack tools to simplify data use and interpretation.

To address these challenges, the ITI developed in this study for deploying the DM within the DPP focuses on optimizing the use of blockchain technology to reduce costs and energy consumption, while ensuring scalability for large-scale applications. A fully decentralized ITI is proposed to guarantee interoperability across sectors, maintaining security and transparency. Additionally, the platform is designed to be accessible, with user-friendly tools that simplify data access and interpretation for all stakeholders, including manufacturers and recyclers. This approach aims to create a more inclusive and sustainable DPP system, effectively supporting the entire lifecycle of batteries.

Chapter 3.

Strategic Pathways to Meet European Regulatory Targets

The European Union's ambitious 2030 objectives for the battery sector require a comprehensive strategy to address critical challenges in resource availability, recycling efficiency, and geopolitical risks while ensuring alignment with environmental and circular economy goals. This chapter outlines the analytical groundwork and key findings that shaped the development of an integrated strategy to achieve these targets. The analysis builds upon extensive data collection from global and European sources, forecasting battery-related critical raw material (CRM) production, consumption, and recycling potential. By evaluating historical trends, material compositions, and future scenarios, it identifies significant gaps and opportunities in the EU's supply chain, including the role of recycling, domestic production, and import diversification. The findings highlight the necessity of innovative solutions, such as digital infrastructure developed in this research required to monitor, adapt, and align battery production with regulatory thresholds.

3.1. Literature Data Collection

The data collection process relied on international sources and industry reports. Historical data on the production and reserves of the selected CRMs for each country, spanning from 2019 to 2023, were extracted from various reports published by the United States Geological Survey (USGS) on Mineral Commodities. Table 5 provides a detailed summary of the considered data, including historical and forecasted series.

Table 5 - Historical data and 2030 projections for global and EU battery metrics.

Series	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
World (W) CRM Production, Reserves (t) [90]–[94]	Data from 2019 to 2023 for all the producer countries											
W Battery Demand Historical (GWh) [95], [96]	135	168	334	551	800							
W Battery Demand Estimated (GWh) [97]							1327			2208		3127
EU Battery Demand (GWh) [98]				150	195	260	370	410	480	610	800	1050
EU Battery Demand (t) [98]				833333	1083333	1444444	2055556	2277778	2666667	3388889	4444444	5833333
EU Battery Supply (GWh) [99]				71			520					713-1197
EU Recycling Capacity (GWh) [100]					10	10	30	60	90	120	130	140
EU Recycling Capacity (t) [100]					55556	55556	166667	333333	500000	666667	722222	777778
Market Share – LFP [98]				15%								35%
Market Share – NCA [98]				14%								7%
Market Share – NMC [98]				71%								26%
Market Share - Other Technologies [98]				0%								32%

Among the various estimates for global battery demand in 2030 available in the literature, the most conservative estimate was selected due to the current inability to accurately forecast the contribution of recycling and the management of secondary raw materials on a global scale. Consequently, it is assumed that the actual demand may be higher, with the shortfall expected to be addressed through future recycling efforts. Furthermore, it should be noted that both the EU battery demand and the EU recycling capacity are expressed in GWh in the referenced studies. To facilitate a more precise material flow analysis, these studies assume an average energy density of 180 Wh/kg. Consequently, the values have been converted and are also reported in tonnes to provide a more accurate representation of the material quantities involved. Table 6 details the average composition of different battery types, and Table 7 presents the average material recovery rates for various recycling technologies, as well as the projected market share of recycling technologies in Europe by 2030; these data are provided by the Polytechnic University of Turin [101].

Table 6 - Material recovery rates for battery recycling methods and EU market share by 2030.

Treatment	Share (2030)	Li	Co	Ni	Mn	Gr	Cu	Al
Pyrometallurgy	56%	0%	86%	98%	88%	0%	96%	99%
Hydrometallurgy	21%	95%	95%	97%	91%	0%	95%	71%
Pyro+Hydro	23%							

Table 7 - Composition percentages of key materials in different battery chemistries.

Composition	Li	Co	Ni	Mn	Gr	Cu	Al
LFP	1,4%	0,0%	0,0%	0,0%	16,6%	14,5%	7,5%
NCA	2,2%	2,8%	14,9%	0,0%	22,0%	16,9%	8,8%
NMC 111	2,7%	6,9%	6,9%	6,4%	19,0%	16,4%	8,2%
NMC 622	2,5%	3,8%	11,5%	3,6%	20,7%	16,8%	8,4%
NMC 811	2,4%	1,9%	14,9%	1,7%	20,6%	15,7%	8,0%

3.2. World Battery CRMs 2030 Forecasting

The production forecast of battery-related CRMs for 2030 on a global scale was calculated by correlating the historical production data of each CRM, from 2019 to 2023, with the global battery demand during the same period. This correlation was used to determine the weighting factor, denoted as β1, which defines the Compound Annual Growth Rate (CAGR) of production in alignment with the projected growth in battery demand by 2030 ($CAGR_{bd}$). The use of correlation as a weighting factor is based on the methodology discussed by Waller and Jones [102]. Additionally, a technological evolution factor (Tf) was incorporated into the model to reflect technological changes and shifts in battery chemistries, a concept adapted from the study by Feng et al. [103]. A secondary weighting factor, β2, was set as 1−correlation, representing the proportion of the CAGR influenced by the historical production trend of the CRM itself ($CAGR_{hp}$). The production forecast for each CRM and each producing country for each year from 2024 to 2030 was then estimated using the following formula, applicable when YearX > YearY:

$$Battery\ Production\ Year_X = Battery\ Production\ Year_Y \times \left[1 + (\beta 1 \times CAGR_{bd} \times Tf) + (\beta 2 \times CAGR_{hp}\right)^{(Year_X - Year_Y)}$$

The technological evolution factor was derived by analyzing the market share of different battery chemistries and their respective CRM compositions. This allowed for an estimation of the average CRM content in a representative battery in both 2022 and 2030, resulting in the determination of a specific growth rate (Tf) for each CRM, as detailed in Table 8. The term representative battery refers to an average battery composition derived from a weighted mean based on the market share of each battery chemistry type.

Table 8 - Average battery composition in a representative battery in 2022 and 2030.

Year	Li	Co	Ni	Mn	Gr	Cu	Al
2022	2,3%	3,4%	10,0%	2,8%	19,8%	16,1%	8,2%
2030	1,3%	1,3%	3,9%	1,0%	12,6%	10,5%	5,4%
Tf	0,931	0,887	0,890	0,882	0,945	0,948	0,949

For P, as it is a CRM used exclusively in LFP batteries, the CAGR of the market share for this battery type was applied, resulting in a Tf of 1,112. For Ti and Si, the average Tf of the other elements was used, which is 0,919. For each relationship between the historical production series of a given country and the global battery demand series, a regression analysis was conducted to assess the reliability of the model, using criteria of $R^2 > 0,7$ and P-Value < 0,05. This evaluation confirmed that the relationships for the major producers of each CRM met these thresholds, indicating strong model reliability.

Per each CRM, three additional factors were also considered: the Depletion Time (DT) using the 2030 production levels, the Herfindahl-Hirschman Index (HHI), and the Fragile States Index (FSI). The DT, by Schrijvers et al. [104], was calculated to estimate how long the remaining reserves of each CRM will last if production continues at the forecasted 2030 rate. The formula used for depletion time is:

$$Depletion\,Time\;(years) = \frac{Total\,Reserves_{2030}}{Production_{2030}}$$

The HHI was used to measure the concentration of CRM production across different countries. It is calculated as the sum of the squares of the market shares of all producing countries:

$$HHI = \sum_{i=1}^{n} s_i^2$$

Where s_i is the share of production for country i in relation to the total global production, and n is the number of producing countries. An HHI close to 1 indicates a high concentration of production in a few countries, implying higher supply risk [105].

To assess the geopolitical risk of CRM supply, the FSI was considered for the main producing countries. Published annually by The Fund for Peace, the FSI provides a composite measure of a country's vulnerability based on indicators such as political stability, economic pressure, and social cohesion [106]. For this analysis, the FSI of the country with the largest market share in 2023 and the projected largest market share in 2030 was used to understand potential differences over time. The most recent FSI report was utilized, and it was assumed that these values would remain constant through 2030. Starting with the production of CRMs, forecasts from 2023 to 2030 indicate substantial growth rates across various materials. This growth ranges from an annual increase of +18% for graphite, a key component of the anode, to +6% for Cu. Despite the anticipated decline in the market share of NMC batteries, both Co and Ni are expected to experience considerable growth, with overall increases of 199% and 147%, respectively, during the period. P presents a unique trend; historically, it has shown a negative CAGR of -1%. However, from 2024 onward, projections suggest a reversal, with an average annual growth rate of 8%, potentially reflecting the increased demand for LFP batteries, where P plays a crucial role.

The estimates for reserves indicate a variable depletion of resources over the analysis period. Notably, Co reserves are expected to deplete by 29% and Ni by 33% between 2023 and 2030. Depletion times vary significantly among the CRMs, with Ni and Co showing shorter depletion times of 10-11 years, suggesting a potential supply risk in the near future. On the other hand, materials like P exhibit much longer depletion times (195 years), indicating a more stable supply. Turning to the HHI, the situation in 2023 indicates that the CRMs with the highest market concentration are graphite and Co, with HHI values of 61% and 56%, respectively. According to the model, these concentrations are projected to exceed 70% by 2030, as will the HHI for Si. This suggests a trend toward an increasingly oligopolistic market structure for these materials, where production is dominated by a small number of countries, potentially leading to increased supply risks and market power for dominant producers. In contrast, the HHI for Li is expected to drop significantly from 31% to 9% by 2030, indicating a diversification of supply sources and a movement toward a more competitive market structure. This diversification could mitigate some supply chain risks and provide more stability for the Li market.

The geopolitical risk assessment based on the FSI indicates a generally worsening scenario, as the FSI scores of the current leading producers in 2023 are often better or at least comparable to those projected to be leaders by 2030. The Democratic Republic of Congo (DRC) presents the highest geopolitical risk, maintaining its position as the dominant producer of Co throughout the analysis period. Furthermore, by 2030, the DRC is projected to become the leading producer of Cu, surpassing

Chile, which currently has a relatively moderate to low geopolitical risk. China, with a medium-high FSI, currently leads the production of graphite, Ti, Al, and Si. It is also the largest producer of P in 2023. However, the model predicts that China will be overtaken by Morocco in phosphorus (P) production by 2030, which has a slightly higher FSI, thereby suggesting an increase in geopolitical risk for this material. In contrast, the outlook for Li is comparatively more favorable. Although the leading production shifts from Australia to Chile by 2030, resulting in a slight increase in geopolitical risk, the overall risk remains within a manageable range. The complete results are shown in Annex I.

3.3. EU Battery CRMs 2030 Forecasting

The material demand for batteries in the EU by 2030 has been estimated, taking into account the average material composition within representative batteries as specified in Table 8. Due to the absence of comprehensive data regarding the quantities of Ti and Si in batteries, the assessment focuses solely on the materials for which such data is available. Starting from this demand, several factors were considered:

- Battery Recycling Potential: This was calculated using the estimated EU recycling capacity, factoring in the types of recycling facilities and their material-specific recovery rates.
- Share of CRM Usage in the Battery Sector: The percentage of CRM usage specific to batteries was sourced from the Raw Materials Information System (RMIS) [107]. The share of CRM usage in other sectors was then determined as the remaining percentage (100% - battery share). Given the diversity of applications in these sectors, it was necessary to make assumptions about the proportion of CRM demand in these sectors that could be met through recycling.
- Total CRM Demand: This included both the quantity required for battery production and the estimated amounts needed by other sectors.
- Extraction Potential: This encompassed both existing extraction capabilities and newly discovered deposits. The data provided by USGS was used to estimate CRM supply. Li is the only

CRM requiring conversion to its lithium carbonate equivalent (LCE) using a factor of 5.32, as it is reported in its raw metal form [108]. Other CRMs are reported in forms directly applicable to battery production and, therefore, do not require conversion. The conversion for Li was applied exclusively to internal production and reserve data since the other figures were derived from the average battery composition, representing the actual quantities used.

Given that the battery demand in the EU stood at approximately 150 GWh in 2022 and recognizing that not all of these batteries will reach their end-of-life by 2030, the projected recycling capacity of 140 GWh for 2030 is expected to sufficiently handle the volume of batteries entering the recycling stream. However, as shown in Table 9, confining the analysis to the battery sector, the contribution of recycled materials to meeting the total demand remains limited. The analysis indicates that, for all the materials considered, over 66% of the demand must be met through the extraction and processing of primary raw materials, underscoring the significant reliance on primary resource production even with optimized recycling efforts.

Table 9 - EU battery sector CRMs 2030 demand, recycling contributions and required primary supply.

EU Demand 2030	Demand (t)	Recycled (t)	Supply Needed (t)	Supply Needed (%)
Li	75989	7532	68457	90,1%
Co	75133	23867	51266	68,2%
Ni	229192	76154	153038	66,8%
Mn	59150	19629	39521	66,8%
Graphite	733600	0	733600	100,0%
Cu	612267	121150	491117	80,2%
Al	313425	59342	254083	81,1%

To analyze potential shortages, several baseline data are necessary (Table 10). The first is the battery sector share, provided by the RMIS for specific materials such as Li, Co, Ni, and graphite, which batteries play a substantial role in driving overall demand. For other materials, which are broadly grouped under “electronics” or “other sectors” due to their diverse applications beyond batteries, a more conservative estimate of 15% has been selected as the reference share. The statistical model, while robust globally, shows limited applicability for Europe, proving functional mainly for

Co production in Turkey. Therefore, the following analysis focuses on both existing reserves and production data for 2023, as reported by the USGS report, as well as new discoveries across Europe for each CRM. Europe's known Li production is primarily located in Portugal. However, geothermal resources present a promising new source due to high Li concentrations found in regions such as Italy (Cesano, Nepi, Campi Flegrei), Germany (Upper Rhine Valley), France (Alsace), and Greece (the island of Milos). An analysis of the REFLECT H2020 project database [109], though not accounting for recent discoveries in Italy that may significantly increase these estimates, indicates that over 20.000 tons of metallic Li could potentially be sourced from geothermal sites with concentrations exceeding 125 mg/L, a threshold identified by Sanjuan to ensure economic feasibility [30]. This estimate translates to over 100.000 tons of LCE potentially obtainable from geothermal sources. However, one of the main challenges lies in the high capital expenditure (CAPEX) required for the installation of geothermal plants [110], necessitating an evaluation of the economic feasibility of solutions that combine power generation and Li extraction. Turning to Co, aside from the production occurring in Turkey, Europe contains approximately 1.342.649 tons of Co spread across 509 deposits in 25 countries. Nonetheless, most of these deposits are not currently commercially viable due to low Co grades and challenging geological conditions [111]. Consequently, these reserves are excluded from the scenarios considered in this study. Regarding Ni, New Caledonia, a French territory, has established production and reserves of Ni, offering a reliable European source that could help reduce dependence on non-EU suppliers. About Mn, Ukraine is the primary producer in Europe, but Romania, particularly the Bucovina region, has been identified as a potential secondary source to support future demand [112]. For graphite, the situation is more geographically distributed, with lasting production expected in Norway and Turkey. In contrast, Germany and Ukraine currently face complete depletion of their resources. Additionally, Greenland (a Danish territory) possesses significant reserves of high-grade graphite, making it a valuable asset for Europe, second only to Turkey's reserves in terms of potential exploitation [113]. For Cu, Poland is currently the leading producer in Europe. However, Serbia has recently discovered substantial Cu reserves, which significantly enhance its position in Europe's production landscape and reduce the region's reliance on imports [114]. P is currently produced in Finland and Turkey. However, the balance of production may soon shift as a recently discovered phosphate rock deposit in Norway is considered one of the largest of its kind. This deposit has the potential to position Europe as the world leader in P production, surpassing both Morocco and China [115]. For Ti, Al, and Si, Norway serves as the key hub of production for all three CRMs in Europe. Ukraine stands as the second-largest producer of titanium (Ti), while France and Iceland are notable secondary producers of silicon (Si).

Table 10 – Battery sector share, 2023 production and reserves, and potential additional sources.

CRM	Battery Sector Share	Production 2023	Reserves 2023	Notes and Discovered Reserves
Li	32,00%	380 (Portugal)	310000 (Portugal)	Geothermal - Potential production +20000 t/y
Co	40,00%	2800 (Turkey)	91000 (Turkey)	From model estimation 2030: Turkey - 8077 t/y, 53427 t reserves; Currently, unfeasible 1342649 t in 509 deposits
Ni	5,00%			New Caledonia (France territory) 230000 t/y, 7100000 t reserves
Mn	0,75%	320000 (Ukraine)	140000000 (Ukraine)	Romania - Potential production 45000 t/y, 1500000 t reserves
Graphite	13,00%	150 (Germany) 7200 (Norway) 2000 (Turkey) 2000 (Ukraine)	0 (Germany) 600000 (Norway) 6900000 (Turkey) 0 (Ukraine)	Greenland (Denmark territory) - 4710000 t reserves
Ti	0,15%	430000 (Norway) 110000 (Ukraine)	37000000 (Norway) 5900000 (Ukraine)	
Cu	4,35%	400000 (Poland)	34000000 (Poland)	Serbia - 450000 t/y, 20000000 t reserves
P	1,50%	950000 (Finland) 800000 (Turkey)	1000000000 (Finland) 71000000 (Turkey)	Norway - 70000000000 t reserves
Al	0,15%	1300000 (Norway)		
Si	2,25%	110000 (France) 60000 (Germany) 130000 (Iceland) 340000 (Norway) 50000 (Poland) 56000 (Spain) 2000 (Ukraine)		

Three scenarios were developed for the year 2030: Base, Optimistic, and Pessimistic. Each scenario varies the key parameters based on different assumptions:

- Base Scenario: The share of CRM usage in the battery sector remains constant at the latest values reported by RMIS. The recycling potential for the remaining CRM demand (from non-battery sectors) is assumed to meet 50% of their needs. Internal production grows according to the projected CAGR for 2023-2030, and 50% of newly discovered reserves or additional production is included.

- Best Scenario: Here, the CRM share for the battery sector increases by 40%, indicating a shift in market focus towards batteries. It is further assumed that 75% of CRM demand in other sectors is covered by recycling. Internal production is boosted by 40% above the CAGR estimate, and 100% of the newly discovered reserves or additional production is included.
- Worst Scenario: In this case, the CRM share for the battery sector decreases by 40%, suggesting reduced reliance on batteries compared to other sectors. Only 25% of CRM demand in other sectors is assumed to be met through recycling. Internal production growth is reduced by 40% below the CAGR, and only 25% of the new reserves are considered viable.

The analysis of the three scenarios reveals several critical insights into Europe's potential CRM supply landscape by 2030, which are further detailed in Annex II. In the Best Scenario, despite the utilization of newly discovered resources and optimized recycling efforts, Europe will still depend significantly on imports for certain CRMs. Specifically, Co (~83% shortage) and graphite (~62% shortage) remain critical weak points in the supply chain. This indicates that even with favorable conditions, domestic production and recycling alone will not suffice to meet the battery market's demands for these materials. In the Base Scenario, the situation deteriorates, with noticeable shortages across almost all key CRMs. Li, which showed no shortage in the best case, now faces a ~60% shortfall, while Co and graphite face even higher shortages of ~93% and ~95%, respectively. The mid scenario highlights the limitations of Europe's current production capacities and recycling infrastructure, suggesting increased dependency on external suppliers, particularly for Ni (~75% shortage), Co, and graphite. The Worst Scenario presents a stark outlook, where almost every CRM, faces more than a 90% shortage, including materials that showed relative sufficiency in the other scenarios, like Cu and Mn. This scenario assumes higher growth in other sectors, minimal recycling capability, and production challenges, resulting in Europe being almost entirely dependent on imports. While

Norway's newly discovered P reserves may help mitigate P shortages, this remains a rare exception in an otherwise dire supply picture.

3.4. Environmental Impacts Issues

Three simplified comparative LCAs were conducted to evaluate the environmental impacts of key elements associated with the battery life cycle. This analysis aimed to identify strategies for establishing a sustainable battery supply chain in Europe. These LCAs are termed "simplified" because the data were derived from secondary sources within the ecoinvent 3.10 database and are not specific to any particular battery type or scenario.

The assessments employed several midpoint indicators from the ReCiPe method, including: Terrestrial Acidification Potential (TAP)(kg SO_2-Eq); Global Warming Potential (GWP100)(kg CO_2-Eq); Freshwater Ecotoxicity Potential (FETP)(kg 1,4-DCB-Eq); Marine Ecotoxicity Potential (METP)(kg 1,4-DCB-Eq); Terrestrial Ecotoxicity Potential (TETP)(kg 1,4-DCB-Eq); Fossil Fuel Potential (FFP)(kg oil-Eq); Freshwater Eutrophication Potential (FEP)(kg P-Eq); Marine Eutrophication Potential (MEP)(kg N-Eq); Human Toxicity Potential (HTP, Carcinogenic)(kg 1,4-DCB-Eq); Human Toxicity Potential (HTP, Non-Carcinogenic)(kg 1,4-DCB-Eq); Ionising Radiation Potential (IRP)(kBq Co-60-Eq); Agricultural Land Occupation (LOP)($m^2 \cdot a$ crop-Eq); Surplus Ore Potential (SOP)(kg Cu-Eq); Ozone Depletion Potential (ODP, Infinite)(kg CFC-11-Eq); Particulate Matter Formation Potential (PMFP)(kg PM2.5-Eq); Photochemical Oxidant Formation Potential for Human Health (HOFP)(kg NOx-Eq); Photochemical Oxidant Formation Potential for Ecosystems (EOFP)(kg NOx-Eq); Water Consumption Potential (WCP)(m^3). For each LCA, a specific functional unit (FU), goal, and database activity item were identified. The three simplified LCAs conducted are as follows:

- *Battery Raw Materials.* This simplified LCA compares the environmental impact of extracting the CRMs identified in the geopolitical analysis. The "market for" activity items in the ecoinvent database were used, encompassing the average transportation of materials to production facilities. Although different battery types contain varying amounts of these materials, as shown in Table 5, the FU was set to 1 kg of material. This choice focuses on the extraction activities themselves to inform better strategies for a sustainable European supply chain. For Li, as described in Section 2.4, LCE was used. An in-depth comparison was also made between the impacts of LCE production from spodumene and those from brine, a topic of particular interest discussed in the results section.

- *EU Countries Energy Mix.* Due to the energy-intensive nature of battery production and the ongoing technological advancements aimed at improving efficiency, this LCA focused on the energy production mix in each European country to understand the current situation and inform differentiated strategies. The FU was defined as 1 kWh of medium voltage energy production, utilizing the "market for" activity items in the ecoinvent database.
- *Battery Recycling Treatment.* This LCA focuses on the environmental impacts of treating 1 kg of batteries (functional unit) through the primary recycling methods: pyrometallurgy and hydrometallurgy. To provide a more comprehensive assessment, the analysis was extended by incorporating net environmental savings associated with resource recovery for both pyrometallurgical and hydrometallurgical processes. These extended analyses utilized average battery compositions for the years 2023 and projected for 2030 to evaluate how changes in battery chemistry over time influence the environmental performance of each recycling method.

For LCAs 1 and 3, global (GLO) or Rest of the World (RoW) values were used, depending on availability, to obtain generalized results. In contrast, for LCA 2, country-specific data were employed to capture the diversity of energy mixes across Europe. Annex III provides the complete results of the three LCAs, while the following section discusses these outcomes in detail.

3.4.1. Environmental Impact Assessment of CRMs

Analyzing the environmental aspects of 1 kg of each CRM, it is evident that Co and Ni have the most significant overall impacts, followed by Ti, while Graphite is the least impactful (Figure 4). Co stands out as the most impactful CRM, leading in 12 of the 18 environmental categories. Its GWP is high at 48,5 kg CO_2-eq per kg, second only to TI, with a difference of just 3,9%. Co's TEP is particularly severe at 2.575,6 kg 1,4-DCB-eq per kg, reflecting the significant environmental and health risks associated with its extraction. Most of the world's Co supply comes from the DRC, where unsafe mining practices result in water and soil contamination and pose serious health risks to local communities. The HTP of Co is alarming, with 17,4 kg 1,4-DCB-eq for HTPc and 613 kg 1,4-DCB-eq for HTPnc. These high toxicity levels are due to exposure to harmful substances such as heavy metals and sulfuric acid [116]. Ni displays the highest impacts in TAP and TEP, with the latter reaching 2.797,75 kg 1,4-DCB-eq per kg. These impacts are largely driven by the emissions generated during the smelting and refining processes, which release large amounts of sulfur dioxide, contributing to acid rain and soil contamination. Additionally, Ni has the highest PMFP. According to research by Golroudbary et al. [117], Ni's extensive use in batteries and other renewable technologies places it at the center of discussions on reducing environmental impacts in production chains. Mn is generally one of the more sustainable CRMs, second only to graphite. However, it stands out as the most carcinogenic, with a HTPc of 366 kg 1,4-DCB-eq per kg. This characteristic indicates that despite its lower impacts across most other environmental indicators, Mn extraction and processing must be carefully managed to mitigate health risks [118]. LCE exhibits the highest SOP, reaching 26,8 kg Cu-eq per kg. This significant impact is primarily due to the extensive mining processes required to extract Li from ores, such as spodumene. The extraction process involves large-scale disturbance of rock and soil, leading to substantial environmental degradation and resource depletion [119]. In addition, LCE heavily impacts in terms of MEP, with a value of $6,21 \times 10^{-3}$ kg N-eq per kg, indicating potential nutrient releases and ecosystem disturbances resulting from mining activities. Additionally, Li's extraction from spodumene often results in land use impacts due to the disruption of ecosystems during mining, as noted by multiple studies [120], but geothermal brine extraction methods show promise in reducing these environmental impacts. Indeed, the analysis reveals a notable reduction in all impact indicators when using geothermal brine extraction compared to traditional spodumene mining. The reductions range from a smaller difference of 12% for HTP, carcinogenic to an impressive 97% reduction in SOP. Graphite, P, Cu, and Si exhibit lower environmental impacts across most indicators. Graphite is the least impactful overall, with extremely low values in GWP and ecotoxicity potentials. P, the second least impactful, shows no particularly high values in any category. Cu has reduced impacts on TAP, FFP and a low GWP. Si also demonstrates lower impacts, particularly in TETP, making it less harmful compared to other CRMs in the supply chain.

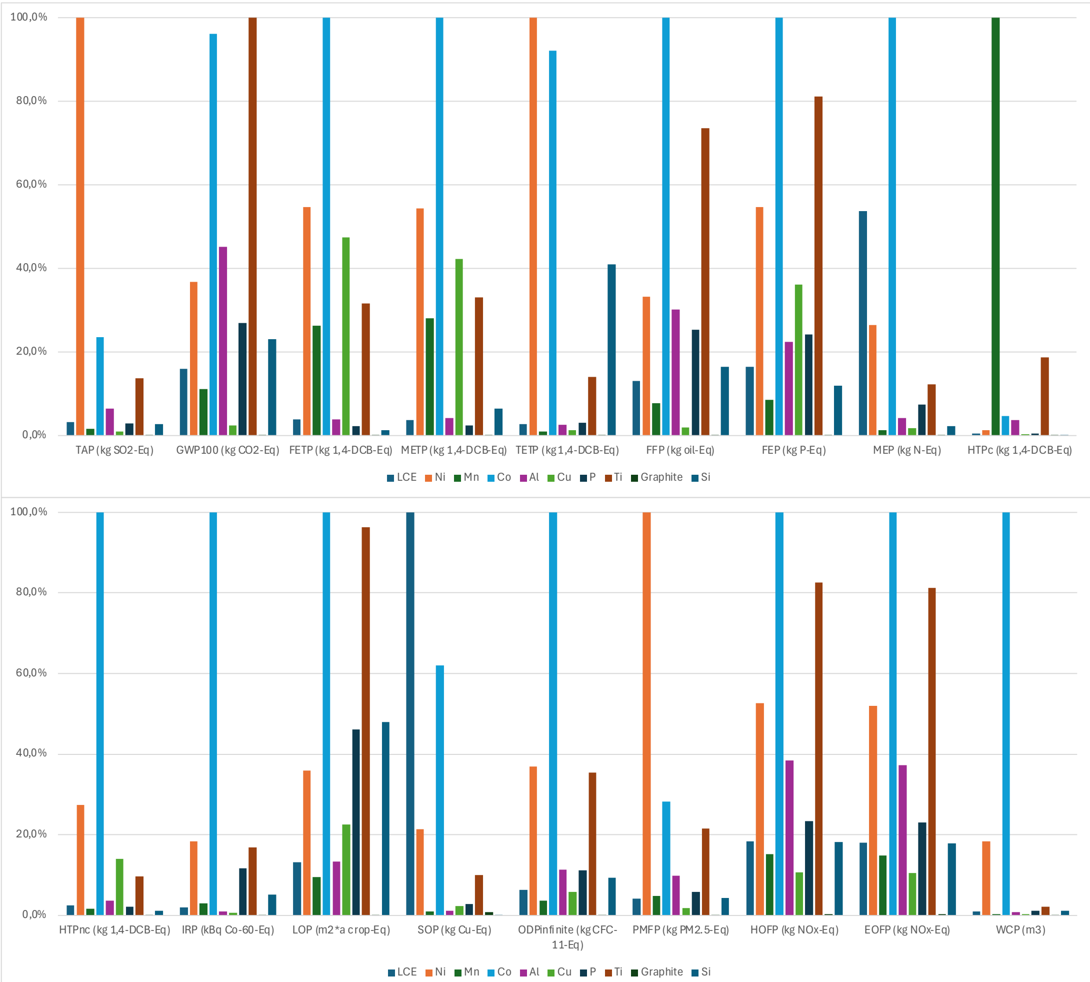

Figure 4 - Normalized values of ReCiPe midpoint indicators for CRMs

3.4.2. Environmental Performance of European Energy Mixes

Passing to the second LCA, it compares the environmental performance of the energy mix across various European countries, revealing notable disparities. Norway and Sweden exhibit the best performance in both GWP and Cumulative Energy Demand (CED) (Figure 5). Norway leads with the lowest GWP (0,0187 kg CO_2-eq) and CED (4,14 MJ-Eq), largely due to its substantial reliance on hydropower, resulting in minimal carbon emissions and energy consumption. Similarly, Sweden maintains a low GWP (0,0302 kg CO_2-eq) and CED (7,05 MJ-Eq), supported by its mix of hydro and wind energy. These countries exemplify how renewable energy sources can significantly reduce not only CF but also other environmental impacts, such as TAP and ecotoxicity. Denmark also performs well, with a relatively low GWP (0,153 kg CO_2-eq) and CED (6,29 MJ-Eq), attributed to its strong investment in wind power and other renewable energy technologies. Austria follows with a GWP of 0,223 kg CO_2-eq and a CED of 6,62 MJ-Eq, reflecting a predominantly renewable-based energy mix, including hydropower and biomass. These renewable-dominant countries generally exhibit lower impacts across indicators like TAP and HTP, highlighting the benefits of a cleaner energy portfolio. Conversely, countries with the highest environmental impacts include Poland and Czechia. Poland has one of the highest GWP values (0,916 kg CO_2-eq) and a high CED (12,1 MJ-Eq), primarily due to its heavy reliance on coal-based energy production. Czechia displays a similar profile with a GWP of 0,637 kg CO_2-eq and a CED of 12,0 MJ-Eq, reflecting its dependence on fossil fuels, which results in high emissions and energy consumption. This trend is seen in other fossil-fuel-heavy countries like Greece, with a GWP of 0,649 kg CO_2-eq and a CED of 11,4 MJ-Eq. These nations not only have elevated GWP and CED values but also show significant impacts across other toxicity indicators, emphasizing the environmental burdens of coal and oil reliance. France presents a contrasting scenario with a notably low GWP (0,0788 kg CO_2-eq) due to its extensive use of nuclear power. However, its CED (12,1 MJ-Eq) is relatively high, highlighting that nuclear energy, while low in carbon emissions, involves significant energy consumption, particularly in uranium mining, enrichment, and facility maintenance. This pattern is mirrored by Belgium, which has a low GWP (0,207 kg CO_2-eq) but a high CED (9,91 MJ-Eq). While nuclear power reduces certain environmental impacts like GWP and TAP, it raises concerns in other areas, such as IRP and CED. Germany and

Italy represent intermediate cases with mixed outcomes. Germany has a moderate GWP (0,426 kg CO_2-eq) and CED (8,57 MJ-Eq), reflecting a transitional energy mix that includes renewables, coal, and natural gas. Similarly, Italy, with a GWP of 0,384 kg CO_2-eq and a CED of 8,67 MJ-Eq, demonstrates a balanced yet still fossil-fuel-reliant energy portfolio. Spain shares this profile with a relatively low GWP (0,206 kg CO_2-eq) but a higher CED (8,99 MJ-Eq), likely due to its varied energy mix. These countries, while not performing as poorly as coal-heavy nations, still face challenges in reducing their overall environmental impact, particularly regarding FETP and METP.

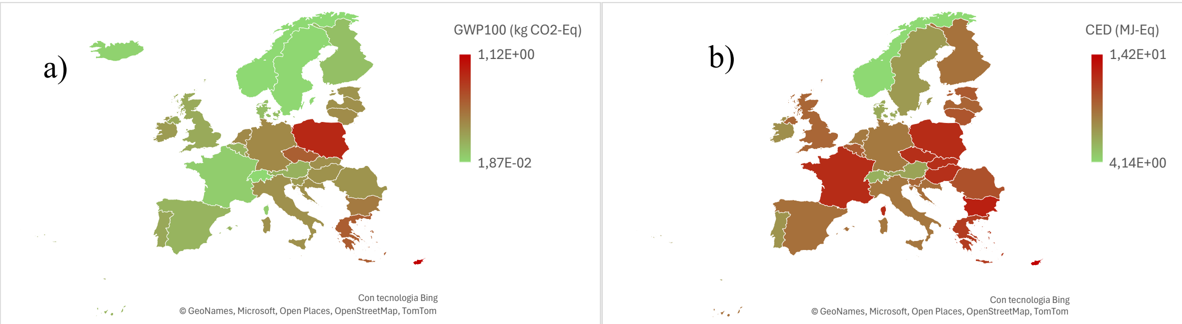

Figure 5 - EU national energy mixes: a) Global Warming Potential (GWP100) b) Cumulative Energy Demand (CED).

3.4.2. Environmental Impact Assessment of Battery Recycling Methods

In assessing the environmental impacts of pyrometallurgical and hydrometallurgical recycling methods for batteries, both direct impacts and net environmental savings from resource recovery were considered. The direct impact analysis indicates that landfill disposal appears to have the lowest impacts across most categories—for instance, it has the lowest GWP100 at 7,33E-03 kg CO_2-Eq compared to pyrometallurgy's 1,55E+00 kg CO_2-Eq and hydrometallurgy's 9,46E-01 kg CO_2-Eq. However, landfill does not allow for the recovery of valuable materials, leading to the loss of resources and potential environmental burdens in the long term. Between the two recycling methods, pyrometallurgy performs better than hydrometallurgy in categories such as TAP, FETP, METP, TETP, HTPnc, and WCP. Conversely, hydrometallurgy performs better in categories like GWP100, FFP, and ODPinf, indicating lower impacts in terms of greenhouse gas emissions and fossil fuel consumption. When incorporating net environmental savings through resource recovery—including the substitution of slag for clinker in pyrometallurgy and the recovery of valuable metals in both methods—the comparative performance shifts. Using the 2023 average battery composition, pyrometallurgy not only maintains its superiority in TAP, FETP, and METP but also surpasses hydrometallurgy in GWP100, achieving a greater net negative impact of -4,44 kg CO_2-Eq compared to hydrometallurgy's -4,24 kg CO_2-Eq. Interestingly, pyrometallurgy now outperforms in PMFP, reversing the trend seen in direct impacts where hydrometallurgy was better. However, hydrometallurgy continues to excel in categories such as TETP, HTPnc, and WCP, likely due to its higher recovery rates of metals like Li and its lower energy requirements for certain processes. Hydrometallurgy is particularly advantageous when the goal is to maximize the recovery of metals like Li, Co, Ni, and Mn, as it achieves higher recovery rates for these elements. This makes hydrometallurgy more suitable for scenarios where the battery composition is rich in these metals and their recovery is prioritized. On the other hand, pyrometallurgy becomes more beneficial when considering the recovery of materials like Cu and Al and when factoring in the substitution of slag for clinker, which contributes significantly to environmental savings in categories like GWP100. Projected changes in battery composition by 2030, characterized by reduced proportions of metals such as Co, Ni, and Mn (e.g., Co content decreasing from 3,4% in 2022 to 1,3% in 2030), further influence the comparative environmental performance. With these future compositions, pyrometallurgy's environmental benefits become more pronounced. It not only maintains advantages in previously mentioned categories but also surpasses hydrometallurgy in HTPc, HOFP, and EOFP. This improvement can be attributed to pyrometallurgy's efficiency in processing lower metal concentrations and the significant environmental credits gained from clinker substitution. The differences between the 2023 and 2030 results emphasize the importance of aligning recycling strategies with future material compositions to maximize environmental benefits. While hydrometallurgy currently offers advantages in specific impact categories and with present-day battery chemistries, pyrometallurgy's expanding benefits suggest it may become the more sustainable option in the near future.

3.6. Black Mass Hazardousness Analysis

In this section, the hazardous analysis of BM derived from various battery chemistries, is conducted. The classification process followed a structured methodology, beginning with a detailed analysis of BM composition and progressing through a multi-scenario hazard assessment.

The chemical elements present in BM were identified and assigned Hazardous Substance Classifications (HSCs) based on criteria outlined in EU Regulation No. 1357/2014 [121]. These criteria include the mere presence of an element, its concentration exceeding specified regulatory thresholds, or the cumulative concentration of multiple elements within the same hazard category surpassing defined limits. These HSCs are then classified under one or more of the 15 Hazardous Properties (HPs), which are used to determine whether a material should be considered hazardous waste based on its specific hazardous characteristics. To capture the full range of hazard potentials, three distinct classification scenarios were employed, each building on the previous to offer a progressively broader assessment:

- Scenario 1 adhered strictly to the Classification, Labeling, and Packaging (CLP) Regulation (EU) No. 1272/2008, which aligns with the United Nations (UN) Globally Harmonized System (GHS) for chemical classification and labeling [122].
- Scenario 2 expanded the analysis by integrating the Registration, Evaluation, Authorization and restriction of chemicals (REACH) Regulation (EU) No. 1907/2006, incorporating additional hazard considerations related to the registration and evaluation of chemicals [123].
- Scenario 3 represented the most precautionary approach, including data from notifications submitted to the European Chemicals Agency (ECHA) by importers and manufacturers, thereby identifying further potential hazards not covered under the previous scenarios [124].

A comprehensive literature review was conducted to compile data on BM composition. This effort identified 30 unique characterizations of BM, expressed in weight percentage (wt.%), capturing the presence of elements such as Li, Co, Ni, Mn, aluminum (Al), iron (Fe), carbon (C), cadmium (Cd), potassium (K), Ti, Si, calcium (Ca), magnesium (Mg), Cu, zinc (Zn), Pb, P, fluorine (F), sodium (Na), tin (Sn), arsenic (As), and silver (Ag). The study categorized BM by the types of batteries from which it originated, including LIBs, Ni-Cd, nickel–metal hydride (Ni-MH), and two separate groups of zinc/manganese batteries—zinc/manganese carbon (Zn/Mn Mn-C) and zinc/manganese (Zn/Mn). This categorization reflects the distinct chemical compositions and recycling challenges of each battery type. Ni-Cd batteries contain Cd, a toxic heavy metal necessitating specialized handling and recycling processes to mitigate environmental risks. In contrast, Ni-MH batteries, while also relying on Ni-based chemistry, replace Cd with a metal hydride, resulting in differing chemical profiles and recycling challenges. Similarly, Zn/Mn batteries are categorized based on their internal chemistry into Zn/Mn Mn-C batteries and Zn/Mn batteries. Zn/Mn Mn-C batteries, commonly referred to as alkaline batteries, include added carbon, influencing their chemical properties and recycling methods. On the other hand, Zn/Mn batteries, also known as zinc–carbon batteries, have a simpler composition and are primarily utilized in household applications, resulting in distinct BM characteristics and recycling challenges.

The hazard assessment applied to both individual BM samples and Composite Samples of BM (CSBM), evaluating minimum and average values to account for variability across samples. The analysis revealed key trends in hazard classification. Scenario One serves as the baseline of our analysis. Here, the classification is conservative, primarily driven by the flammability risk due to the presence of elements like Li, K, Na, and Ca, which directly contribute to HP3—Flammable. In this baseline scenario, other substances such as F play a role in HP4—Irritant and HP8—Corrosive, while Co influences HP7—Carcinogenic; HP10—Toxic for reproduction; and HP11—Mutagenic. In contrast, Scenario Three is recognized as the most precautionary, given that it considers a wider array of properties. By incorporating average values in each CSBM, Scenario Three takes into account the international concern related to BM elements, revealing a broadened hazard profile. The final line of

Table 11 contemplates a generic BM classification based on HPs that appear across all CSBMs. This reveals that, within the baseline scenario, HP3—Flammable is the sole HP involved, dictated by the aforementioned elements.

Table 11 - Range of HPs classification of CSBM and generic BM

CSBM	Baseline Scenario	Comprehensive Scenario
LIBs	HP3—Flammable; HP4—Irritant;	HP2—Oxidizing; HP3—Flammable; HP4—Irritant; HP5—Specific Target Organ Toxicity (STOT); HP6—Acute Toxicity; HP7—Carcinogenic; HP8—Corrosive; HP10—Toxic for reproduction; HP11—Mutagenic; HP13—Sensitizing
Ni-Cd	HP3—Flammable; HP7—Carcinogenic; HP10—Toxic for reproduction;	HP3—Flammable; HP4—Irritant; HP5—STOT; HP6—Acute Toxicity; HP7—Carcinogenic; HP10—Toxic for reproduction; HP11—Mutagenic; HP13—Sensitizing
Ni-MH	HP3—Flammable; HP4—Irritant; HP7—Carcinogenic; HP10—Toxic for reproduction; HP11—Mutagenic	HP3—Flammable; HP4—Irritant; HP5—STOT; HP6—Acute Toxicity; HP7—Carcinogenic; HP8—Corrosive; HP10—Toxic for reproduction; HP11—Mutagenic; HP13—Sensitizing
Zn/Mn Mn-C	HP3—Flammable; HP8—Corrosive	HP3—Flammable; HP4—Irritant; HP5—STOT; HP6—Acute Toxicity; HP7—Carcinogenic; HP8—Corrosive; HP10—Toxic for reproduction; HP11—Mutagenic
Zn/Mn	HP3—Flammable	HP3—Flammable; HP4—Irritant; HP5—STOT; HP6—Acute Toxicity; HP10—Toxic for reproduction; HP11—Mutagenic
Generic BM	HP3—Flammable	HP3—Flammable; HP4—Irritant; HP5—STOT; HP6—Acute Toxicity; HP10—Toxic for reproduction; HP11—Mutagenic

Further details, including specific tables summarizing hazard classifications and methodological specifics for each scenario, are provided in Annex IV.

3.7. EU 2030 Strategy

The potential to lead the global battery market appears contingent on timely investments in local resources, the adoption of innovative technologies, and the commitment to sustainability. By capitalizing on existing strengths and addressing critical weaknesses, the EU can position itself to meet its regulatory objectives and establish a standard for ethical, responsible battery production.

The following SWOT analysis (Table 12) provides a concise summary of the internal and external factors influencing the EU's strategy, offering a framework to guide future actions.

Table 12 – SWOT analysis of the EU battery supply chain toward 2030 regulatory goals.

Strengths	**Weaknesses**
Domestic Resource Potential: Availability of Li and phosphorus (P) resources, including geothermal Li and Norwegian phosphate deposits.	*Limited Production Capacity:* Current insufficient production of CRMs like Co and graphite.
Advanced Recycling Infrastructure: Capable recycling technologies with projections to meet regulatory targets for several CRMs by 2030.	*Li Recycling Shortfall:* Projected Li recovery rates fall short of BO9 targets, needing technological advancement.
Integrated Sustainability Initiatives: Implementation of the DPP, LCA, and eco-design tools enhancing transparency and compliance.	*Regulatory and Bureaucratic Hurdles:* Lengthy permitting processes delaying domestic resource development.
Low-Carbon Energy Mix in Some Countries: Nations like Norway and Sweden support environmentally friendly battery production.	*Energy Mix Disparities:* High-carbon energy profiles in certain member states undermining overall sustainability goals.
Shift Toward LFP Batteries: Reduces dependence on high-impact CRMs, aligning with resource availability and environmental objectives.	*Fragmented Data Systems:* Lack of standardization in DPP implementation across the industry.
Opportunities	**Threats**
Growing Global Battery Market: Increased demand for electric vehicles (EVs) and renewable energy storage solutions.	*Geopolitical Risks:* Political instability in key supplier countries like the DRC and China affecting supply security.
Technological Advancements: Innovations in battery technologies and recycling methods improving efficiency and performance.	Market Volatility: Fluctuations in global demand and raw material prices impacting investment viability.
International Collaborations: Partnerships with stable countries for import diversification (e.g., Australia, Canada).	*Environmental and Social Concerns:* Public opposition to mining activities posing delays and legal challenges.
Policy Support and Funding: EU initiatives and funding programs promoting sustainable technologies and infrastructure development.	Technological Uncertainties: Rapid changes potentially rendering current strategies obsolete or less effective.
Global Leadership in Sustainability: Opportunity to set international standards and lead in ethical sourcing and environmental responsibility.	*Competition from Other Regions:* Other countries advancing in battery technology and resource acquisition, increasing competition.

To meet the EU's 2030 regulatory objectives and establish a sustainable, secure, and globally competitive battery industry, three overarching strategic priorities emerge:

1. *Transition to LFP Battery Production.* The adoption of LFP battery production represents a critical pivot for Europe, addressing both supply chain vulnerabilities and environmental challenges. Co and Ni reserves, crucial for many existing battery chemistries, are concentrated in geopolitically unstable regions and face rapid depletion. These

materials also have high environmental and social costs associated with their extraction and processing. Europe, however, holds substantial Li and P resources, including geothermal Li reserves and newly identified phosphate deposits in Norway. P extraction, in particular, has significantly lower environmental impacts compared to Co and Ni, making LFP batteries a logical choice to enhance supply chain security and sustainability. LFP technology aligns with European regulatory goals by reducing dependence on imports from high-risk regions, minimizing the CF, and promoting responsible raw material sourcing. The absence of Co and Ni further reduces greenhouse gas emissions and ecological degradation, positioning Europe to lead in environmentally responsible battery production. Prioritizing LFP battery production ensures the EU's battery industry can meet long-term strategic and regulatory goals while addressing critical supply chain vulnerabilities.

2. *Targeted Investments Based on Energy Mix Analysis.* Europe's diverse energy profiles necessitate tailored investment strategies for battery production and electrification initiatives. Table 13 summarizes investment recommendations based on the carbon intensity of electricity generation.

Table 13 - Investment recommendations for national energy mixes.

Energy Mix Group	Countries	Investment Recommendation
Low-Carbon Energy Mix	Norway, Sweden, Switzerland, France, Finland, Iceland	Immediate investment in battery production, recycling, and electrification initiatives due to clean energy infrastructure.
Transitioning Energy Mix	Germany, Italy, Spain, United Kingdom, Austria, Belgium, Croatia, Ireland, Latvia, Lithuania, Luxembourg, Netherlands, Portugal, Slovenia	Phased investment in battery infrastructure alongside policies to accelerate renewable energy adoption and reduce reliance on fossil fuels.
High-Carbon Energy Mix	Poland, Czechia, Greece, Bulgaria, Cyprus, Estonia, Hungary, Romania, Slovak Republic	Prioritize energy decarbonization through renewable energy projects before expanding battery infrastructure investments.

3. *Development of an Integrated Sustainability Suite.* Meeting the European Union's regulatory objectives in the battery sector demands an integrated sustainability suite that ensures comprehensive monitoring and compliance throughout the lifecycle of batteries. This research directly addresses these needs by proposing and developing a tailored solution to bridge current gaps and enhance sustainability efforts. Currently, no clearly defined system exists to fulfill these requirements. However, it is essential to decentralize data collection while centralizing data management to ensure all stakeholders operate on a unified platform. This approach not only directly satisfies BO6 by implementing the DPP but also enables the monitoring of other Battery Objectives (BOs). Moreover, the automated LCA integrated into design tools allows for immediate estimation of the CF, directly addressing BO2, while facilitating compliance with critical thresholds defined in the Circular Objectives (COs). Chapters 4 through 6 will detail the entire structure of the proposed framework and its associated tools.

Meeting the European Union's regulatory objectives in the battery sector necessitates strategic actions tailored to different scenarios. In the *Best Scenario*, the EU is well-positioned to exceed regulatory targets, driven by strong internal production growth, advanced recycling rates, and diversified import sources. Investments in geothermal Li extraction in Germany, France, Italy, and Greece should be accelerated, aiming to make these resources operational by 2027. Phosphate deposits in Norway require prioritized attention, with fast-tracked mining operations enabling the EU to secure a significant share of P demand. These initiatives align with CO1 by bolstering domestic production. Advanced recycling facilities in low-carbon countries like Norway and Sweden can enhance recovery rates for Li, Co, and Ni, addressing BO9 and CO3. Hydrometallurgical methods should be refined through research and development to improve Li recovery rates, aligning with BO8's 70% efficiency target by 2030. Stable partnerships with Australia and Canada for Li and Ni, and diversification of Co and graphite imports through emerging suppliers like Brazil and India, will reduce over-reliance on geopolitically unstable regions, fulfilling CO4's goal to limit dependency on single non-EU countries. Aligning investments with demand forecasts and regulatory updates ensures timely resource availability, while pre-emptive regulatory compliance mitigates risks. This proactive approach secures the EU's supply chain stability and aligns with long-term sustainability goals. Under moderate conditions, in the *Base Scenario*, where resource shortages persist and import reliance remains significant, the EU must focus on expanding domestic capabilities while mitigating risks associated with external dependencies. Accelerating key projects like geothermal Li extraction and expanding geological surveys for Ni, Mn, and graphite will partially address gaps in domestic production. These efforts directly support CO1 while contributing to future CO2 compliance by increasing domestic processing potential. Existing recycling facilities should be upgraded to handle increased volumes of end-of-life batteries, while innovative startups and research institutions developing next-generation recycling technologies should be supported. These measures aim to meet BO8 and BO9 by enhancing efficiency and recovery rates for CRMs. Agreements with Turkey (Co, graphite), South Africa (Mn), and Indonesia (Ni) provide diversification while mitigating risks from over-reliance on single suppliers. Strategic stockpiles of critical materials should be developed to buffer against potential disruptions, ensuring alignment with CO3. Resources should be allocated in phases based on progress indicators and demand projections. Contingency plans addressing delays in production or recycling capacity expansions ensure supply chain resilience. In the *Worst Scenario*, the EU faces severe resource shortages and high import dependency, requiring immediate, aggressive actions to maintain a functioning battery supply chain. Significant capital should be mobilized to fund domestic mining projects, even in less optimal locations, with fast-tracked approvals to expedite permitting and construction. While raising environmental concerns, these measures are vital to meeting CO1 and ensuring basic supply chain functionality. Strict recycling quotas should be mandated across all industries using CRMs to increase the availability of secondary materials. Investments in advanced recovery technologies, particularly for mixed and low-grade waste, are essential to meet BO8 and BO9 under these constraints. Engagement with high-risk suppliers such as the Democratic Republic of Congo (Co) and China (graphite) may become unavoidable. Temporary agreements should be accompanied by stringent monitoring for compliance with ethical and environmental standards, aligning with CO4. Collaboration with other regions facing similar shortages could also provide shared solutions. Activating emergency protocols and reallocating resources toward critical materials and recycling capacity expansions are essential to mitigate the immediate effects of supply shortages. These measures will help stabilize the supply chain while longer-term strategies are implemented.

Chapter 4.

Framework for Sustainable Battery Lifecycle Management

This chapter presents the proposed framework for sustainable battery lifecycle management, detailing its architecture, workflow, and unique contributions. The framework integrates advanced tools developed ad hoc to address regulatory, technological, and industrial challenges. The chapter is structured as follows: Section 4.1 introduces the framework's architecture and its main and secondary tools, while Section 4.2 explores the detailed workflow and use scenarios across the Plan-Do-Check-Act cycle. Finally, Section 4.3 highlights the framework's benefits and unique contributions to achieving regulatory compliance, closing technological gaps, and supporting European battery sector development.

4.1. Framework Architecture

The architecture of the framework, as described by Figure 6, is built around two primary tools: BatPaC with Integrated LCA (hereafter BatPaC-LCA) and the DPP. BatPaC-LCA performs predictive simulations and enables eco-design by evaluating technical, economic, and environmental parameters. The DPP ensures real-time data collection, compliance verification, and feedback throughout the battery's lifecycle. Together, these tools form the core of an iterative process that bridges the gap between pre-production design and operational lifecycle management. In addition to these main tools, a set of Pre-Design Tools identifies initial constraints through methods like market analysis and regulatory reviews. These inputs feed BatPaC-LCA, which performs simulations and optimizations to generate battery configurations. The environmental indicators provided by BatPaC-LCA form the foundation for assessments conducted by the Post-Design Tools, such as QFD and compatibility matrices. These tools finalize the configurations, which will constitute the basis of the DPP.

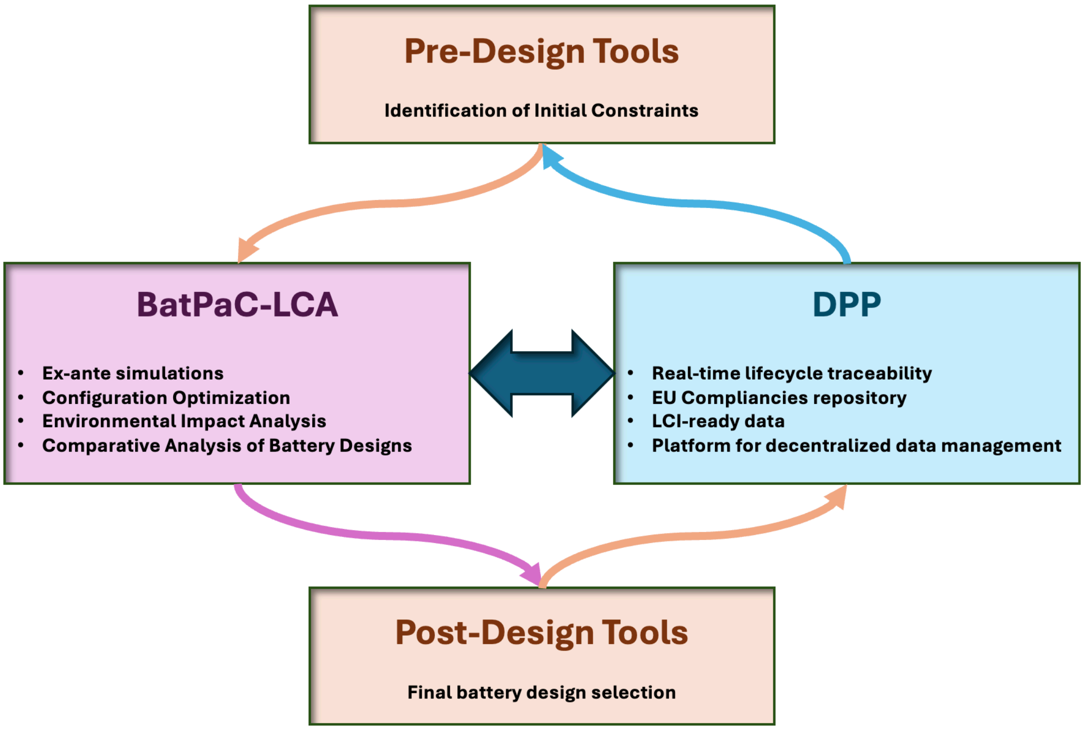

Figure 6 - Framework architecture

4.1.1. Main Tools

The proposed framework leverages two primary tools to address the lifecycle sustainability challenges of EV batteries: BatPaC-LCA and the DPP. Each tool provides distinct yet complementary functionalities that collectively enable a comprehensive approach to sustainable battery lifecycle management.

BatPaC-LCA is a versatile tool designed for predictive analysis during the battery design phase. Its functionalities are tailored to enable informed decision-making through the simulation of technical, economic, and environmental parameters. Originally, BatPaC's primary functionality allowed users to model battery configurations through the input of technical parameters. These include electrode chemistry, cell design, and pack assembly. The tool enables a detailed evaluation of performance, configuration, and cost analysis. Performance, such as energy density and cooling system requirements, is calculated using primary data collected by ANL, ensuring alignment with operational requirements and application-specific demands. Configuration involves optimizing cell designs, including electrode thicknesses and separator properties, to balance capacity and longevity while customizing battery layouts for automotive applications. Cost analysis utilizes manufacturing process parameters like slurry mixing, electrode coating, and pack assembly to estimate material and operational expenses, providing comprehensive economic feasibility insights. The LCA module, implemented as part of this research, quantifies cradle-to-grave impacts using 18 midpoint indicators from the ReCiPe 2016 method. It offers users a high degree of granularity in data interpretation, enabling evaluations across different FUs, such as impacts per kWh, per kilometer, or per battery unit. This flexibility ensures precise environmental performance assessments. Furthermore, it supports graphical visualization of specific lifecycle phases, such as manufacturing, or globally for each midpoint indicator. Users can also define and compare end-of-life scenarios, including pyrometallurgy, hydrometallurgy, and landfill disposal, to evaluate different lifecycle strategies and guide sustainable decision-making. Additionally, the structure created allows users to modify the entire database, including characterization factors, enabling tailored LCA analyses to address specific scenarios or regulatory requirements. Furthermore, outputs align with the EU Battery Regulation, incorporating a compliant CF indicator developed following the LCA guidelines specified in the regulation. By running multiple simulations simultaneously, up to seven batteries at a time using the same chemistry, BatPaC-LCA enables comparative environmental analysis, empowering designers to optimize battery configurations across multiple criteria. Details about the functioning of BatPaC, the implementation of the LCA module, and how its results align with findings from existing literature will be thoroughly discussed in Chapter 5.

As described in Section 2.6, the DPP is designed to ensure real-time lifecycle monitoring and data sharing among stakeholders. It is built upon two main components: the DM and the ITI, each playing a critical role in enabling its functionality. The DM captures lifecycle data through a hierarchical tree structure that considers the battery as a modular product and its components as independent parts. Within this structure, sub-nodes are dedicated to each lifecycle phase, containing sections specifically designed for environmental impacts and the regulatory parameters required by the EU Battery Regulation. For the former, data is organized in an LCI-ready format, allowing seamless exportation for external LCA studies. The model includes a dedicated section for inserting LCA results, calculated externally. All mandatory parameters from the EU Battery Regulation are embedded within the model, ensuring compliance with legal requirements. Furthermore, the DM is encoded in eXtensible Markup Language (XML), which guarantees interoperability across diverse systems and facilitates integration with external tools and platforms. The ITI is developed around the XML-based DM and provides a comprehensive framework for managing DPPs across their lifecycle. It enables the creation, updating, and validation of DPPs through a user-friendly interface. The platform supports multi-stakeholder collaboration by enabling different levels of authorization for creating, modifying, and viewing the DPP, as specified by the EU Battery Regulation, decentralizing the collection and sharing of information to ensure maximum integrity and accuracy. The blockchain technology underpinning the infrastructure has been optimized to reduce costs, while its interaction with users has been automated through smart contracts to eliminate barriers related to expertise. Details of the DPP's architecture and its role in lifecycle management will be explored in Chapter 6.

The integration of BatPaC-LCA and DPP creates a synergistic system that bridges the gap between predictive modeling and dynamic lifecycle monitoring. Data collected from the DPP feed into BatPaC-LCA, enabling iterative refinements in design configurations. This feedback loop ensures that the framework remains adaptive to real-world conditions and regulatory changes. The functionalities of the two tools are summarized and compared in Table 14.

Table 14 - Main tools functionality comparison

Characteristic	DPP	BatPaC-LCA
Inputs	Real-time data from value chain actors.	Design requests and needs based on identified constraints.
Outputs	Battery lifecycle information, LCI-ready data, stakeholders feedback, compliancy reports repository	Configuration, performance, cost, and environmental impacts simulations, and comparative analysis of different EV battery designs.
Timing	Real-time, dynamically updated to reflect lifecycle data and operational conditions.	Predictive, ex-ante simulations conducted during the design phase.
Stakeholders	All value chain actors	Designers and product managers
Inter-tool Connection	Provides primary data to enhance BatPaC-LCA modeling accuracy.	Enables the creation of a comprehensive digital twin of the DPP ex-ante, facilitating detailed lifecycle planning.

4.2.2. Secondary Tools

To define the initial constraints that guide battery design, various pre-design tools from the literature have been identified as instrumental. These tools contribute to the framework by offering insights into market needs, regulatory requirements, and competitive dynamics. Table 15 summarizes the tools and their contributions.

Table 15 – Pre-Design tools

Tool	Function	Rationale for Inclusion	Contribution
Market Segmentation Analysis	Utilizes statistical analysis and modelling to dissect the market into distinct groups based on consumer preferences, usage patterns, and demographic factors. [125], [126]	Critical for identifying nuanced consumer demands in different segments, enabling precision in tailoring battery specifications such as energy density, charge rates, and lifecycle expectations to distinct market needs.	Facilitates the engineering of battery designs that precisely align with segment-specific requirements, enhancing application efficiency and market penetration. For instance, it enables the tailoring of battery chemistries and form factors to specific applications like high-energy-density for EVs or high-power-density for portable electronics, guided by detailed market insights.
Competitive Landscape Assessment	Applies competitive intelligence frameworks and tools to analyse competitors' strategies, product offerings, and market positioning. [127]	Essential for identifying technological gaps and opportunities in the battery sector, enabling the development of innovative solutions that surpass existing market offerings in sustainability and performance.	Informs the strategic development of battery technologies and eco-design practices that establish competitive advantages, such as adopting cutting-edge materials science innovations or advanced manufacturing processes that reduce environmental impact while enhancing performance and cost-effectiveness.
SWOT Analysis	Conducts a systematic evaluation of internal and external factors affecting the eco-design project, leveraging engineering and business analysis techniques. [128]–[130]	Provides a comprehensive overview of the strengths to leverage, weaknesses to address, opportunities to capture, and threats to mitigate in the context of sustainable battery design and development.	Directs the eco-design process towards exploiting technical and market opportunities (e.g., emerging battery materials or recycling technologies) while addressing engineering challenges (e.g., thermal management system (TMS), energy density) and regulatory constraints, ensuring a balanced approach to innovation that is both sustainable and viable.
Regulatory Environment Analysis	Reviews and interprets current and forthcoming regulations using legal and technical analysis to understand their impact on battery design and lifecycle management. [131]	Guarantees that battery designs not only meet current environmental and safety standards but are also forward compatible with anticipated regulatory changes, ensuring long-term viability.	Ensures the integration of compliance into the eco-design process, driving the adoption of battery technologies and materials that meet stringent environmental regulations, such as minimizing hazardous substance use and optimizing for end-of-life recyclability or reusability, thus embedding regulatory foresight into the engineering design process.

These tools collectively provide the foundation for defining the constraints necessary to guide the battery design process. They help ensure that designs align with market demands, competitive landscapes, and regulatory frameworks while integrating sustainability principles. Once the initial designs are generated through BatPaC-LCA, additional tools are required to refine and optimize them. Table 16 outlines tools essential for post-design evaluations:

Table 16 – Post-Design tools

Tool	Function	Rationale for Inclusion	Contribution
Quality Function Deployment (QFD)	Implements the House of Quality (HOQ) to systematically translate customer and stakeholder requirements into engineering specifications and technical features.[131], [132]	Bridges the gap between market/stakeholder needs, regulatory requirements included, and technical solutions, ensuring that battery designs are aligned with both consumer expectations and regulatory requirements, emphasizing sustainability.	Facilitates a structured approach to integrating sustainability criteria into battery design parameters, such as material selection, energy efficiency, and lifecycle impact, ensuring that technical solutions are directly aligned with eco-design principles and stakeholder expectations. This methodical alignment enables the development of batteries optimized for both performance and environmental impact.
Compatibility Matrix	Utilizes systems engineering principles to assess the interoperability and synergistic potential of various technical solutions within the battery design. [131]	Essential for identifying optimal combinations of materials, technologies, and design approaches that together enhance the battery's overall sustainability and performance, while avoiding incompatible interactions.	Facilitates informed decision-making for battery manufacturers by highlighting material and technology combinations that enhance battery efficiency, safety, and recyclability. For example, it aids in selecting cathode and electrolyte pairs that maximize energy density while ensuring environmental compliance. This targeted approach streamlines the design process, aligning product development with eco-design goals and market expectations.

4.2. Framework Workflow and Use Scenarios

The proposed framework for sustainable battery lifecycle management is structured around a systematic and iterative approach, divided into four distinct phases: Plan, Do, Check, and Act, as illustrated in Figure 7. Each phase corresponds to a specific set of processes aimed at achieving a comprehensive and adaptive management of the battery lifecycle. The Plan phase focuses on identifying constraints, gathering data, and generating optimized design configurations through predictive simulations of performance, costs, and environmental impacts. The Do phase transitions from planning to execution, involving the implementation of selected designs and the initialization of the

DPP. The Check phase emphasizes validation and verification, ensuring compliance with regulatory requirements and alignment with sustainability goals through LCAs and performance evaluations. Finally, the Act phase leverages insights from discrepancies and stakeholder feedback to enhance the framework, optimize battery design, and guide future product improvements for continuous improvement. The successful implementation of this framework relies on the involvement of multiple stakeholders, each playing a specific role at different stages of the workflow. The key actors and their responsibilities are outlined below:

- *Battery Designers:* Responsible for defining technical specifications and optimizing the design based on performance, cost, and environmental impact.
- *Project Managers:* Oversee the entire workflow, ensuring alignment with project objectives and regulatory requirements.
- *LCA Experts:* Conduct environmental impact assessments, ensuring that sustainability metrics are integrated into the design process.
- *Regulatory Experts:* Ensure compliance with industry regulations and evolving legislative requirements.
- *Suppliers:* Provide raw materials and components, influencing design constraints and sustainability considerations.
- *Manufacturers:* Translate the selected design into production, implementing quality control and process optimization.
- *Value Chain Stakeholders:* Actively involved throughout the battery lifecycle, including Manufacturers and Suppliers. They update the DPP with real-time lifecycle data, ensuring traceability and continuous monitoring.

Each of these phases will be explored in detail in the following subsections, highlighting their respective workflows, involved stakeholders, and the tools utilized to support the activities.

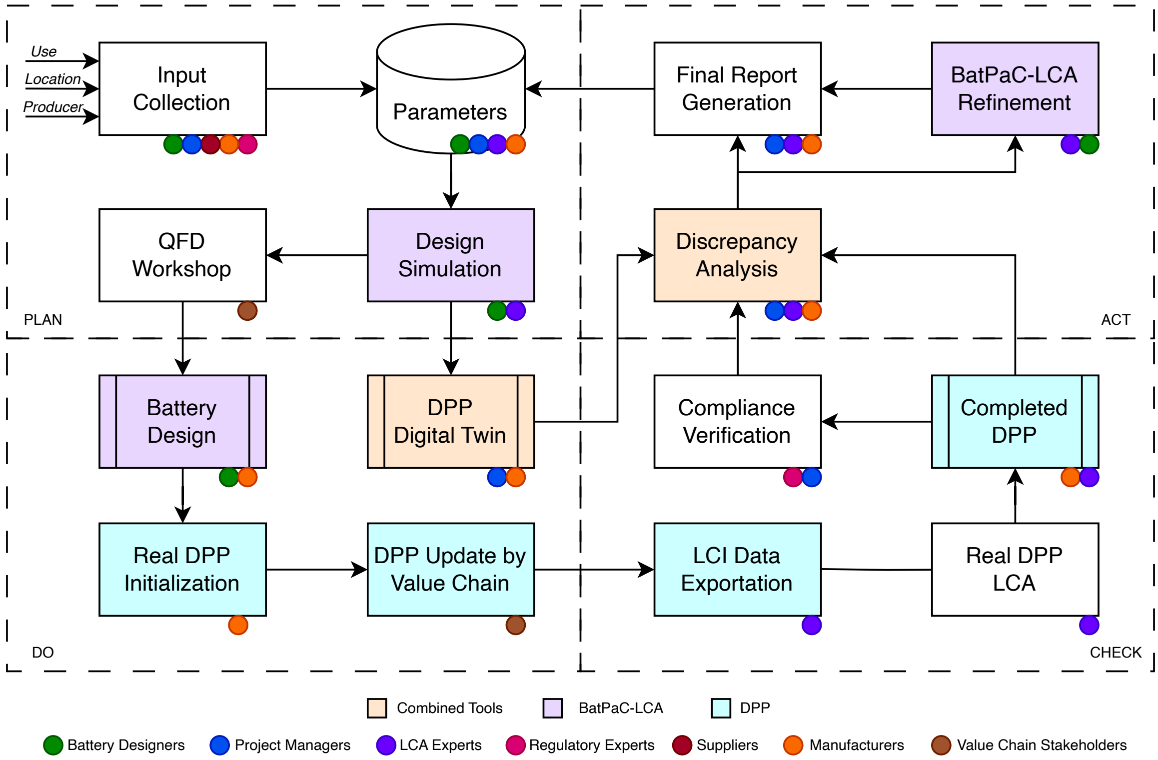

Figure 7 - Framework Workflow illustrating key phases, tools, and involved stakeholders

4.2.1. Plan Phase

The Plan phase of the Deming cycle spans from the initial collection of design inputs to the generation of optimized battery configurations ready for further analysis and refinement. It focuses on structuring the data and parameters necessary to transition smoothly into the subsequent phases of the workflow. The first step in this phase is *Input Collection*, which involves gathering essential data required for battery design. This process is structured around three key aspects: battery destination, production territory, and corporate capacity. The battery destination determines the specific performance characteristics required, as different applications have varying demands. For instance, electric vehicle batteries require high energy density and extended cycle life, whereas consumer electronics prioritize high power density and long standby times. The production territory plays a crucial role, as different regions have specific environmental regulations, resource availability, recycling infrastructure, and climatic conditions that influence battery design choices. Finally, corporate capacity, both in technical and economic terms, impacts feasibility. Technical capacity refers to manufacturing processes, material science, and engineering expertise, while economic capacity considers financial resources, market demand, and supply chain management. Project Managers, Battery Designers, Suppliers, and Regulatory Experts collaborate to ensure that the collected data accurately reflects technical feasibility and compliance. Several tools support this phase, including market segmentation analyses to define performance requirements, regulatory environment reviews to ensure adherence to standards, and competitive landscape assessments such as SWOT analysis to evaluate the manufacturer's capabilities. Additionally, the DPP contributes historical and real-time data from previous projects, enhancing accuracy and contextual relevance. Once data collection is complete, the next step involves consolidating this information into actionable design *Parameters* that define technical constraints for battery simulations in BatPaC-LCA. These parameters include fundamental specifications such as battery chemistry, vehicle type, peak power ratings, operating SOC levels, thermal conditions, and overall energy storage capacity. Manufacturing-related parameters encompass production plant type, annual manufacturing capacity, cell quality yield, and FU definitions for lifecycle assessments, including end-of-life scenarios for production scrap and exhausted batteries. Users also have the option to specify additional chemistry-related details, such as electrode thickness, specific capacity of active materials, void volume fractions, and separator thickness, providing a more tailored analysis. Costs of primary components, recharge times, and other configurations can be manually overridden to fine-tune simulations. Battery Designers, supported by LCA Experts, ensure that these parameters align with the constraints identified in the previous stage. Subsequently, the parameters serve as inputs for BatPaC-LCA, where they are processed by the software to generate optimized battery designs. If multiple design alternatives are available, BatPaC-LCA allows for up to seven configurations to be simulated in parallel, ensuring a comprehensive comparative assessment. Following parameter definition, a *Design Simulation* is conducted as an initial evaluation of the technical, economic, and environmental aspects of different battery configurations. BatPaC-LCA provides instant assessments of cost-effectiveness, performance metrics, and environmental footprint, allowing Battery Designers and LCA Experts to identify the most viable options. Once simulations are complete, a *QFD Workshop* is conducted to align technical, economic, and environmental objectives. The Quality Function Deployment (QFD) framework is a structured methodology used to translate stakeholder requirements into engineering characteristics. Within this framework, the House of Quality (HoQ) serves as a matrix to systematically map customer needs against technical solutions, allowing for an organized prioritization of design features. The HoQ consists of multiple relationship matrices, where different technical specifications are scored based on their impact on customer priorities, helping designers to make data-driven decisions. Each design parameter is evaluated based on its relative importance, using a scoring system from 1 to 5, where higher values indicate greater relevance to the final product. For example, in an electric vehicle battery, energy density and cycle life may receive the highest scores due to their direct impact on performance and longevity. Legislative constraints are also integrated into this evaluation, with regulations currently in force receiving greater weight than anticipated future policies. The HoQ process also includes an assessment of interactions between technical solutions, identifying both positive and negative synergies, ensuring a balance between performance, cost, and sustainability. To enhance decision-making, the Matrix Compatibility tool is employed to examine interactions between design choices. This tool helps identify potential conflicts and synergies, guiding the selection of the most effective configuration. For instance, increasing the cathode thickness may improve energy density but could also reduce power capability, requiring a trade-off analysis. The QFD Workshop also incorporates insights from prior DPP data, applying weighted scoring methods to assess trade-offs between technical, economic, and environmental factors. LCA Experts play a crucial role in ensuring that sustainability metrics are accurately represented and prioritized, particularly in scenarios where environmental impact must be weighed against cost-effectiveness. The refined inputs from the QFD Workshop undergo a final systematic evaluation, leading to the optimal battery design selection.

4.2.2. Do Phase

The Do phase of the Deming cycle transitions from planning to execution, focusing on the implementation of battery designs and the establishment of a robust digital framework for lifecycle management. The phase begins with the selection of the final *Battery Design* from the configurations generated in BatPaC-LCA and subsequently refined through the QFD Workshop during the Plan phase. The selection is based on a comprehensive evaluation of sustainability metrics, including environmental impact, cost efficiency, and performance. Battery Designers take the lead in finalizing the design. Once selected, the design undergoes detailed engineering, translating the simulated configuration into a manufacturable blueprint. This step ensures that the design is ready for real-world production, incorporating both technical specifications and sustainability objectives identified earlier. Following the selection of the battery design, a *DPP Digital Twin* is created. This digital representation is based on the data generated by BatPaC-LCA simulations that are loaded into an empty DM. The Digital Twin includes all relevant lifecycle data, with the exception of the personal identifiers of value chain actors. However, it can be beneficial to predefine the value chain stakeholders responsible for each lifecycle phase. This structure provides a predictive overview of the battery's lifecycle, enabling a proactive management of possible bottlenecks and allowing for greater control over discrepancies that may arise when compared with the real DPP. The next step involves the *Real DPP Initialization*, transitioning the Digital Twin into a live, operational state. At this stage, the DPP is initially populated by the producer with static data corresponding to the design and production phases. Over time, the process evolves into the critical phase of *DPP Update*, where real-time data is dynamically integrated by Value Chain Stakeholders. This updating process requires a high level of collaboration among value chain actors. Each update follows a defined methodology and occurs through a structured procedure: stakeholders complete their respective lifecycle stages and execute updates using a defined methodology. The workflow and use scenarios of the Real DPP, along with its practical implementation, will be detailed in Chapter 6 and demonstrated in Chapter 7.

4.2.3. Check Phase

The Check phase of the Deming cycle focuses on validating and verifying the performance, compliance, and environmental impacts of the battery lifecycle. It ensures that data collected and analyzed aligns with regulatory requirements and sustainability goals. The Check phase begins with the *LCI Data Exportation* from the DPP. This data, gathered and organized within specific nodes in the Real DPP during the Do phase, is prepared for external analysis in professional LCA software. This exportation can occur either incrementally, at each update of the DPP, or more conveniently at the completion of the DPP, allowing internal or external collaborators who are experts in the field to perform the analysis in a single comprehensive step. The inherent structure and nature of the DPP enable the creation of a complete cradle-to-grave LCI, ensuring that all lifecycle phases are accounted for in a detailed and systematic manner. The DM format that constitutes the DPP was designed in XML specifically because software like SimaPro ensures compatibility, facilitating straightforward data insertion. Using the exported LCI primary data, an in-depth *Real DPP LCA* ISO-compliant is performed. For results to be comparable with the predictive analysis conducted in BatPaC-LCA, the environmental analysis must use the same FU, database, and method. While the FU can be selected directly within the developed tool, the database and method need to be predefined. LCA Experts play a critical role in interpreting these results to inform decision-making and identify areas for improvement. The LCA results are then integrated back into the DPP, marking the transition to a *Completed DPP* status. This integration finalizes the DPP, transforming it into a comprehensive repository of lifecycle data and analytical outcomes for ongoing monitoring, reporting, and decision-making, providing stakeholders with actionable insights into both compliance and sustainability performance. Regulatory Experts conduct the *Compliance Verification* with regulatory requirements, in particular the EU Battery Regulation 2023/1542. This step can be performed either during the progressive filling of information in the Real DPP and upon its completion, allowing the inclusion of key data such as the CF results. To streamline this process, a DAX-based code can be developed to automate data ingestion, transforming the XML into structured visualizations and reports in Power BI. The functionality and implementation of this DAX code will be further elaborated in Chapter 6, during the discussion of the DM. This code can also facilitate real-time comparisons against regulatory benchmarks, generate alerts for discrepancies, and create dashboards for tracking compliance trends and sustainability metrics over time.

4.2.4. Act Phase

The Act phase of the Deming cycle focuses on leveraging insights from the previous phases to refine tools, optimize battery design, and improve future product iterations, ensuring continuous enhancement of both the framework and battery lifecycle management. Unlike the Check phase, which validates compliance and performance, the Act phase emphasizes learning and iterative enhancement, making it an essential part of the framework's adaptive capabilities. The Act phase starts with a *Discrepancy Analysis* between the predictions of environmental impacts and costs conducted with the implemented version of BatPaC-LCA and the actual costs and LCA results derived from primary data. This analysis aims to uncover inefficiencies or errors in the initial design parameters, providing a foundation for optimizing the current battery design and refining predictive tools for future developments. As we have seen previously with regulatory compliance, a DAX-based code can be employed to automate the data ingestion into Power BI, creating visualizations that highlight inconsistencies and trends. This automation allows for an efficient evaluation of deviations, enabling Manufacturers and Battery Designers to prioritize necessary adjustments in workflows or parameter settings. Following, a *Final Report* is generated to document the outcomes of the entire lifecycle management process. This report includes: (i) A detailed evaluation of regulatory objectives and their achievement; (ii) Feedback from value chain actors on the efficiency and effectiveness of the framework; (iii) Actionable recommendations for refining battery designs, enhancing manufacturing processes, and guiding future iterations of battery development. The report serves as both a record of accomplishments and a roadmap for future enhancements. By consolidating insights from all phases, it supports strategic decision-making and reinforces the iterative nature of the framework. This *BatPaC-LCA Refinement* ensures that the tool remains aligned with evolving industry needs, regulatory requirements, and sustainability goals, while also enhancing its capability to support continuous improvements in battery design and lifecycle assessment. Discrepancies, such as variations in predicted and actual energy densities, cost deviations in manufacturing steps, or unexpected environmental impacts during specific lifecycle phases, are analyzed to replace outdated or inaccurate parameters. For example, if primary data indicates higher emissions during the recycling phase than originally modeled, the tool's LCA module can be adjusted to reflect these findings. These adjustments make BatPaC-LCA's predictive models and eco-design functionalities more robust and adaptive.

4.3. Unique Value Proposition

The proposed framework for sustainable battery lifecycle management contributes significantly to achieving the objectives of the Battery Regulation, the CRMA, and the ESPR. It aligns with key goals such as responsible sourcing (BO1, CO1), CF reduction (BO2, CO7), increased recycling efficiency (BO8, CO3), and enhanced resource efficiency (CO8). The DPP ensures compliance with mandatory labelling and DPP requirements (BO6), while BatPaC-LCA's predictive capabilities streamline eco-design processes and lifecycle impact assessments, ensuring alignment with evolving regulatory standards.

Beyond regulatory alignment, the framework actively supports the development of the European battery sector by fostering circular economy practices, promoting innovation in recycling technologies, and reducing dependency on imported raw materials. By offering a unified tool, as emphasized in the EU's 2030 strategy, it simplifies the integration of sustainability and compliance processes. Additionally, the framework enhances value chain collaboration, operational transparency, and compliance efficiency through its tools driving competitiveness and sustainability across the industry. Moreover, it addresses challenges such as the scalability of recycling infrastructure, the standardization of lifecycle data, and the implementation of efficient eco-design methodologies to meet the needs of diverse stakeholders.

From a technological perspective, the framework's core functionalities address critical gaps identified in Sections 2.4 to 2.6 of this thesis. These include the need for improved standardization in eco-design methodologies, enhanced lifecycle impact assessment capabilities, and the creation of a seamless data ecosystem for traceability. BatPaC-LCA's capabilities in cradle-to-grave impact assessments, design optimization, and cost modeling empower stakeholders to create environmentally efficient configurations. Meanwhile, the DPP addresses specific challenges highlighted in Section 2.6, such as the lack of standardization in DMs, incomplete lifecycle solutions, and the high costs and scalability limitations of blockchain infrastructures. Further details and technical insights into how the framework resolve these gaps are provided in the subsequent chapters.

Chapter 5.

Evaluating Environmental Sustainability of Batteries during Design Phase: Integrating BatPaC with LCA Indicators for EV Battery Eco-Design

This chapter marks the first of two dedicated to explaining the tools developed and integrated within the framework for sustainable battery lifecycle management. It focuses on how the evaluation of environmental impacts has been embedded directly into the design phase by leveraging data inherent to the tools. As outlined in Section 2.5, BatPaC was selected as the foundational design tool, with further details on its structure and functionalities provided in Section 5.1. Subsequently, Section 5.2 explores the development and implementation of the LCA module within BatPaC, structured according to the ISO phases described in Section 2.5. This includes Goal and Scope Definition, LCI, LCIA and Interpretation, providing a systematic approach to cradle-to-grave impact evaluation. Finally, Section 5.3 provides a preliminary evaluation of BatPaC-LCA's reliability by comparing its outputs with existing literature, offering an initial assessment of its robustness and alignment with established benchmarks.

5.1. BatPaC Tool

BatPaC is a simulation tool that models battery design and performance by integrating user-defined parameters with electrochemical and economic equations. Developed by

ANL and initially released in 2011, BatPaC has undergone continuous updates, reaching version 5.1, which was utilized for the implementation described in this study. Created in Microsoft Excel, BatPaC is freely available to users who submit a request and provide justification for its use from ANL's official website (Figure 8) [133].

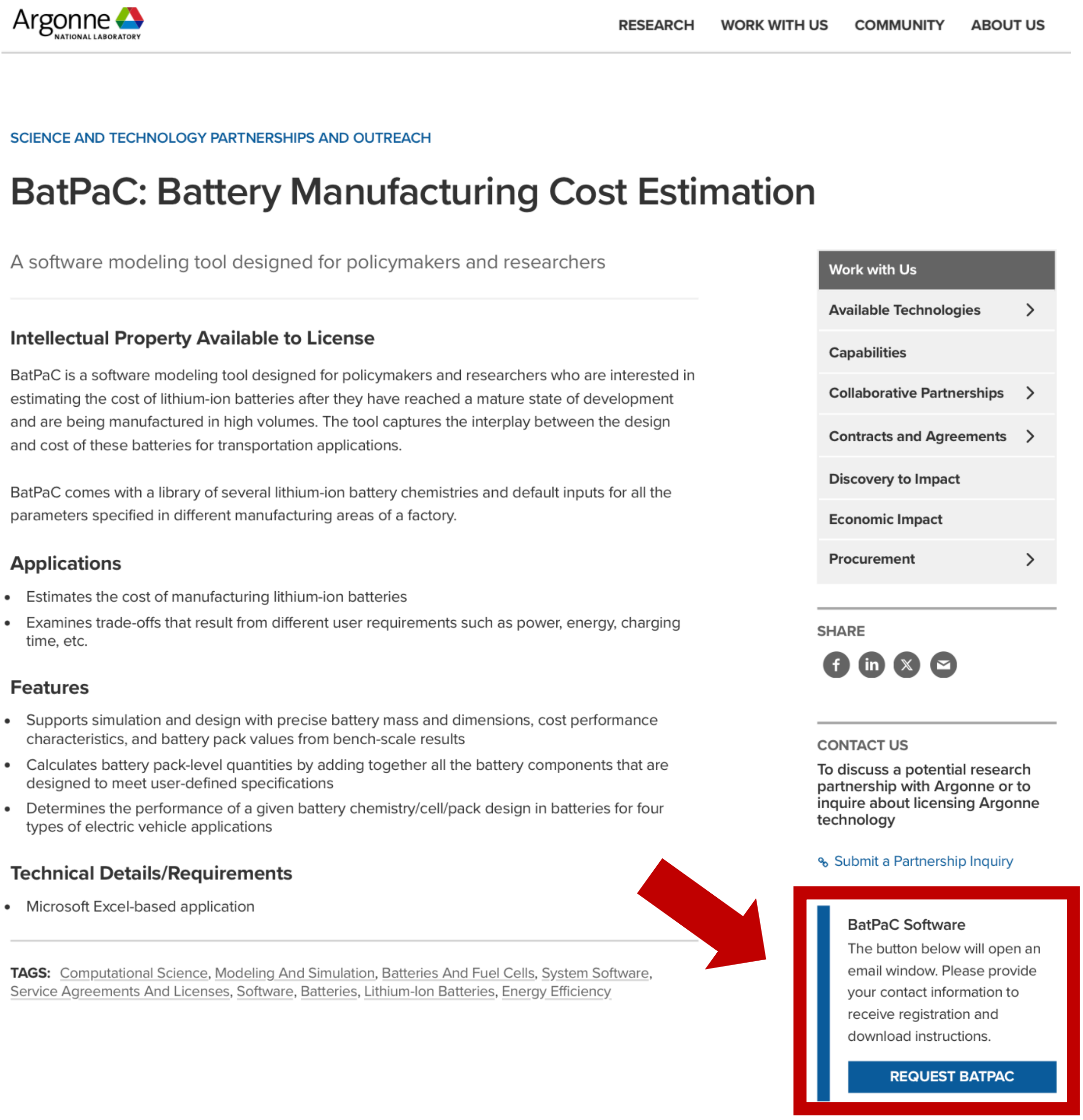

Figure 8 - BatPaC Download

The tool consists of multiple interconnected worksheets that guide users through the design, calculation, and analysis process. The key worksheets are organized as follows:

- *Dashboard Worksheet*: This is the central interface for user inputs, where users specify battery design parameters. These include a wide range of variables such as:
    - *Chemistry*: Users can select from a variety of electrode chemistries, including lithium nickel manganese cobalt oxide (NMC811, NMC622, NMC532), LFP, lithium manganese oxide (LMO), lithium nickel cobalt aluminum oxide (NCA), lithium cobalt oxide (LCO), and lithium titanate (LTO).
    - *Power Requirements*: Parameters include target rated peak power (kW), duration at rated power (s), and operating initial SOC (%).
    - *Storage Specifications*: Includes total pack capacity (Ah), total pack energy (kWh), and usable energy as a percentage of total capacity.
    - *Pack Configuration*: Inputs cover the number of cells per module, cells in parallel, and module rows within a pack.
    - *Manufacturing Strategies*: Users define plant size, annual production rate, and cell yield rates.
    - *Optional inputs* allow further customization, such as adjusting electrode thickness, Si content in anodes, separator properties, and costs for raw materials.

It also provides a quick summary of outputs, error messages, and warnings to ensure the configuration aligns with physical and manufacturing constraints.

- *Summary of Results Worksheet*: This sheet compiles key metrics such as battery size, weight, cost, and configuration parameters at the cell, module, pack, and system levels. It also allows dynamic customization of variables for inclusion in summary tables or graphical comparisons.

- *Design Sheets*: A collection of worksheets dedicated to:
    - *Chem Worksheet*: Managing and adjusting the electrochemical and physical properties of battery components, such as electrode porosity, separator thickness, and specific capacity. Users can customize these values to reflect new chemistries or material configurations.
    - *Battery Design and BMS Worksheets*: Detailing the structural and functional aspects of the battery pack, from the cell level to the battery management system. Inputs include the arrangement of cells and modules, cooling system configurations, and specifications for battery interconnects.
- *Cost Sheets*: These provide a comprehensive breakdown of manufacturing costs, including raw materials, labor, and capital expenses. The cost sheets also include options to adjust assumptions about plant size and production scale to model different economic scenarios. Specific sheets include:
    - *Manufacturing Costs*: Tracks expenses associated with production processes.
    - *Cost Input*: Allows users to enter cost data for raw materials and labor.
    - *Cost Breakdown and Detailed Cost Breakdown*: Offers high-level and granular analyses of cost distribution across the manufacturing pipeline.
- *TMS Worksheets*: These calculate thermal behavior within the pack, using assumptions about coolant flow and material properties to estimate temperature gradients and ensure effective heat dissipation.
- *Other Sheets*: Handle background calculations essential for generating the outputs, such as efficiency adjustments, scrap rates, and additional computational processes.

Each worksheet contributes to a bottom-up simulation approach that integrates design inputs with physical and economic models to deliver detailed results. Outputs are dynamically updated as user inputs change, making BatPaC a flexible tool for iterative design and cost analysis. This detailed modular approach enables users to explore trade-offs between design choices, evaluate the feasibility of various configurations, and optimize battery systems to meet specific requirements.

The data processed by BatPaC are empirically derived from ANL's Cell Analysis, Modeling, and Prototyping (CAMP) Facility, providing validated input parameters on material properties, electrode behavior, and manufacturing costs. This empirical foundation ensures that the model's outputs reflect realistic and experimentally verified conditions. BatPaC's calculations rely on established electrochemical principles and cost modeling equations. Specifically, the tool employs the area-specific impedance (ASI) model, which is derived from porous electrode theory to calculate battery impedance during operation. This model integrates factors such as electrode porosity, particle size, ionic conductivity, and exchange current densities, providing precise insights into electrochemical performance under varying conditions [134]. In addition to electrochemical modeling, BatPaC includes a robust cost estimation framework. It calculates production costs by incorporating material usage, labor expenses, and capital investments, offering a detailed breakdown of economic feasibility. For instance, users can adjust parameters like plant capacity, production yield rates, and material costs to explore different cost scenarios. A key feature of BatPaC is its ability to model and compare up to seven battery configurations simultaneously. All cases share the same electrode chemistry and target application but vary in design parameters, such as pack configuration, cooling requirements, or manufacturing details. This parallel modeling approach allows users to assess trade-offs between design choices, such as energy density versus cost-efficiency, and evaluate their impact on performance metrics like power density and total cost. The outputs generated by BatPaC span a comprehensive range of metrics, including battery pack size, weight, energy density, power density, and cost. These metrics enable users to analyze how variations in design and manufacturing processes influence overall performance and economic viability. For instance, detailed visualizations and tabulated results on the Dashboard allow for quick comparisons of key outputs across configurations. To further enhance usability, BatPaC includes options for scenario analysis. Users can simulate how different operating conditions, such as ambient temperature or SOC ranges, affect performance and lifetime [73].

5.2. Integrating BatPaC with LCA Indicators

This section outlines the implementation of the LCA tool integrated into BatPaC. As shown in Figure 9, the original BatPaC workflow (a) has been expanded to incorporate LCA functionalities (b).

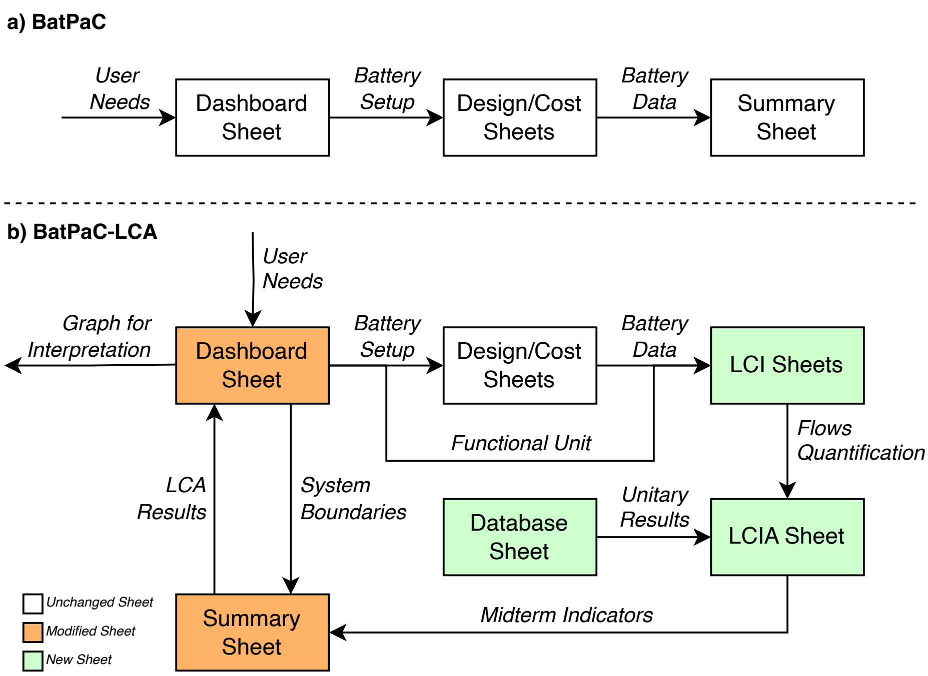

Figure 9 - a) BatPaC System Workflow; b) BatPaC-LCA's System Workflow

This integration was achieved by introducing new spreadsheets (highlighted in green) that align with the ISO phases for LCA. These spreadsheets include the LCI Sheets for organizing input-output flows into black boxes during the inventory phase and the LCIA Sheet for applying characterization factors derived from the chosen database and method. Additionally, modifications were made to existing spreadsheets (highlighted in orange) to support the Goal and Scope and Interpretation phases. Specifically, the Dashboard Sheet now includes the *LCA* section for selecting the FU and End-of-Life scenarios. Furthermore, the Dashboard Sheet features a graphical visualization section for interpreting results, while the Summary Sheet has been enhanced with granular result tables to facilitate detailed analysis.

5.2.1. Goal and Scope Definition Phase Implementation

To accommodate varying objectives in LCA, five FUs were incorporated, reflecting common practices in the literature [135]. These FUs can be selected via the *Dashboard* (Figure 10), in the *LCA* section. Each FU is associated with a specific conversion factor, which dynamically adjusts the subsequent LCI and LCIA calculations to reflect the initial selection. The available FUs are as follows:

- *Kilograms of battery per kWh*: Aligned with the Battery Regulation, Art. 7, par. 1(d), this FU is the baseline. Therefore, the conversion factor used for this FU is 1.
- *Kilograms of battery per* mile: Derived from the "Energy requirement of battery pack, Wh/mile" in the Battery Design sheet, this FU relates to the energy efficiency in terms of distance traveled. The value is divided by 1.000 to convert Wh/mile into kWh/mile to be compatible with the chosen baseline. Generally, the resulting conversion factor is less than 1.
- *Kilograms of battery per km*: Conceptually similar to the previous FU, this one is expressed in kilometers, a unit widely used in Europe and other contexts. The conversion factor for this FU is obtained by dividing the conversion factor of the FU "kg/mile" by 1,60934 to account for the transformation of miles into kilometers.

- *Kilograms of battery*: This FU is based on the total weight of the battery. To use this FU, the entries in the baseline, expressed in kg per 1 kWh, are multiplied by the total energy of the battery in kWh, as specified in the Battery Design sheet.
- *A kilogram of battery*: To determine the conversion factor for this FU, the inverse of the energy-to-mass ratio (expressed as kWh per kg in the baseline FU) is applied. This approach shifts the perspective from energy-based impacts to mass-based impacts, providing a more granular evaluation of the environmental footprint per kilogram of battery.

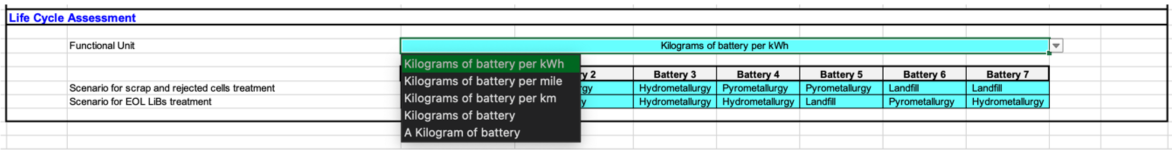

Figure 10 – Functional Unit (FU) Selection Menu in *Dashboard* Sheet

The system boundaries for this LCA follow a cradle-to-grave approach (Figure 11), compliant with the Battery Regulation, Annex II, Par. 4. This includes impacts from all material inputs, manufacturing processes, and end-of-life (EoL) stages, covering both production scraps and rejected cells, and EoL battery. Transport is included, but the use phase is excluded as it is not under direct manufacturer control unless design choices significantly influence it. Although the Regulation considers machinery negligible, they are included in this tool to validate this assumption. The manufacturing phase begins with the production of the positive and negative electrodes through processes such as materials preparation/mixing, electrode coating, calendering, notching, and vacuum drying. This is followed by cell assembly in a dry room, encompassing steps like electrode slitting, cell stacking, current collector welding, X-ray inspection, and electrolyte filling. The formation cycling tests cells, with a selectable discard rate in the Dashboard sheet, after which cells are assembled into modules and then packs. The tool also accounts for processes related to warehousing and building support systems. Process efficiencies, indicated in the *Cost Input* sheet and suggested by the BatPaC guide [73], are adjustable as needed and were necessary to calculate production scraps.

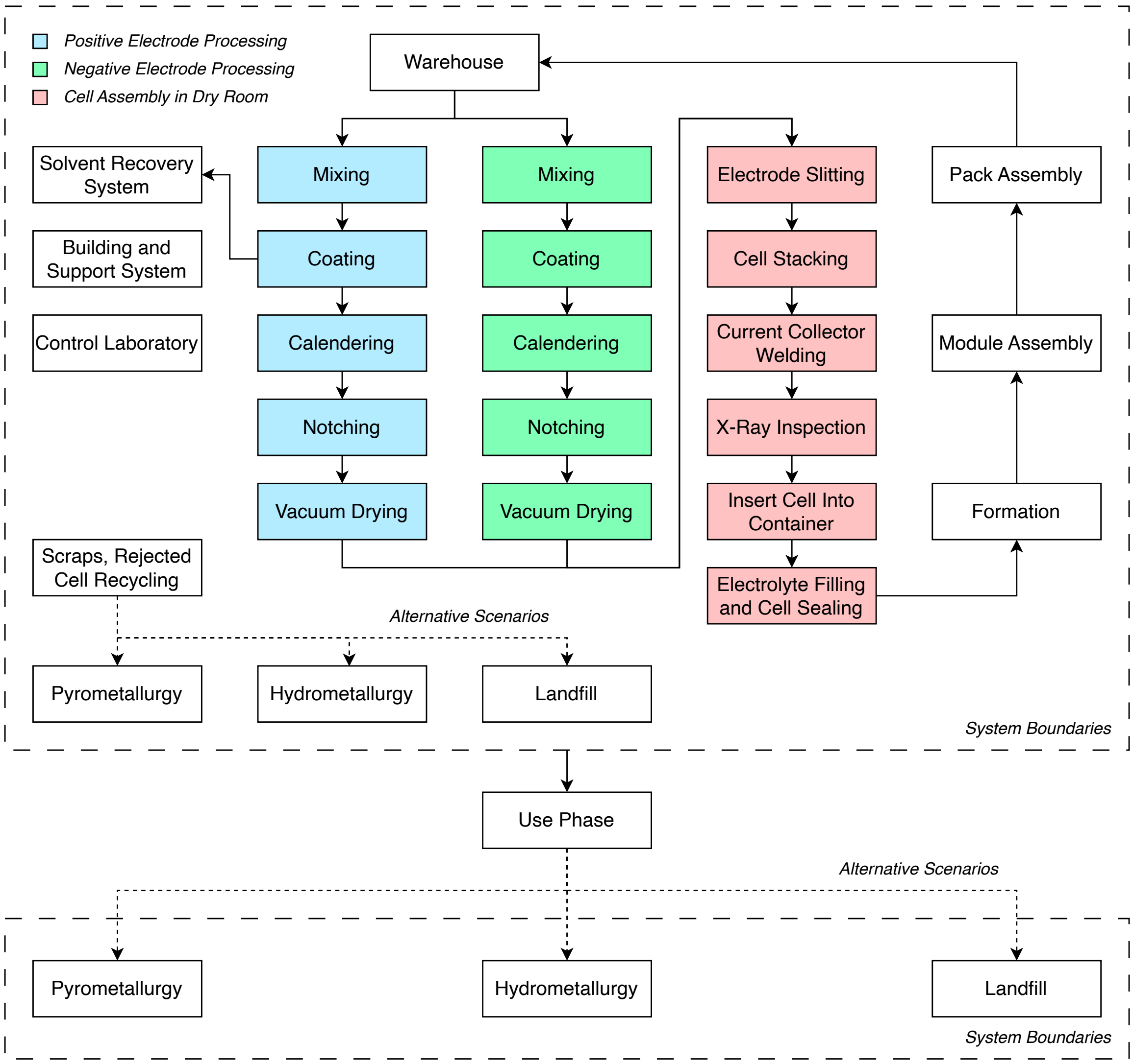

Figure 11 – BatPaC-LCA's System Boundaries. Diagram adapted from [73]**.**

For EoL stage, three scenarios are considered with different recovery percentages selected from scientific literature and adjustable as needed:

- *Pyrometallurgy*: Recovers Ni (98,39%), Co (98,83%), and Cu (93,57%), generates a slag containing Li, Mn, Al, Fe, and Si used in the construction sector, with unrecovered materials sent to landfill [136].
- *Hydrometallurgy*: Recovers Li (66,83%), Ni (84,83%), Mn (99,80%), Co (98,51%) after mechanical pretreatment, which also recovers Al (76,90%) and Cu (59,00%). Unrecovered materials are landfilled [137], [138].
- *Landfill*: No material recovery. While this scenario is not a legally viable option in the EU context, it is included to highlight the comparative benefits of recycling technologies.

Two distinct waste streams were considered: scraps production and rejected cells, and EoL batteries. These streams were treated separately, with independent scenarios developed for each to ensure detailed, flexible assessments (Figure 12).

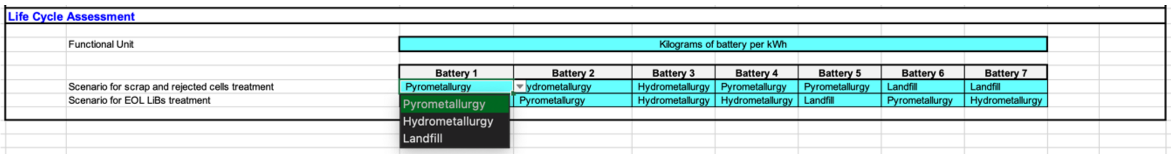

Figure 12 - End-of-Life Selection Menu in *Dashboard* Sheet

5.2.2. LCI Phase Implementation

In the LCI section of the tool, three sheets were developed to comprehensively capture the data necessary for a robust LCA: *LCI Materials*, *LCI Processes*, and *LCI Black Boxes*. The *LCI Materials* and *LCI Processes* sheets function as a detailed inventory system, gathering information from across the original BatPaC software. These sheets collect and organize data related to elemental flows associated with specific components or processes. The information is then processed and arranged into *LCI Black Boxes*, the third spreadsheet, which consolidates these inputs into a structured format suitable for the LCI phase.

LCI Materials focuses on collecting data for all input and output materials across various processes and phases. It is structured based on the *Recycling* sheet (*Other Sheets*) and provides a detailed data collection method, normalized to kg/kWh, the baseline FU as outlined in section 5.2.1.

The sheet is divided into several sections. The “Elemental Analysis of Electrodes and Electrolyte” excludes binder and conductive additives and details the active materials of the anode, cathode, electrolyte, separator, and various additives (Figure 13). The data are extracted from the *Battery Design*, *Manufacturing Cost*, and *List* sheets (*Other Sheets*). When specific material allocation between the anode and cathode cannot be extrapolated, a 50% split is applied.

Elemental Anaylsis of Electrodes and Electrolyte (Excludes Binder and Conductive Additives)							
Cell balance							
Positive active material, g/cell	319,191	319,191	319,191	319,191	319,191	319,191	319,191
Negative active material per cell, g/cell	216,521	216,521	216,521	216,521	216,521	216,521	216,521
Electroylte mass, g/cell	85,054	85,054	85,054	85,054	85,054	85,054	85,054
Electroylte volume, L/cell	0,071	0,071	0,071	0,071	0,071	0,071	0,071
Separator, g/cell	6,698	6,698	6,698	6,698	6,698	6,698	6,698
Positive additive, g/cell	-	-	-	-	-	-	-
Negative additive, g/cell	-	-	-	-	-	-	-
Electrolyte additive, g/cell	85,054	85,054	85,054	85,054	85,054	85,054	85,054
Positive electrode carbon additive, g/cell	7,439	7,439	7,439	7,439	7,439	7,439	7,439
Positive electrode binder, g/cell	7,439	7,439	7,439	7,439	7,439	7,439	7,439
Positive electrode binder solvent (NMP), g/cell	119,019	119,019	119,019	119,019	119,019	119,019	119,019
Negative electrode carbon additive, g/cell	-	-	-	-	-	-	-
Negative electrode binder, g/cell	4,943	4,943	4,943	4,943	4,943	4,943	4,943
Negative electrode binder solvent (Water), g/cell	197,720	197,720	197,720	197,720	197,720	197,720	197,720
Positive active material, kg/kWh	1,277	1,277	1,277	1,277	1,277	1,277	1,277
Negative active material, kg/kWh	0,866	0,866	0,866	0,866	0,866	0,866	0,866
Electrolyte, kg/kWh	0,340	0,340	0,340	0,340	0,340	0,340	0,340
Separator, kg/kWh	0,027	0,027	0,027	0,027	0,027	0,027	0,027
Positive additive, kg/kWh	-	-	-	-	-	-	-
Negative additive, kg/kWh	-	-	-	-	-	-	-
Electrolyte additive, kg/kWh	0,340	0,340	0,340	0,340	0,340	0,340	0,340
Positive electrode carbon additive, kg/kWh	0,030	0,030	0,030	0,030	0,030	0,030	0,030
Positive electrode binder, kg/kWh	0,030	0,030	0,030	0,030	0,030	0,030	0,030
Positive electrode binder solvent (NMP), kg/kWh	0,476	0,476	0,476	0,476	0,476	0,476	0,476
Negative electrode carbon additive, kg/kWh	-	-	-	-	-	-	-
Negative electrode binder, kg/kWh	0,020	0,020	0,020	0,020	0,020	0,020	0,020
Negative electrode binder solvent (Water), kg/kWh	0,791	0,791	0,791	0,791	0,791	0,791	0,791
Lithium Balance							
Li mass in positive active material, g/cell	22,768	22,768	22,768	22,768	22,768	22,768	22,768
Li mass in negative active material, g/cell	-	-	-	-	-	-	-
Li mass in electroylte, g/cell	0,590	0,590	0,590	0,590	0,590	0,590	0,590
Li mass in positive additive, g/cell	-	-	-	-	-	-	-
Li mass in negative additive, g/cell	-	-	-	-	-	-	-
Li mass in electrolyte additive, g/cell	-	-	-	-	-	-	-
Li mass, g/cell	23,358	23,358	23,358	23,358	23,358	23,358	23,358
Li mass, kg/pack	9,343	9,343	9,343	9,343	9,343	9,343	9,343
Li mass, kg/kWh	**0,093**	**0,093**	**0,093**	**0,093**	**0,093**	**0,093**	**0,093**
Li mass in positive active material, kg/kWh	**0,091**	**0,091**	**0,091**	**0,091**	**0,091**	**0,091**	**0,091**
Li mass in negative active material, kg/kWh	-	-	-	-	-	-	-
Ni Balance							
Ni mass in positive active material, g/cell	154,086	154,086	154,086	154,086	154,086	154,086	154,086
Ni mass in negative active material, g/cell	-	-	-	-	-	-	-

Figure 13 - LCI Materials sheet, active materials

The “Elemental Analysis of Additional Components” includes materials for components such as Al, Cu, steel, stainless steel, and systems like the BMS and TMS which are found in cells, modules, and packs, as illustrated in Figure 14. Data are derived from the Battery Design and Chem sheets.

Elemental Analysis of Additional Components (Binder and Conductive Additives)							
Aluminum							
Aluminum in cell current collectors, kg/pk	7,674	7,674	7,674	7,674	7,674	7,674	7,674
Aluminum in cell terminals, kg/pk	2,300	2,300	2,300	2,300	2,300	2,300	2,300
Aluminum in thermal conductors, kg/pk	10,171	10,171	10,171	10,171	10,171	10,171	10,171
Aluminum in pack jacket, kg/pk	33,233	33,233	33,233	33,233	33,233	33,233	33,233
Total aluminum content, kg/pk	53,378	53,378	53,378	53,378	53,378	53,378	53,378
Aluminum in cell current collectors, kg/kWh	**0,077**	**0,077**	**0,077**	**0,077**	**0,077**	**0,077**	**0,077**
Aluminum in cell terminals, kg/kWh	**0,023**	**0,023**	**0,023**	**0,023**	**0,023**	**0,023**	**0,023**
Aluminum in thermal conductors, kg/kWh	**0,102**	**0,102**	**0,102**	**0,102**	**0,102**	**0,102**	**0,102**
Aluminum in pack jacket, kg/kWh	**0,332**	**0,332**	**0,332**	**0,332**	**0,332**	**0,332**	**0,332**
Aluminum content, kg/kWh	**0,534**	**0,534**	**0,534**	**0,534**	**0,534**	**0,534**	**0,534**
Copper							
Copper in cell current collectors, kg/pk	18,116	18,116	18,116	18,116	18,116	18,116	18,116
Copper in cell terminals, kg/pk	5,088	5,088	5,088	5,088	5,088	5,088	5,088
Copper in cell interconnects, kg/pk	6,758	6,758	6,758	6,758	6,758	6,758	6,758
Copper in tabs to module terminals, kg/pk	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Copper in module terminals, kg/pk	0,990	0,990	0,990	0,990	0,990	0,990	0,990
Copper in module interconnects, kg/pk	1,944	1,944	1,944	1,944	1,944	1,944	1,944
Copper in bus bars, kg/pk	0,979	0,979	0,979	0,979	0,979	0,979	0,979
Copper in pack terminals, kg/pk	0,466	0,466	0,466	0,466	0,466	0,466	0,466
Total copper content, kg/pk	35,341	35,341	35,341	35,341	35,341	35,341	35,341
Copper in cell current collectors, kg/kWh	**0,181**	**0,181**	**0,181**	**0,181**	**0,181**	**0,181**	**0,181**
Copper in cell terminals, kg/kWh	**0,051**	**0,051**	**0,051**	**0,051**	**0,051**	**0,051**	**0,051**
Copper in cell interconnects, kg/kWh	**0,068**	**0,068**	**0,068**	**0,068**	**0,068**	**0,068**	**0,068**
Copper in tabs to module terminals, kg/kWh	**0,010**	**0,010**	**0,010**	**0,010**	**0,010**	**0,010**	**0,010**
Copper in module terminals, kg/kWh	**0,010**	**0,010**	**0,010**	**0,010**	**0,010**	**0,010**	**0,010**
Copper in module interconnects, kg/kWh	**0,019**	**0,019**	**0,019**	**0,019**	**0,019**	**0,019**	**0,019**
Copper in bus bars, kg/kWh	**0,010**	**0,010**	**0,010**	**0,010**	**0,010**	**0,010**	**0,010**
Copper in pack terminals, kg/kWh	**0,005**	**0,005**	**0,005**	**0,005**	**0,005**	**0,005**	**0,005**
Copper content, kg/kWh	**0,353**	**0,353**	**0,353**	**0,353**	**0,353**	**0,353**	**0,353**
Steel							
Steel in row racks, kg/pk	55,738	55,738	55,738	55,738	55,738	55,738	55,738
Steel in pack jacket, kg/pk	20,035	20,035	20,035	20,035	20,035	20,035	20,035
Steel in support frame, kg/pk	15,926	15,926	15,926	15,926	15,926	15,926	15,926
Total steel content, kg/pk	91,699	91,699	91,699	91,699	91,699	91,699	91,699
Steel in row racks, kg/kWh	**0,557**	**0,557**	**0,557**	**0,557**	**0,557**	**0,557**	**0,557**
Steel in pack jacket, kg/kWh	**0,200**	**0,200**	**0,200**	**0,200**	**0,200**	**0,200**	**0,200**
Steel in support frame, kg/kWh	**0,159**	**0,159**	**0,159**	**0,159**	**0,159**	**0,159**	**0,159**
Steel content, kg/kWh	**0,917**	**0,917**	**0,917**	**0,917**	**0,917**	**0,917**	**0,917**
Stainless steel							
Stainless steel in module encolsures, kg/pk	15,465	15,465	15,465	15,465	15,465	15,465	15,465
Stainless steel in cooling panels, kg/pk	16,725	16,725	16,725	16,725	16,725	16,725	16,725

Figure 14 - LCI Materials sheet, additional components

The "Recoverable Materials Rejected from Plant Floor" section provides information on recoverable materials from production scraps and rejected cells. The quantities and relevant processes are determined using data present in the *Cost Input* sheet, which indicates the material yields during electrode and cell fabrication (Figure 15). These data are adjustable based on the efficiency of the plants during processes where materials are added, such as mixing, coating, electrode slitting, cell stacking, and electrode filling, and are categorized separately for anode and cathode.

Cell yield, %	95	*(change in dashboard)*					
Materials yield per accepted cell, %			Effective Yield Across All Steps	Mixing	Coating	Electrode Slitting	Cell Stacking	Electrolyte Filling
Positive electrode material, dry (default = 99, 97, 99, 99, -), %			94,1	99	97	99	99	
Negative electrode material, dry (defulat = 99, 97, 99, 99, -), %			94,1	99	97	99	99	
Positive current collector foil (default = -, 97, 92, 99, -), %			88,3		97	92	99	
Negative current collector foil (default = -, 97, 92, 99, -), %			88,3		97	92	99	
Separators (default = -, -, -, 99, -), %			99,0				99	
Electrolyte (default = -, -, -, -, 99), %			99,0					99
Binder (NMP) solvent recovery, %			99,5					

Figure 15 - Effective yield per stages per component in *Cost Input* sheet

In the Dashboard, the user inputs both the yield of cells accepted and the Number of accepted cells per year. From these inputs, additional metrics are derived, as shown in Figure 16. The Number of cells rejected per year during the testing phase is calculated, and the sum of the accepted and rejected cells yields the Number of cells per year adjusted for yield, which represents the annual production capacity of the facility. This metric is essential for accurately estimating material usage and scrap generation throughout the manufacturing process. Therefore, for each material involved in the various manufacturing stages mentioned in Figure 15, the associated scrap was estimated. These values were allocated based on the number of cells produced and subsequently normalized to the baseline FU. As shown in Figure 16, the resulting figures are minimal but represent values that contribute positively to the LCA analysis.

Recoverable Materials Rejected from Plant Floor									
Number of accepted cells per year			200.000.000	200.000.000	200.000.000	200.000.000	200.000.000	200.000.000	200.000.000
Number of cells per year adjusted for yield			210.526.316	210.526.316	210.526.316	210.526.316	210.526.316	210.526.316	210.526.316
Number of cells rejected per year			10.526.316	10.526.316	10.526.316	10.526.316	10.526.316	10.526.316	10.526.316
Material Available for Recycle from Plant Floor, kg/year (Not Including Rejected Cells)									
Component Breakdown, kg/kWh									
Positive active material, kg/kWh			0,084	0,084	0,084	0,084	0,084	0,084	0,084
Negative active material, kg/kWh			0,057	0,057	0,057	0,057	0,057	0,057	0,057
Positive current collector, kg/kWh			0,011	0,011	0,011	0,011	0,011	0,011	0,011
Negative current collector, kg/kWh			0,025	0,025	0,025	0,025	0,025	0,025	0,025
Separator, kg/kWh	*Wasted during Cell Stacking process		0,000	0,000	0,000	0,000	0,000	0,000	0,000
Electrolyte, kg/kWh	*Wasted during Electrolyte Filling process		0,004	0,004	0,004	0,004	0,004	0,004	0,004
Positive electrode binder solvent (NMP), kg/kWh	0,50%	*Wasted during Coating	0,002	0,002	0,002	0,002	0,002	0,002	0,002
Elemental Breakdown, kg/kWh									
From Elemental Analysis of Electrodes and Electrolyte (Excluding Binder and Conductive Additive)									
Li, kg/kWh			0,006	0,006	0,006	0,006	0,006	0,006	0,006
Li wasted during Mixing in positive active material, kg/kWh			0,001	0,001	0,001	0,001	0,001	0,001	0,001
Li wasted during Mixing in negative active material, kg/kWh			0,000	0,000	0,000	0,000	0,000	0,000	0,000
Li wasted during Coating in positive active material, kg/kWh			0,003	0,003	0,003	0,003	0,003	0,003	0,003
Li wasted during Coating in negative active material, kg/kWh			0,000	0,000	0,000	0,000	0,000	0,000	0,000
Li wasted during Electrode Slitting in positive active material, kg/kWh			0,001	0,001	0,001	0,001	0,001	0,001	0,001
Li wasted during Electrode Slitting in negative active material, kg/kWh			0,000	0,000	0,000	0,000	0,000	0,000	0,000
Li wasted during Cell Stacking in positive active material, kg/kWh			0,001	0,001	0,001	0,001	0,001	0,001	0,001
Li wasted during Cell Stacking in negative active material, kg/kWh			0,000	0,000	0,000	0,000	0,000	0,000	0,000
Ni, kg/kWh			0,039	0,039	0,039	0,039	0,039	0,039	0,039
Ni wasted during Mixing in positive active material, kg/kWh			0,007	0,007	0,007	0,007	0,007	0,007	0,007
Ni wasted during Mixing in negative active material, kg/kWh			0,000	0,000	0,000	0,000	0,000	0,000	0,000
Ni wasted during Coating in positive active material, kg/kWh			0,020	0,020	0,020	0,020	0,020	0,020	0,020
Ni wasted during Coating in negative active material, kg/kWh			0,000	0,000	0,000	0,000	0,000	0,000	0,000
Ni wasted during Electrode Slitting in positive active material, kg/kWh			0,006	0,006	0,006	0,006	0,006	0,006	0,006
Ni wasted during Electrode Slitting in negative active material, kg/kWh			0,000	0,000	0,000	0,000	0,000	0,000	0,000
Ni wasted during Cell Stacking in positive active material, kg/kWh			0,006	0,006	0,006	0,006	0,006	0,006	0,006
Ni wasted during Cell Stacking in negative active material, kg/kWh			0,000	0,000	0,000	0,000	0,000	0,000	0,000

Figure 16 - LCI Materials sheet, production waste

A similar approach was applied to materials from cells that fail testing, which are recycled according to one of the methodologies selected by the user, as illustrated in Figure 17.

Materials in Cells Rejected after Testing, kg/year							
Elemental Breakdown, kg/kWh							
From Elemental Analysis of Electrodes and Electrolyte (Excluding Binder and Conductive Additive)							
Li (Positive Electrode), kg/kWh	0,005	0,005	0,005	0,005	0,005	0,005	0,005
Li (Negative Electrode), kg/kWh	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Ni (Positive Electrode), kg/kWh	0,032	0,032	0,032	0,032	0,032	0,032	0,032
Ni (Negative Electrode), kg/kWh	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Mn (Positive Electrode), kg/kWh	0,004	0,004	0,004	0,004	0,004	0,004	0,004
Mn (Negative Electrode), kg/kWh	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Co (Positive Electrode), kg/kWh	0,004	0,004	0,004	0,004	0,004	0,004	0,004
Co (Negative Electrode), kg/kWh	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Al (Positive Electrode), kg/kWh	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Al (Negative Electrode), kg/kWh	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Fe (Positive Electrode), kg/kWh	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Fe (Negative Electrode), kg/kWh	0,000	0,000	0,000	0,000	0,000	0,000	0,000
P (Positive Electrode), kg/kWh	0,000	0,000	0,000	0,000	0,000	0,000	0,000
P (Negative Electrode), kg/kWh	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Ti (Positive Electrode), kg/kWh	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Ti (Negative Electrode), kg/kWh	0,000	0,000	0,000	0,000	0,000	0,000	0,000
O (Positive Electrode), kg/kWh	0,022	0,022	0,022	0,022	0,022	0,022	0,022
O (Negative Electrode), kg/kWh	0,000	0,000	0,000	0,000	0,000	0,000	0,000
S (Positive Electrode), kg/kWh	0,000	0,000	0,000	0,000	0,000	0,000	0,000
S (Negative Electrode), kg/kWh	0,000	0,000	0,000	0,000	0,000	0,000	0,000
C (Positive Electrode), kg/Wh	0,000	0,000	0,000	0,000	0,000	0,000	0,000
C (Negative Electrode), kg/Wh	0,046	0,046	0,046	0,046	0,046	0,046	0,046
Si (Positive Electrode), kg/kWh	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Si (Negative Electrode), kg/kWh	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Al in cell current collectors, kg/kWh	0,004	0,004	0,004	0,004	0,004	0,004	0,004
Al in cell terminals, kg/kWh	0,001	0,001	0,001	0,001	0,001	0,001	0,001
Cu in cell current collectors, kg/kWh	0,010	0,010	0,010	0,010	0,010	0,010	0,010
Cu in cell terminals, kg/kWh	0,003	0,003	0,003	0,003	0,003	0,003	0,003
Cu in cell interconnects, kg/kWh	0,004	0,004	0,004	0,004	0,004	0,004	0,004
Separator, kg/kWh	0,001	0,001	0,001	0,001	0,001	0,001	0,001
Electrolyte, kg/kWh	0,018	0,018	0,018	0,018	0,018	0,018	0,018

Figure 17 - *LCI Materials* sheet, rejected cell materials

The “End of Life Materials” section is divided into materials from production scraps and rejected cells, and those from EoL batteries. Based on EoL scenarios, the tool calculates recovered materials, unrecovered materials, and slag quantities for use in the building and construction sector. Recovery rates for each material are based on literature values but can be modified, just like other aspects of the tool. As shown in the example in Figure 18, which illustrates the pyrometallurgical process, adjusting the yellow-highlighted cells modifies the recovery rates and, consequently, the entire scenario.

Output Scenarios									
S1: Pyrometallurgy	(%)	Description							
Li, kg/kWh	1	Slag, used as clinker in B&C sector	0,093	0,093	0,093	0,093	0,093	0,093	0,093
Ni, kg/kWh	0,9839	Recovered	0,606	0,606	0,606	0,606	0,606	0,606	0,606
Mn, kg/kWh	1	Slag, used as clinker in B&C sector	0,072	0,072	0,072	0,072	0,072	0,072	0,072
Co, kg/kWh	0,9883	Recovered	0,076	0,076	0,076	0,076	0,076	0,076	0,076
Al, kg/kWh	1	Slag, used as clinker in B&C sector	0,534	0,534	0,534	0,534	0,534	0,534	0,534
Fe, kg/kWh	1	Slag, used as clinker in B&C sector	0,000	0,000	0,000	0,000	0,000	0,000	0,000
P, kg/kWh	0	Recovered	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Ti, kg/kWh	0	Recovered	0,000	0,000	0,000	0,000	0,000	0,000	0,000
O, kg/kWh	1	Not recovered	0,420	0,420	0,420	0,420	0,420	0,420	0,420
S, kg/kWh	1	Not recovered	0,000	0,000	0,000	0,000	0,000	0,000	0,000
C, kg/Wh	1	Not recovered	0,866	0,866	0,866	0,866	0,866	0,866	0,866
Si, kg/kWh	1	Slag, used as clinker in B&C sector	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Cu, kg/kWh	0,9357	Recovered	0,331	0,331	0,331	0,331	0,331	0,331	0,331
Steel, kg/kWh	1	Slag, used as clinker in B&C sector	0,917	0,917	0,917	0,917	0,917	0,917	0,917
Stainless Steel, kg/kWh	1	Slag, used as clinker in B&C sector	0,331	0,331	0,331	0,331	0,331	0,331	0,331
BMS, kg/kWh	1	Not recovered	0,036	0,036	0,036	0,036	0,036	0,036	0,036
Ethylene glycol, kg/kWh	1	Not recovered	0,132	0,132	0,132	0,132	0,132	0,132	0,132
Separator, kg/kWh	1	Not recovered	0,027	0,027	0,027	0,027	0,027	0,027	0,027
Electrolyte, kg/kWh	1	Not recovered	0,340	0,340	0,340	0,340	0,340	0,340	0,340
Ni, kg/kWh	0,0161	Not recovered	0,010	0,010	0,010	0,010	0,010	0,010	0,010
Co, kg/kWh	0,0117	Not recovered	0,001	0,001	0,001	0,001	0,001	0,001	0,001
P, kg/kWh	1	Not recovered	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Ti, kg/kWh	1	Not recovered	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Cu, kg/kWh	0,0643	Not recovered	0,023	0,023	0,023	0,023	0,023	0,023	0,023

Figure 18 - *LCI Materials* sheet, end-of-life scenario

Transitioning to the second sheet, *LCI Processes* this section captures energy consumption data from the Manufacturing Cost and Cost Input sheets, as well as equipment details derived from the BatPaC guide. For the Electrode Processing phase, each energy consumption value is divided between the anode and cathode to accurately assess their respective impacts. These calculations are based on data provided by ANL and are normalized to kW/kWh, as illustrated in Figure 19.

Manufacturing Processes - Energy Consumption							
Electrode Processing							
Materials Preparation/mixing							
Positive slurry (volume/yr)							
Operating Power, kW	6.939,87	6.939,87	6.939,87	6.939,87	6.939,87	6.939,87	6.939,87
Operating Power, kW/y	53.298.171,99	53.298.171,99	53.298.171,99	53.298.171,99	53.298.171,99	53.298.171,99	53.298.171,99
Energy Consumption, kW/kWh	**1,07**	**1,07**	**1,07**	**1,07**	**1,07**	**1,07**	**1,07**
Negative slurry (volume/yr)							
Operating Power, kW	7.938,68	7.938,68	7.938,68	7.938,68	7.938,68	7.938,68	7.938,68
Operating Power, kW/y	60.969.090,23	60.969.090,23	60.969.090,23	60.969.090,23	60.969.090,23	60.969.090,23	60.969.090,23
Energy Consumption, kW/kWh	**1,22**	**1,22**	**1,22**	**1,22**	**1,22**	**1,22**	**1,22**
Electrode Coating							
Positive materials (positive area/yr)							
Coater & dryer power, kW	4.340,94	4.340,94	4.340,94	4.340,94	4.340,94	4.340,94	4.340,94
Power to heat air, kW	21.206,76	21.206,76	21.206,76	21.206,76	21.206,76	21.206,76	21.206,76
Operating power, kW	25.547,70	25.547,70	25.547,70	25.547,70	25.547,70	25.547,70	25.547,70
Operating Power, kW/y	196.206.307,58	196.206.307,58	196.206.307,58	196.206.307,58	196.206.307,58	196.206.307,58	196.206.307,58
Energy Consumption, kW/kWh	**3,92**	**3,92**	**3,92**	**3,92**	**3,92**	**3,92**	**3,92**
Negative materials (negative area/yr)							
Coater & dryer power, kW	4.344,48	4.344,48	4.344,48	4.344,48	4.344,48	4.344,48	4.344,48
Power to heat air, kW	4.064,97	4.064,97	4.064,97	4.064,97	4.064,97	4.064,97	4.064,97
Operating power, kW	8.409,44	8.409,44	8.409,44	8.409,44	8.409,44	8.409,44	8.409,44
Operating Power, kW/y	64.584.503,74	64.584.503,74	64.584.503,74	64.584.503,74	64.584.503,74	64.584.503,74	64.584.503,74
Energy Consumption, kW/kWh	**1,29**	**1,29**	**1,29**	**1,29**	**1,29**	**1,29**	**1,29**

Figure 19 - *LCI Processes* sheet, energy consumption

Similarly, equipment-related energy consumption, though excluded from the system boundaries concerning the CF under the Battery Regulation, is included here to substantiate its negligible contribution. These values are also allocated between the anode and cathode until the cells are fully assembled and are expressed in unit/kWh to ensure comprehensive and transparent impact evaluation (Figure 20).

Manufacturing Processes - Equipments								
Electrode Processing	Quantity							
Materials Preparation/mixing								
Positive slurry (volume/yr)								
Planetary mixer 2,300L, unit	18							
Planetary mixer 2,300L, unit/kWh		**0,00000003**	**0,00000003**	**0,00000003**	**0,00000003**	**0,00000003**	**0,00000003**	**0,00000003**
Negative slurry (volume/yr)								
Planetary mixer 2,700L, unit	24							
Planetary mixer 2,700L, unit/kWh		**0,00000005**	**0,00000005**	**0,00000005**	**0,00000005**	**0,00000005**	**0,00000005**	**0,00000005**
Electrode Coating								
Positive materials (positive area/yr)								
Slot-die coater, unit	5							
Slot-die coater, unit/kWh		**0,00000001**	**0,00000001**	**0,00000001**	**0,00000001**	**0,00000001**	**0,00000001**	**0,00000001**
Negative materials (negative area/yr)								
Slot-die coater, unit	5							
Slot-die coater, unit/kWh		**0,00000001**	**0,00000001**	**0,00000001**	**0,00000001**	**0,00000001**	**0,00000001**	**0,00000001**

Figure 20 - *LCI Processes* sheet, equipments

Building upon the results obtained in the *LCI Materials* and *LCI Processes* sheets, these data are consolidated in the *LCI Black Boxes* sheet, which reorganizes all collected information into black boxes that adhere to the processes outlined by ANL, as represented in Table 17. Each black box is structured to include input flows and output flows, providing a clear depiction of material and energy exchanges (Figure 21). For all processes related to Electrode Processing, the inputs and outputs are further divided into contributions from the cathode (P: positive electrode) and the anode (N: negative electrode), ensuring a detailed and component-specific analysis.

Table 17 - LCI Black Boxes, (P) = Positive Electrode, (N) Negative Electrode

Black Box	Input	Output
Mixing (P), (N)	Active Materials, Carbon Additive, Binder, Binder Solvent, Machinery, Energy	Waste (Active Materials)
Coating (P), (N)	Current Collectors, Machinery, Energy	Waste (Active Materials, Solvent, Current Collectors)
Electrode Slitting (P), (N)	Machinery, Energy	Waste (Active Materials, Current Collectors)
Cell Stacking	Cell Interconnects, Separator, Machinery, Energy	Waste (Active Materials, Current Collectors, Separator)
Current Collector Welding	Cell Terminals, Machinery, Energy	
Electrolyte Filling and Cell Sealing	Electrolyte, Machinery, Energy	
Formation Cycling	Machinery, Energy	Waste (Rejected Cells)
Module Assembly	Thermal Conductors, Tabs, Module Terminals, Module Interconnects, Module Enclosures, Machinery, Energy	
Pack Assembly	Pack Jacket, Bus Bars, Pack Terminals, Row Racks, Pack Jacket, Support Frame, Cooling Panels and Manifolds, BMS, TMS, Machinery, Energy	
EOL Scenarios	Selected Treatment, Landfill Treatment	Recovered and Not Recovered Materials, Slag for Construction
All the other processes	Machinery, Energy	

Process	Input	Output	Battery 1	Battery 2	Battery 3	Battery 4	Battery 5	Battery 6	Battery 7
Materials Preparation/mixing (P)									
	Li, kg/kWh		1,01E-01	1,01E-01	1,01E-01	1,01E-01	1,01E-01	1,01E-01	1,01E-01
	Ni, kg/kWh		6,87E-01	6,87E-01	6,87E-01	6,87E-01	6,87E-01	6,87E-01	6,87E-01
	Mn, kg/kWh		8,04E-02	8,04E-02	8,04E-02	8,04E-02	8,04E-02	8,04E-02	8,04E-02
	Co, kg/kWh		8,63E-02	8,63E-02	8,63E-02	8,63E-02	8,63E-02	8,63E-02	8,63E-02
	Al, kg/kWh		0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
	Fe, kg/kWh		0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
	P, kg/kWh		0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
	Ti, kg/kWh		0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
	O, kg/kWh		4,68E-01	4,68E-01	4,68E-01	4,68E-01	4,68E-01	4,68E-01	4,68E-01
	S, kg/kWh		0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
	C, kg/kWh		0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
	Si, kg/kWh		0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
	Positive electrode carbon additive, kg/kWh		2,98E-02	2,98E-02	2,98E-02	2,98E-02	2,98E-02	2,98E-02	2,98E-02
	Positive electrode binder, kg/kWh		2,98E-02	2,98E-02	2,98E-02	2,98E-02	2,98E-02	2,98E-02	2,98E-02
	Positive electrode binder solvent (NMP), kg/kWh		4,76E-01	4,76E-01	4,76E-01	4,76E-01	4,76E-01	4,76E-01	4,76E-01
	Planetary mixer 2,300L, unit/kWh		3,42E-08	3,42E-08	3,42E-08	3,42E-08	3,42E-08	3,42E-08	3,42E-08
	Energy Consumption, kW/kWh		1,07E+00	1,07E+00	1,07E+00	1,07E+00	1,07E+00	1,07E+00	1,07E+00
		Li, kg/kWh	9,50E-04	9,50E-04	9,50E-04	9,50E-04	9,50E-04	9,50E-04	9,50E-04
		Ni, kg/kWh	6,57E-03	6,57E-03	6,57E-03	6,57E-03	6,57E-03	6,57E-03	6,57E-03
		Mn, kg/kWh	7,69E-04	7,69E-04	7,69E-04	7,69E-04	7,69E-04	7,69E-04	7,69E-04
		Co, kg/kWh	8,24E-04	8,24E-04	8,24E-04	8,24E-04	8,24E-04	8,24E-04	8,24E-04
		Al, kg/kWh	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
		Fe, kg/kWh	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
		P, kg/kWh	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
		Ti, kg/kWh	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
		O, kg/kWh	4,48E-03	4,48E-03	4,48E-03	4,48E-03	4,48E-03	4,48E-03	4,48E-03
		S, kg/kWh	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
		C, kg/kWh	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
		Si, kg/kWh	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00

Figure 21 - ***LCI Black Boxes*** **sheet frame**

All entries and values adjust based on the selected FU, with units and values automatically updated according to the specific FU. It should be noted that active materials, carbon, binder, and binder solvent are grouped under the Mixing process, which typically exhibits the highest impacts. Material inputs include both basic components for battery composition and associated production scraps and rejected cell.

5.2.3. LCIA Phase Implementation

In the LCIA section, two sheets were created: *LCIA Database* and *LCIA Results*. The *LCIA Database* sheet comprehensively lists all input and output flows, associating them with entries from the ecoinvent 3.10 database and applying relevant characterization factors from the ReCiPe 2016 v1.03 method for impact assessment (Figure 22).

Ecoinvent v3.10 - cutoff Method: ReCiPe 2016 v1.03, midpoint (H)				
		Acidification: Terrestrial	Climate Change	Ecotoxicity: Fre
Flow	Ecoinvent Activity Name	Terrestrial Acidification Potential (TAP)(kg SO2-Eq)	Global Warming Potential (GWP100)(kg CO2-Eq)	Freshwater Ecot
Li	market for lithium (GLO)	4,10E-01	8,44E+01	
Ni	market for nickel, class 1 (GLO)	1,51E+00	1,86E+01	
Mn	market for manganese (GLO)	2,55E-02	5,65E+00	
Co	market for cobalt (GLO)	3,56E-01	4,85E+01	
Al	market for aluminium, primary, ingot (RoW)	9,80E-02	2,28E+01	
Fe	Market for cast iron (GLO)	4,89E-03	1,98E+00	
P	market for phosphorus, white, liquid (GLO)	4,50E-02	1,36E+01	
Ti	market for titanium (GLO)	2,08E-01	5,05E+01	
O	market for oxygen, liquid (RoW)	3,64E-03	1,15E+00	
S	market for sulfur (GLO)	1,76E-02	1,96E-01	
C	market for graphite (GLO)	3,30E-04	7,43E-02	
Si	market for silicon, metallurgical grade (GLO)	4,06E-02	1,17E+01	
Positive electrode carbon additive	market for carbon black (GLO)	6,25E-03	2,51E+00	
Positive electrode binder	market for acrylic binder, with water, in 54% solution state (RoW)	8,82E-03	2,98E+00	
Positive electrode binder solvent (NMP)	market for N-methyl-2-pyrrolidone (GLO)	2,61E-02	9,09E+00	
Planetary mixer 2,300L	market for electronic component machinery, unspecified (GLO)	1,07E+02	2,48E+04	
Energy Consumption	market group for electricity, medium voltage (GLO)	2,35E-03	7,41E-01	
Negative electrode carbon additive	market for carbon black (GLO)	6,25E-03	2,51E+00	
Negative electrode binder	market for acrylic binder, with water, in 54% solution state (RoW)	8,82E-03	2,98E+00	
Negative electrode binder solvent (Water)	market for tap water (RoW)	4,40E-06	1,31E-03	
Planetary mixer 2,700L	market for electronic component machinery, unspecified (GLO)	1,07E+02	2,48E+04	
Aluminum in cell current collectors	market for aluminium collector foil, for Li-ion battery (GLO)	7,06E-02	1,63E+01	
Copper in cell current collectors	market for copper collector foil, for Li-ion battery (GLO)	4,31E-01	9,09E+00	
Slot-die coater	market for electronic component machinery, unspecified (GLO)	1,07E+02	2,48E+04	

Figure 22 - ***LCIA Database*** **sheet frame**

These selections were made to facilitate direct comparison with LCA results from the literature, as discussed in Section 5.3. The entries chosen for the database align with descriptions provided by ecoinvent and the compositions of existing entries within it, such as “battery, Li-ion, LFP, rechargeable, prismatic”. For the evaluation of environmental impacts, the tool incorporates 18 midpoint indicators, which are detailed in Section 3.4 of this document. Several critical considerations were made during the selection of database entries to ensure global data relevance:

- Geography: The selection prioritized entries with global (GLO) applicability, and where these were not available, the rest of the world (RoW) entries were used.
- Transport: "Market For" entries were chosen to include average transportation impacts.
- Electricity: "Market group" entries were used to ensure that the electricity values applied would be valid, if not highly precise, across various usage scenarios.

The *LCIA Results* sheet is structured similarly to the *LCI Black Boxes* sheet (Figure 23). It multiplies the values from the *LCI Black Boxes* by the characterization factors from the *LCIA Database*, thereby producing the LCIA results for each process of each battery design. This sheet accommodates all three EoL scenarios for both scrap and EoL batteries.

Functional Unit: Kilograms of battery per kWh			Battery 1					
Process	Input	Output	TAP (kg SO2-Eq)	GWP100 (kg CO2-Eq)	FETP (kg 1,4-DCB-Eq)	METP (kg 1,4-DCB-Eq)	TETP (kg 1,4-DCB-Eq)	FFP (kg c
Materials Preparation/mixing (P)								
	Li		4,16E-02	8,56E+00	5,90E-01	8,12E-01	6,76E+01	
	Ni		1,04E+00	1,28E+01	6,82E+00	9,47E+00	1,92E+03	
	Mn		2,05E-03	4,55E-01	3,84E-01	5,72E-01	2,09E+00	
	Co		3,07E-02	4,19E+00	1,56E+00	2,18E+00	2,22E+02	
	Al		0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	
	Fe		0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	
	P		0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	
	Ti		0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	
	O		1,70E-03	5,39E-01	1,19E-02	1,72E-02	1,46E+00	
	S		0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	
	C		0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	
	Si		0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	
	Positive electrode carbon additive		1,86E-04	7,47E-02	1,32E-03	2,17E-03	4,35E-01	
	Positive electrode binder		2,62E-04	8,86E-02	4,39E-03	6,32E-03	6,76E-01	
	Positive electrode binder solvent (NMP)		1,24E-02	4,33E+00	1,43E-01	2,19E-01	3,68E+01	
	Planetary mixer 2,300L		3,64E-06	8,48E-04	4,03E-04	5,73E-04	4,00E-02	
	Energy Consumption		2,50E-03	7,90E-01	1,84E-02	2,64E-02	2,16E+00	
		Li	5,48E-08	1,82E-05	4,99E-05	6,18E-05	4,40E-04	
		Ni	3,79E-07	1,26E-04	3,45E-04	4,27E-04	3,04E-03	
		Mn	4,43E-08	1,47E-05	4,04E-05	5,00E-05	3,56E-04	
		Co	4,75E-08	1,58E-05	4,33E-05	5,36E-05	3,82E-04	
		Al	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	
		Fe	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	
		P	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	
		Ti	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	
		O	2,58E-07	8,57E-05	2,35E-04	2,91E-04	2,07E-03	
		S	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	
		C	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	
		Si	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	
Tot			1,13E+00	3,18E+01	9,54E+00	1,33E+01	2,26E+03	

Figure 23 - *LCIA Results* sheet frame

5.2.4. Interpretation Phase Implementation

To facilitate interpretation, specific functions were integrated into the *Dashboard* and *Summary of Results* sheets. As described in Section 5.2.1, the *Dashboard* features a “Life Cycle Assessment” section, allowing users to select the FU and EoL scenarios. These selections are dynamically reflected in the *Summary of Results* sheet, specifically in the “Life Cycle Assessment” section, where the environmental impacts for each indicator are reported based on the selected scenarios. The tool's design supports detailed reporting on the environmental impacts of the anode, cathode, cell, module, and pack components. Users can expand specific sections within the sheet to view individual contributions, as shown in Figure 24, enabling a granular examination of each component’s impact across different stages.

182	**Life Cycle Assessment**							
183								
184	LCA - Cradle-to-Grave							
185	Terrestrial Acidification Potential (TAP)(kg SO2-Eq)	1,59E-01	1,76E-01	3,02E-01	2,85E-01	1,23E+00	2,82E-01	4,08E-01
186	Global Warming Potential (GWP100)(kg CO2-Eq)	5,57E+01	5,50E+01	4,21E+01	4,28E+01	6,87E+01	5,73E+01	4,44E+01
187	Freshwater Ecotoxicity Potential (FETP)(kg 1,4-DCB-Eq)	-1,49E+00	-9,32E-01	4,41E+00	3,85E+00	1,90E+01	7,94E-01	6,14E+00
188	Marine Ecotoxicity Potential (METP)(kg 1,4-DCB-Eq)	-1,13E+00	-4,33E-01	6,27E+00	5,57E+00	2,57E+01	1,85E+00	8,55E+00
189	Terrestrial Ecotoxicity Potential (TETP)(kg 1,4-DCB-Eq)	3,71E+02	4,08E+02	7,08E+02	6,72E+02	2,58E+03	6,27E+02	9,27E+02
190	Fossil Fuel Potential (FFP)(kg oil-Eq)	1,41E+01	1,40E+01	1,08E+01	1,10E+01	1,78E+01	1,46E+01	1,14E+01
191	Freshwater Eutrophication Potential (FEP)(kg P-Eq)	1,78E-02	1,81E-02	1,89E-02	1,86E-02	4,22E-02	2,07E-02	2,14E-02
192	Marine Eutrophication Potential (MEP)(kg N-Eq)	6,95E-03	6,66E-03	3,65E-03	3,94E-03	8,45E-03	7,19E-03	4,18E-03
193	Human Toxicity Potential (HTPc)(kg 1,4-DCB-Eq)	4,88E+01	4,57E+01	4,31E+01	4,63E+01	8,46E+01	4,97E+01	4,71E+01
194	Human Toxicity Potential (HTPnc)(kg 1,4-DCB-Eq)	-2,77E+00	6,43E+00	8,52E+01	7,60E+01	3,51E+02	3,75E+01	1,16E+02
195	Ionising Radiation Potential (IRP)(kBq Co-60-Eq)	5,08E+00	5,05E+00	4,61E+00	4,64E+00	7,30E+00	5,37E+00	4,92E+00
196	Agricultural Land Occupation (LOP)(m2*a crop-Eq)	9,14E-01	9,18E-01	9,02E-01	8,97E-01	1,76E+00	1,01E+00	9,96E-01
197	Surplus Ore Potential (SOP)(kg Cu-Eq)	2,01E+01	1,90E+01	9,11E+00	1,02E+01	2,51E+01	2,07E+01	1,08E+01
198	Ozone Depletion Potential (ODPinfinite)(kg CFC-11-Eq)	1,67E-05	1,66E-05	1,50E-05	1,50E-05	2,85E-05	1,81E-05	1,64E-05
199	Particulate Matter Formation Potential (PMFP)(kg PM2.5-Eq)	1,01E-01	1,05E-01	1,28E-01	1,24E-01	4,13E-01	1,37E-01	1,60E-01
200	Photochemical Oxidant Formation Potential: Humans (HOFP)(kg NOx-Eq)	1,28E-01	1,27E-01	9,76E-02	9,90E-02	2,00E-01	1,37E-01	1,08E-01
201	Photochemical Oxidant Formation Potential: Ecosystems (EOFP)(kg NOx-Eq)	1,32E-01	1,31E-01	1,01E-01	1,02E-01	2,07E-01	1,41E-01	1,11E-01
202	Water Consumption Potential (WCP)(m3)	4,81E-01	4,94E-01	5,90E-01	5,77E-01	2,27E+00	6,90E-01	7,85E-01
203	*Other LCA Indicator*							
204	Carbon Footprint (kg CO2-Eq) Battery Regulation 2023/1542 compliant	5,57E+01	5,50E+01	4,21E+01	4,28E+01	6,87E+01	5,73E+01	4,44E+01
205								
206	Cathode - Cradle-to-Gate							
225								
226	Cathode - Materials							
245								
246	Anode - Cradle-to-Gate							
265								
266	Anode - Materials							
285								
286	Electrolyte - Materials							
305								
306	Cell - Cradle-to-Gate							
325								
326	Cell - Materials							
345								
346	Module - Cradle-to-Gate							
365								
366	Module - Materials							
385								
386	Pack - Cradle-to-Gate							
405								
406	Pack - Materials							

Figure 24 - Summary of Results, Life Cycle Assessment (LCA) results

Additionally, a special note is made for the cradle-to-grave LCA, where the CF, compliant with the Battery Regulation, is included as the GWP100 indicator with the FU set to kg/kWh, which remains constant regardless of user choices.

Graphical representations of these results are accessible in the Dashboard under the "Summary of Results and Graphing – LCA" section. This functionality allows users to select the type of LCA and specific indicators for visualization, as demonstrated in Figure 25. These graphical outputs enable users to compare the environmental impacts of different configurations comprehensively. Furthermore, they provide a pathway to verticalize the analysis by identifying the specific components or lifecycle phases contributing most significantly to the overall impacts. This feature enhances interpretability and guides targeted optimization efforts for battery design and production processes.

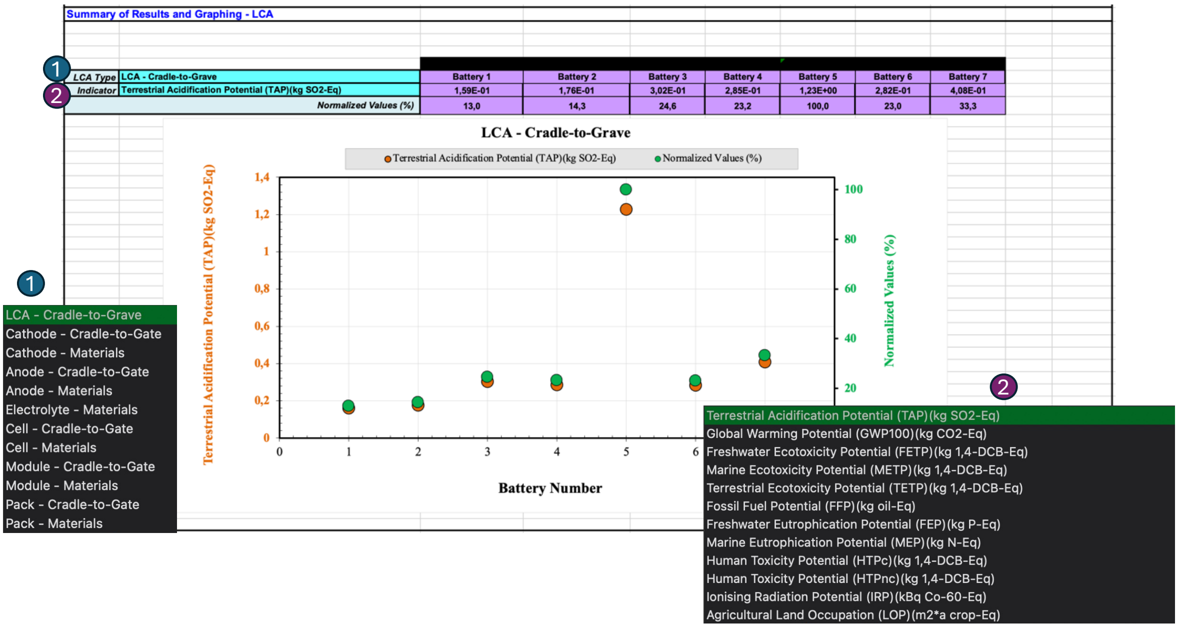

Figure 25 - Dashboard sheet, graphical LCA results comparison

5.3. BatPaC-LCA's Results reliability

In this section, the developed LCA tool is tested by comparing its results with literature data. The analysis involves the literature review conducted by A. Temporelli et al. [135], which compiled a range of cradle-to-gate results for various battery chemistries with a capacity of 40 kWh, specifically designed for EV, using 1 kWh as the FU. These ranges provide a benchmark for comparing different battery chemistries. Temporelli's review highlights key impact categories, including GWP100, TAP, ODP, and FEP. Although the study does not specify the LCIA method employed, it utilizes these midpoint categories and explicitly mentions the use of the ecoinvent database (v3.5). As a result, the review was considered compatible with the results offered by BatPaC-LCA. To ensure alignment, the same FU, battery capacity, and vehicle type were set within BatPaC-LCA for this comparative analysis. The results are presented in Table 18, comparing the range of values from the literature review with the ranges generated by BatPaC-LCA for the least and most impactful scenarios.

Table 18 - BatPaC-LCA results comparison with Temporelli's review.

Type	Indicator	Literature	BatPaC-LCA
NMC	GWP100 (kg CO2eq)	100 – 275	102 – 106 (*)
	Terrestrial Acidification Potential (TAP) (kg SO2eq)	1,5 – 3,5	1,42 – 1,56 (**)
	Ozone Depletion Potential (ODP) (kg CFC11eq)	< 0,002	0,00004 (*)
	Freshwater Eutrophication Potential (FEP) (kg P-Eq)	0,3 – 0,5	0,06 – 0,07 (*)
LFP	GWP100 (kg CO2eq)	150 – 250	95 – 96
	TAP (kg SO2eq)	1 – 1,5	0,60 – 0,65
	ODP (kg CFC11eq)	0,003 – 0,01	0,00003
	FEP (kg P-Eq)	0,4 – 0,5	0,06 – 0,07
LMO	GWP100 (kg CO2eq)	50 – 100	86 – 88
	TAP (kg SO2eq)	0,5 – 1	0,59 – 0,64
	FEP (kg P-Eq)	0,05 – 0,7	0,066 – 0,071
NCA	GWP100 (kg CO2eq)	75 – 125	92 – 95

* NMC333
** NMC95

Considering that literature review used an earlier version of the ecoinvent database, and did not specify the methods, system boundaries, or specific processes involved, the results obtained with BatPaC-LCA are highly satisfactory. All results fall within the upper limit proposed by the literature, and 7 out of 12 results also fall within the lower limit. Furthermore, the LMO and NCA chemistries show a perfect match, while NMC results vary depending on the specific chemistry used. The precise NMC chemistry was not specified in the literature, but the results align closely with NMC333 and NMC95 configurations. The LFP results, however, display lower values than those proposed in the literature. To address discrepancies observed for LFP and NMC chemistries and to ensure robustness, a second case study was conducted comparing BatPaC-LCA's outputs with the cradle-to-grave LCA results reported by Jiang et al. [139]. This study focuses on three chemistries—LFP, NCM622, and NCM811—utilized in EVBs and employs a hydrometallurgical recycling scenario. The study adheres to ISO 14044 standards and sets the FU as a 28 kWh battery pack, a unit compatible with industry practices, which considers the total weight of the entire battery pack as the FU, aligned with the options available in BatPaC-LCA. Within BatPaC-LCA, the FU was accordingly adjusted to kg/battery, along with specific capacity and EoL scenario settings, and the vehicle type. The comparative analysis concentrated on the GWP100 indicator, as Jiang et al. employed multiple methods for their LCIA, with ReCiPe 2016 v1.03 midpoint method being applied only for this specific indicator, making it the sole category available for direct comparison. Contrarily to the previous study, which presented ranges compiled from literature, this analysis conducted a detailed LCA and reported precise values for each chemistry, enabling a direct assessment of the percentage deviation between BatPaC-LCA's results and those provided in the study. The deviations between BatPaC-LCA's results and literature values underscore a strong alignment for NCM chemistries, with BatPaC-LCA estimating 1,86E+03 kg CO2 eq. for NCM622 and 1,83E+03 kg CO2 eq. for NCM811, reflecting deviations of only -1,6% and -3,2%, respectively, from Jiang et al.'s 1,89E+03 kg CO2 eq. for both. For LFP chemistry, however, BatPaC-LCA's estimate of 2,18E+03 kg CO2 eq. is 24,6% higher than the literature's reported 1,75E+03 kg CO2 eq. From these preliminary analyses, it emerges that chemistries such as NMC, LMO, and NCA achieve results comparable to those available in the literature, which typically require significant time and resources to conduct, whereas in BatPaC-LCA, the same results were obtained by simply setting the appropriate inputs. However, it is premature to draw definitive conclusions about the tool's reliability, given the limited availability of comparable LCA studies and the need for a larger set of tests to validate its performance across various scenarios. For LFP, the results are less consistent: the first analysis indicated lower values than the literature, while the second presented higher deviations. A third test will be conducted in the case study of Chapter 7, which pertains to the Check and Act phases, where the LCA performed using the LCI generated by the DPP will be compared with the data provided by BatPaC-LCA.

Chapter 6.

Digital Product Passport: A Universal Solution for Batteries and Other Key Industries

The developed DPP represents an attempt to develop a universal solution for structuring, verifying, and exchanging product data, starting from its implementation in the battery sector. As discussed in Section 2.6, the DPP consists of two fundamental components: the Data Model (DM) and the IT Infrastructure (ITI). Accordingly, this chapter is divided into these two sections, exploring their functionalities, use scenarios, and implementation details.

6.1. Data Model

The DM serves as the core of the DPP, ensuring a structured approach to collecting, validating, and sharing product data while maintaining interoperability across systems. It systematically captures information, organizes it for consistency, enables seamless exchange, and supports regulatory compliance and LCA applications. The model is designed with universality in mind, allowing it to be applied across various product categories while maintaining adaptability for specific sectoral needs. This universal approach has proven to be particularly suitable for the Battery DPP, as described in Section 6.1.3, which details its application to the battery sector. To maintain flexibility while ensuring regulatory compliance, the model is built upon a Foundational Data Model (FDM), a generic structural framework outlined in Section 6.1.1. The FDM provides the fundamental building blocks of the

DM, which are subsequently populated with sector-specific parameters following a structured methodology, as detailed in Section 6.1.2.

6.1.1. Foundational Data Model

The FDM is a high-level structure engineered to map the entire lifecycle of a product. Evolving from established Mandolini's framework [83], it has undergone significant adaptations to encompass the full spectrum of product-specific attributes, aligning data schemas with regulatory requirements, LCA methodologies, and, where applicable, PEFCRs. A principal aspect of the FDM is its modular approach, recognizing products as assemblies of interrelated yet distinct components. This approach is facilitated through an adaptable tree structure, capable of efficiently managing both fixed (e.g., anode and cathode) and variable parts (e.g., cooling systems), thereby eliminating the necessity for distinct DMs for different products. The FDM consists of a series of interlinked nodes, as shown in Figure 26, organized in a parent-child relationship as follows:

- PRODUCT node: This serves as the assembly node, representing the product in its entirety (e.g., battery). This node is the parent to a collection of PART nodes and focuses on the macro structure, aggregating characteristics and operational parameters of the product that are not specific to its individual components but are integral to its complete system (e.g., performance and durability).
- PART nodes: These are subordinate to the PRODUCT node and are dedicated to detailing specific parts of the product, encompassing both fixed and variable components. While, for example, the Battery Regulation, Annex XIII, 2(a), mandates detailed information uniquely for cathodes, anodes, and electrolytes, the unique FDM structure enables a deep dive into intricate detail levels, allowing a comprehensive reflection of real-world intricacies, a thorough comprehension of impacts, and the identification of potential areas for intervention.
- Lifecycle nodes: Present within both PRODUCT and PART nodes, these represent the various stages of a product's lifecycle: MATERIAL, MANUFACTURING, USE, END OF LIFE, and TRANSPORT. The configuration of these nodes diverges depending on whether they are located

within the PRODUCT or PART node. For example, the MATERIAL node, in its principal function, specifically details the materials that constitute the components of the product and is therefore exclusively present within the PART nodes. Additionally, the MATERIAL node appears at various hierarchical levels within the other lifecycle nodes, as explained in the following sections. The MANUFACTURING node pertains to the product's component production (PART nodes) and assembly processes (PRODUCT node). The USE node, located solely within the PRODUCT node, details and tracks the product's overall performance and maintenance. The END OF LIFE node details processes related to product (PRODUCT node) or component (PART node) recycling, disposal, and remanufacturing. The TRANSPORT node documents transport-related information of products (PRODUCT node) and components (PART node) across various stages.

- ATTRIBUTE nodes: Embedded within every node across the hierarchy, from the PRODUCT node to each lifecycle node, the ATTRIBUTE nodes are tasked with a fourfold purpose: (i) to serve as a registry for the parent node (e.g., Part ID), (ii) to fulfill specific legislative requirements, (iii) to provide pivotal information requisite for the formulation of an LCI, and (iv) to incorporate user feedback of any type to enhance continuous improvement.
- ENVIRONMENT node: The data collected in the ATTRIBUTE node undergo external LCA analyses, and the outcomes, mid-point LCA indicators, and CF, are stored in the ENVIRONMENT node. Unlike the ATTRIBUTE node, which varies for each parent node, the ENVIRONMENT node decomposes at lower hierarchical levels and reassembles at higher levels, ensuring a comprehensive environmental impact analysis at every stage. For example, in the context of batteries, the CF is calculated in line with the Battery Regulation, Annex II, 4, with its specifics included within the MANUFACTURING and TRANSPORT nodes of the BATTERY, as well as in every MATERIAL and END OF LIFE node. As for the mid-point indicators, ReCiPe indicators will be included, given their significant attention in the LCA studies of batteries in the literature.

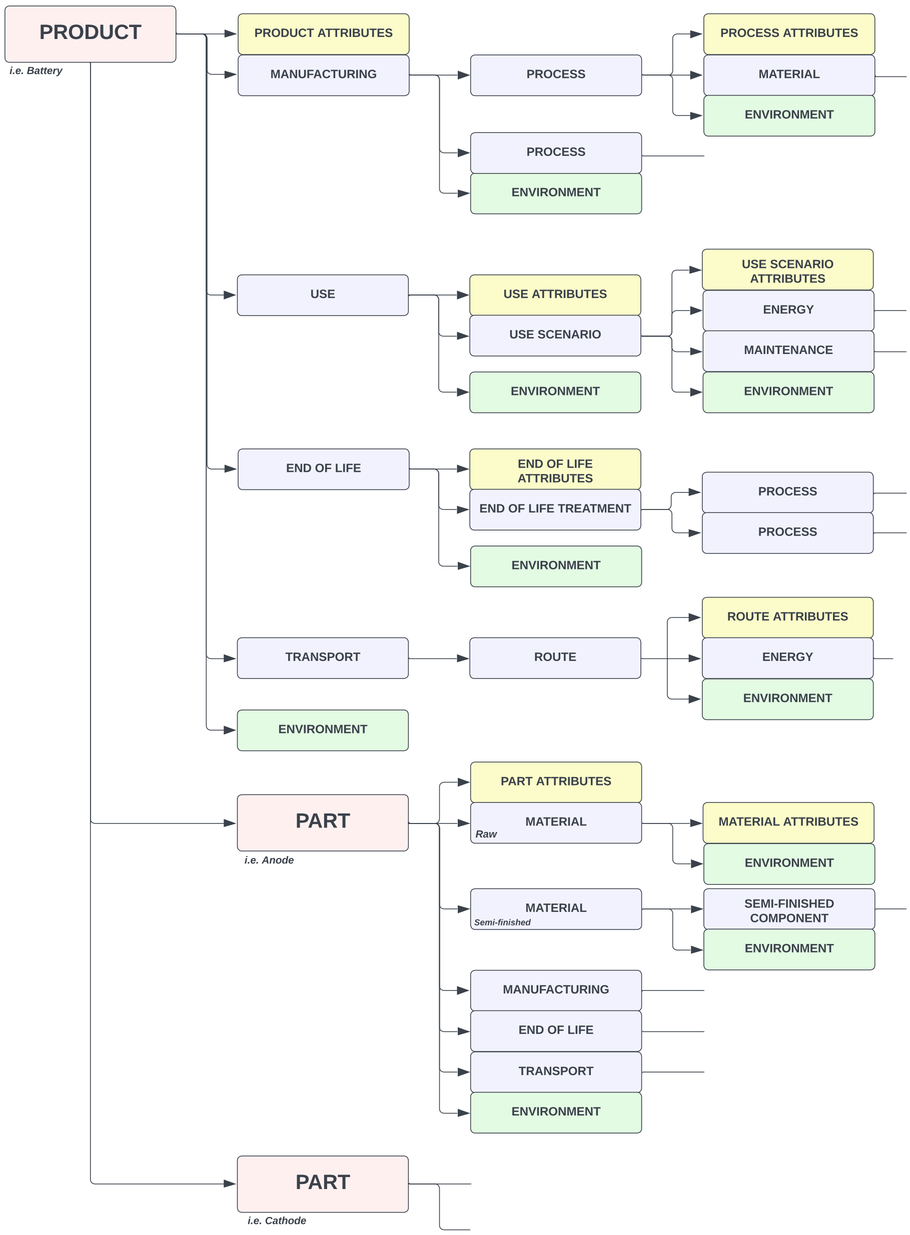

Figure 26 - FDM Structure

Delving deeper into the PRODUCT NODE, it forms the core of the FDM, encompassing PRODUCT ATTRIBUTES, MANUFACTURING, USE, END OF LIFE, TRANSPORT, and ENVIRONMENT child nodes.

PRODUCT ATTRIBUTES captures a wide range of parameters necessary for identifying and describing the product in its entirety and generality. Therefore, this includes product identification data, such as registration and cataloging information as required by the ESPR, alongside general parameters mandated by product-specific regulations. For instance, the Battery Regulation requires details on battery chemistry and EU declarations of conformity, information that cannot be dispersed into any other child or part nodes.

MANUFACTURING node addresses all assembly and testing processes of a product, throughout PROCESS nodes. Each PROCESS node collects information in PROCESS ATTRIBUTES node, such as Manufacturing data, the List of Part/Assembly Parameters (e.g., treated area, removed material quantity) and the LCA Process Parameters (e.g., water, energy, and waste) facilitating the formation of granular LCI. Moreover, the PROCESS node is accompanied by MATERIAL nodes, each representing auxiliary materials used in the process (e.g. solvents), and ENVIRONMENT node related to the impacts of the process. For example, in a battery, this might include details on the assembly of battery packs, tracking specific resources and energy inputs.

USE Node is comprised of USE ATTRIBUTES and a series of USE SCENARIOS, each reflecting every operational life of a product. Each time the product approaches its end-of-life and undergoes remanufacturing, a new USE SCENARIO is appended. The USE ATTRIBUTES section provides extensive data on product performance and durability, in compliance with regulatory standards. For example, for batteries, this includes information such as rated capacity, minimal, nominal, and maximum voltage, along with SOH parameters like self-discharging rates and ohmic resistance. Each USE SCENARIO, defined in the child node USE SCENARIO ATTRIBUTE, is bifurcated into two child nodes: ENERGY and MAINTENANCE. The ENERGY node contains ENERGY ATTRIBUTES detailing the energy source specifics (e.g., origin, type) and an integrated ENVIRONMENT node. The MAINTENANCE node is divided into three child nodes: MAINTENANCE ATTRIBUTES, PROCESS, and ENVIRONMENT. MAINTENANCE ATTRIBUTES encompass Maintenance Frequency, a critical metric, for example, for stationary and industrial batteries requiring regular upkeep. It also tracks the exchange of old PARTs for new ones, with the lifecycle of newly inserted parts being recorded in a subsequent PART node under PRODUCT. Specifically for batteries, the data structure is designed to seamlessly communicate with the BMS, as is the case with the software employed across the battery's entire lifecycle, enabling the integration of dynamic data changes throughout the battery's existence and ensuring the availability of real-time information.

END OF LIFE node encompasses END OF LIFE ATTRIBUTE, END OF LIFE TREATMENT, and ENVIRONMENT nodes. END OF LIFE ATTRIBUTE includes detailed information on the specific end-of-life scenario executed, such as the disposal path and recycling rate, collected in End of Life Scenario Parameters, along with other aspects of the end-of-life phase required by regulations. For example, for batteries, it is necessary to include data on the Prevention and Management of Waste Batteries and Dismantling Information, which comprises exploded diagrams of the battery system or pack and detailed disassembly sequences. The END OF LIFE TREATMENT node consists of a series of PROCESS nodes, described earlier, each providing an in-depth description of the various processes that the product undergoes at the end of its lifecycle. These processes cover a range of activities, including but not limited to collection, disassembly, pre-treatment, remanufacturing, recycling, incineration, and landfill disposal. Notably, during the remanufacturing phase, any new parts that are introduced are meticulously documented and registered within a designated PART node under PRODUCT, ensuring a complete and traceable record of all components and their lifecycle stages.

TRANSPORT node is structured into ROUTE nodes, this section captures critical data on the product's logistical journey, from sourcing components to their eventual disposal. These ROUTE nodes are distinguished by a comprehensive set of ROUTE ATTRIBUTES, which include crucial information like the origin, destination, and life cycle phase. The specific characteristics of each transport are further defined using a dedicated TRANSPORT SCENARIO node, which considers various factors such as the transportation payload's volume, mass, and distance traveled, significantly contributing to the LCI. To offer a widespread view, an ENVIRONMENT node is incorporated, compiling the environmental metrics relevant to each transport route.

Concluding with PART nodes, they mirror the structure of the PRODUCT node but with notable differences: they lack the USE node and include the MATERIAL node, reflecting their focus on specific components of a product. PART ATTRIBUTES, MANUFACTURING, END OF LIFE, and TRANSPORT nodes within PART nodes are analogous to those in the PRODUCT nodes but are specifically tailored to the activities and phases associated with individual parts, such as the manufacturing of a specific component or its recycling processes. For example, in the case of batteries, this could involve the production of separator or the recycling of cathodes. The novelty lies in the MATERIAL node, which serves as the essence of the PART node. It provides detailed descriptions of the materials constituting each part and takes two forms based on the material's origin:

- As Raw Material: Characterized by MATERIAL ATTRIBUTES, this includes identification details and regulatory specifications. For example, in the context of batteries, it covers aspects like responsible sourcing and information on recycled content.
- As Semi-Finished Product: In this form, it becomes a SEMI-FINISHED PART node, reflecting the PART node structure. This sub-node integrates MATERIAL, MANUFACTURING, and TRANSPORT nodes, focusing on raw material, its manufacturing processes, and logistics data tracked from suppliers.

To operationalize the FDM within an ITI, it was transformed into an XML Schema Definition (XSD) framework using Eclipse IDE. The XSD framework was developed to ensure data integrity, validation, and interoperability while maintaining regulatory compliance, providing a structured and standardized approach to managing product information. The primary XSD file, PRODUCT.xsd, serves as the root schema, structuring the overarching product DM. This schema references additional XSD files, which are organized into three dedicated folders, each containing multiple XSDs relevant to their specific domain:

- Product XSDs: This folder contains multiple schema files that define the attributes and structural elements unique to the PRODUCT node, ensuring product-level specificity and compliance with regulations.
- Part XSDs: This folder includes schema definitions detailing the structure and characteristics of PART nodes, accommodating both fixed and variable product components.
- Common XSDs: This folder houses shared schema definitions that are applicable to both PRODUCT and PART nodes, including general ATTRIBUTE and ENVIRONMENT elements, ensuring data consistency across all model components.

Each XSD file is composed of complexType and element definitions, ensuring a modular and hierarchical representation of the DM. The primary PRODUCT.xsd file imports these auxiliary schemas using the import function, which is structured as follows:

```
<import
     schemaLocation="folder/filename.xsd"
     namespace="http://example.com/filename/>.
</import>
```

The attribute specifies the relative path to the referenced XSD files, while the attribute designates a unique identifier for each schema category. For reasons of space and to avoid redundancy, Annex IV contains the final tailored version of the XML for the case study battery in Chapter 7. This version was generated starting from the FDM and structured using the population framework described in Section 6.1.2.

6.1.2. Framework for FDM Population

The framework provides a structured approach to defining product-specific DMs within the DPP system. Building on the FDM described in the previous section, it ensures a seamless transition from generic data structures to tailored product representations. The goal is to standardize and organize product data efficiently while maintaining flexibility for regulatory and lifecycle considerations. The following subsections describe the sequential stages of this process, leading from product identification to the establishment of a specific DM (Figure 27).

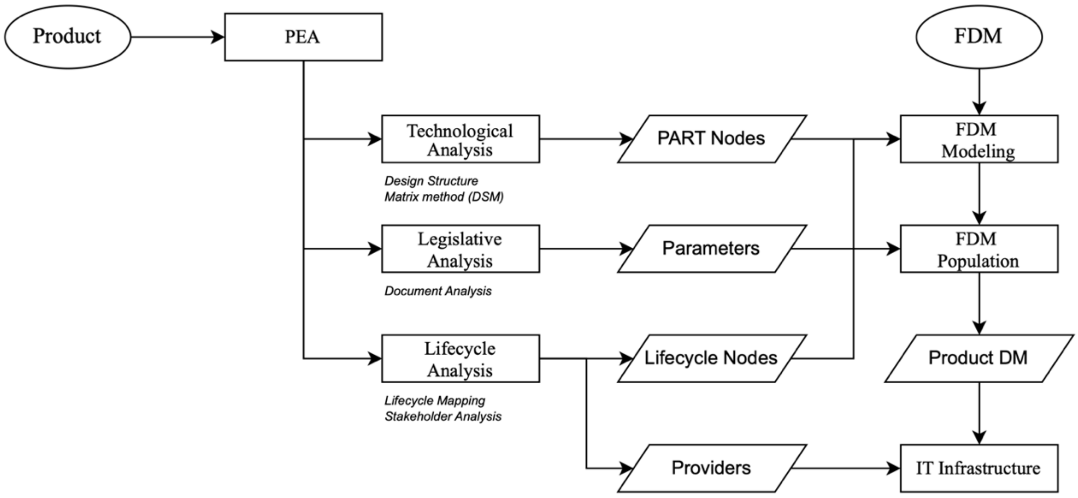

Figure 27 - Framework for FDM population workflow

The initial stage involves a Product Ecosystem Analysis (PEA), which delves into the technological aspects, legislative landscape, and lifecycle of the product. This multi-faceted analysis yields critical data essential for DM composition. An in-depth technology analysis deconstructs the product into its fundamental, in-dependent components, delineating distinct PART nodes. For products with a standardized structural baseline, such as batteries, which exhibit variability in chemical composition and dimensions, component identification is straightforward. For all other products, the adoption of a specific methodology is requisite. The Design Structure Matrix (DSM) Method is recommended for its flexibility, allowing customized applications across products [140]. It uses a matrix to map interactions among product elements, streamlining the elucidation of product architecture and modular disassembly. The legislative analysis is based on documental analysis, with the geographic context to identify relevant regulatory frameworks pertinent for the specific product category. This stage splits into two methodologies based on the regulatory landscape (Figure 28). Where precise product regulations exists, delineating objectives, limitations, thresholds, and requisites, DM parameters are extracted to meet compliance (i.e., Battery Regulation, Annex XIII [141]). Without specific regulations, an unstructured approach is necessitated. This entails reverting to overarching regulatory frameworks that span multiple sectors and impact the product lifecycle. Key aspects from these regulations and relevant voluntary documents are distilled for DM integration. For instance, Electrical and Electronic Equipment (EEE) within Europe, where an unstructured methodology anchored in the ESPR becomes imperative. Product durability, guided by UNI CEN EN 45552, exemplifies this approach. Identifying these parameters requires rigorously examining legislative texts to determine their compulsory or optional nature, engineering specificity, and data type (string, integer, float, Boolean).

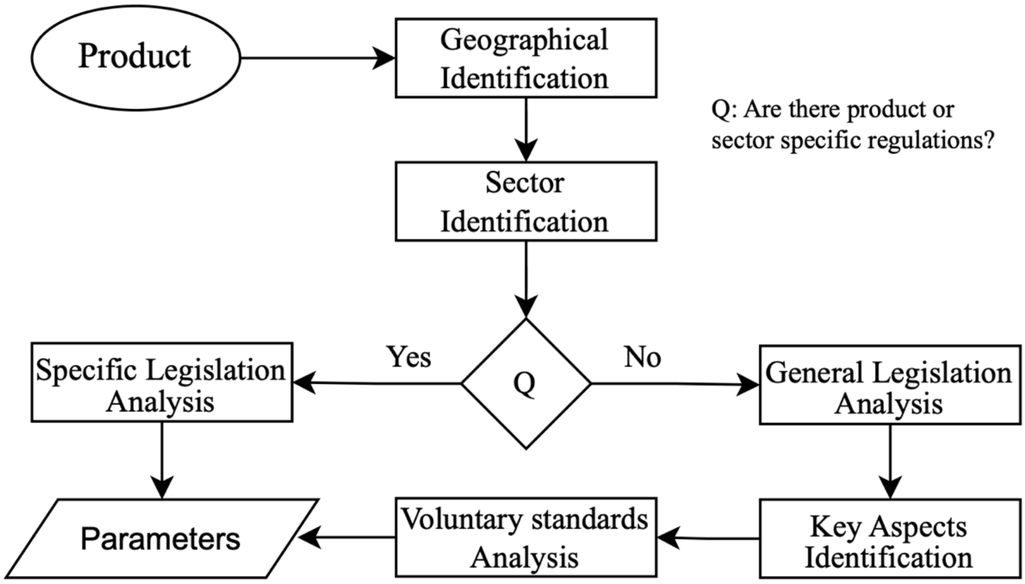

Figure 28 - Parameters identification through legislative analysis.

Lastly, conducting a lifecycle analysis is indispensable for granularizing the FDM through product lifecycle mapping and for identifying involved stakeholders who will act as data providers within an ITI. Upon the completion of PEA, the focus shifts to FDM modeling, establishing the hierarchies and structure of the Product DM collocating all identified nodes.

The subsequent step entails applying the parameters attribution decision-making process outlined in Figure 29 for the FDM population. The methodology aims to assign the parameters to specific ATTRIBUTES nodes, thereby maintaining the integrity of other node structures within the Product DM. Parameters are assessed through a three-tiered process to determine their optimal node allocation. The initial step ascertains if a parameter pertains to a specific product part or the product as a whole, directing its allocation to either the PART or PRODUCT node. Subsequently, the relevance of the parameter to specific lifecycle stages is evaluated, ensuring its association with the most pertinent phase, thereby enhancing the granularity and utility of the DM. If the parameter is not tied to a specific lifecycle stage, it is classified under PART ATTRIBUTES or PRODUCT ATTRIBUTES, depending on its specificity deter-mined in the previous step. The third and final tier encompasses the precise placement of the parameter within the selected ATTRIBUTE node. As expounded in Section 3.1, parameters within the ATTRIBUTES node are segmented into three distinct nodes aimed to properly classify the information. If a parameter is deemed beneficial for LCI, it is allocated to the LCI data child node. Conversely, parameters not relevant to LCI purposes are allocated to the Legislative-imposed data node. Identification data, which provide essential anagraphic information and map out the father-child relationships within a specific node, are excluded from this allocation process. Notably, some parameters may find relevance across multiple nodes. An exemplary case is the "Share Renewable Content" parameter, mandated by the Battery Regulation, which is incorporated into the LCI data. This parameter is uniquely positioned within the PROCESS ATTRIBUTES nodes related to MANUFACTURING and RECYCLING, applicable to both PART and PRODUCT levels.

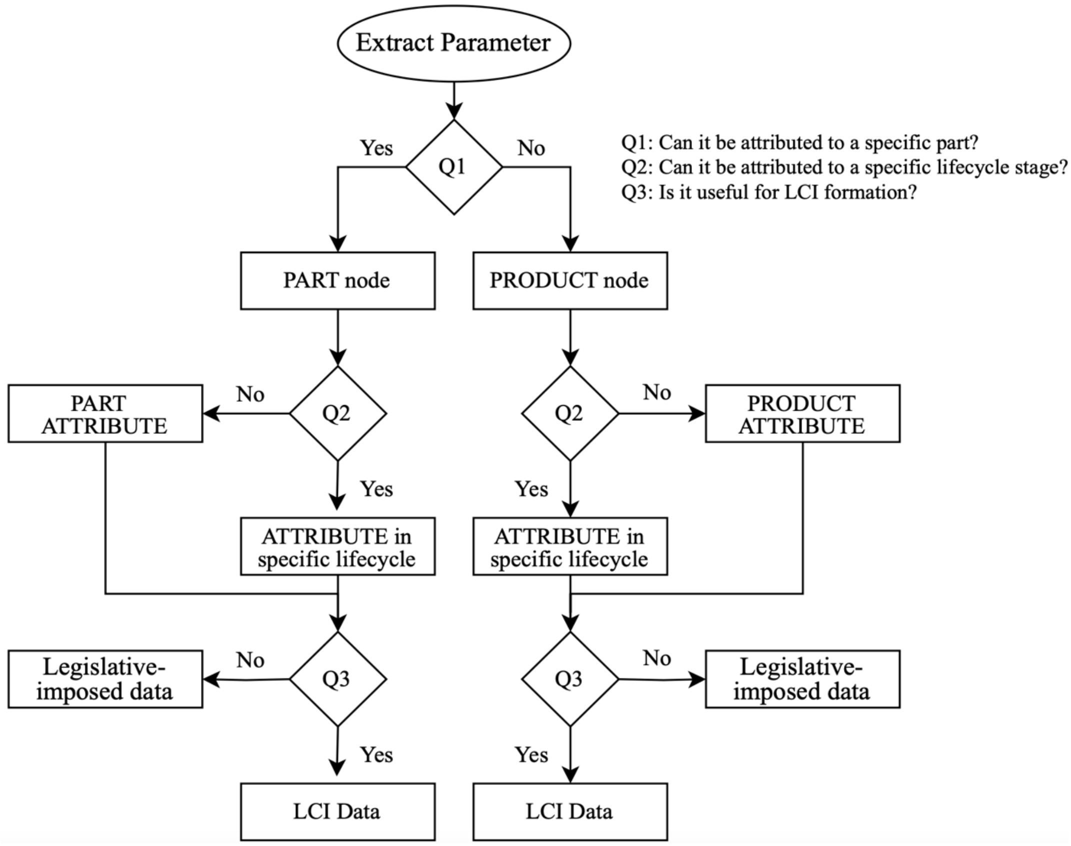

Figure 29 - Parameter attribution decision-making diagram.

Lastly, the ENVIRONMENT nodes, encapsulating their internal subdivisions, under-go modifications driven by regulatory mandates and the integration of environmental standards and scientific advancements. In the context of batteries, the Carbon Foot-print calculation exemplifies this adaptability. It adheres to the specifications of the Battery Regulation, particularly Annex II, Section 4, with detailed allocations within the MANUFACTURING and TRANSPORT nodes for the BATTERY category, extending also to every MATERIAL and END OF LIFE node. On the voluntary aspect, the scientific literature frequently cites the adoption of ReCiPe indicators, which align with the indicators outlined in the specific PEFCR.

6.1.3. Battery Data Model

The Battery DM represents the practical implementation of the FDM principles, and the population framework specifically tailored to meet the sector constraints. Following the structured methodology outlined in 6.1.1. and 6.1.2. this model systematically incorporates all the necessary elements to ensure compliance with regulatory standards while addressing the unique complexities of the battery lifecycle. This DM has been applied in the case study presented in Chapter 7.

Initially, the FDM's generic framework was analyzed and refined through a PEA specific to the battery sector. This included a decomposition of the battery architecture using the FDM's PART node structure, where the battery was broken down into its key components such as cathodes, anodes, electrolytes, and separators. This decomposition was guided by both technological and regulatory priorities, ensuring a detailed mapping of each component. Additionally, a legislative analysis was conducted to thoroughly examine relevant regulatory frameworks, particularly the Battery Regulation. The proposed Battery DM achieves full compliance with the Battery Regulation by extracting, interpreting, and integrating all data requirements specified in Articles 7(1), 7(2), 8(1), 10(1), 13(3), 13(4), 14, 18, 38(6), 38(7), 45(3), 52(3), 74(1, a-f), 77, Annex II, Annex IV(A), Annex IV(B), Annex VI(A), Annex VI(B), Annex VII, Annex IX, Annex X(1), and Annex X(2). Then, the Battery DM is populated following the decision-making framework presented in Section 6.1.2. Table 19 illustrates the alignment of regulatory parameters with the nodes of the model:

Table 19 - DM population with Battery Regulation parameters

Information	Data type	Position
The battery category	String	BATTERY / BATTERY ATTRIBUTES
Weight	Decimal	
Capacity	Decimal	
Chemistry	String	
Usable extinguishing agent	String	
CRMs	String / Decimal	
Commercial Warranty	String	
Marking requirements	Decimal /Boolean	

EU declaration of conformity	String	
Safety Measures	String	
Results of Tests	String	
Status of the battery	String	
Weight	Decimal	PART / PART ATTRIBUTES
Part numbers and contacts details for replacement	String	
Weight	Decimal	PART / MATERIAL / MATERIAL AT-TRIBUTES
Hazardous substances	String	
Responsible sourcing	Boolean/String	
Recycled content	Decimal	
Renewable content	Decimal	
CF	Decimal	NODE/ ENVIRONMENT
Manufacturer's identification	String	NODE/ PROCESS / PROCESS ATTRIB-UTES
Manufacturing place	String	
Manufacturing date	Date	
Rated capacity	Decimal	BATTERY / USE / USE ATTRIBUTES
Voltage and temperatures	Decimal/String	
Power capability, limits, and temperatures	Decimal/String	
Expected lifetime and test	Integer/String	
Capacity threshold for exhaustion	Decimal	
Temperature range and test	Decimal/String	
Initial round trip energy efficiency and at 50% of lifetime	Decimal	
Internal battery cell and pack resistance	Decimal	
C-rate of relevant test	Decimal	
Values for performance and durability parameters	Decimal	
SOH	Decimal	
Use phase data	Integer/String	
Dismantling information	String	BATTERY / END OF LIFE / END OF LIFE ATTRIBUTES
Information regarding prevention and Management	String	

Once all parameters were defined, they were incorporated into the XSDs of the FDM, as described in Section 6.2.1 and documented in Annex IV. Each parameter was meticulously coded with specific rules and constraints based on its type, as well as interpretations derived from regulatory requirements. When regulatory terminology included expressions such as "if available" or required alternatives if data could not be obtained, the XSD schema was designed to include minOccurs="0", allowing optional inclusion of the parameter. Conversely, when only a single value was permitted, maxOccurs="1" was implemented, ensuring compliance with constraints. If a parameter allowed multiple entries, maxOccurs="unbounded" was applied to support an indefinite number of values. For example, in Annex XIII, point 8, the regulation mandates including "The hazardous substances present in the battery, other than mercury, Cd, or Pb." Since these substances may be specific to individual battery components, the parameter was placed in the PART ATTRIBUTE node, allowing its association with elements such as the cathode or anode. The XSD implementation follows:

```
<xs:element name="HazardousSubstances">
  <xs:complexType>
    <xs:sequence>
      <xs:element name="HazardousSubstance" type="xs:string"
minOccurs="0" max-Occurs="unbounded"/>
    </xs:sequence>
  </xs:complexType>
</xs:element>
```

Similarly, some parameters require selecting from a predefined set of values. In Annex XIII, point 36, the regulation specifies that battery status must be classified as 'original,' 'repurposed,' 'reused,' 'remanufactured,' or 'waste.' This was implemented using xs:restriction to enforce allowable values within the PRODUCT ATTRIBUTE node:

```
<xs:element name="BatteryStatus" minOccurs="0">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:enumeration value="original"/>
      <xs:enumeration value="repurposed"/>
      <xs:enumeration value="reused"/>
      <xs:enumeration value="remanufactured"/>
      <xs:enumeration value="waste"/>
    </xs:restriction>
  </xs:simpleType>
</xs:element>
```

In the first example related to hazardous substances, complexType was used because the element contains multiple nested sub-elements structured within a sequence, allowing multiple entries under the same category. In contrast, in the second example for battery status, simpleType was applied since the element contains a single value restricted to a predefined list of options. Another example is simpleType application is the place of manufacture (**Annex XIII, point 3), **implemented in the PROCESS ATTRIBUTE node as:

```
<xs:element name="ManufacturingPlace" type="xs:string"/>
```

For the complete implementation, refer to the case study in Section 7. The full code, along with the structured data input by value chain stakeholders for the case study battery, is provided in Annex IV.

6.2. DPP IT Infrastructure

The ITI serves as the backbone for managing product-related data, enabling data integrity, accessibility, and interoperability across multiple stakeholders throughout the product lifecycle. This section first examines the architectural design of the ITI, detailing the roles and interactions of each module. It then explores the operational workflow, outlining the key processes involved in DPP creation, modification, and consultation. Finally, the chapter provides a technical breakdown of the implementation, describing the structure and logic behind the core scripts, smart contract deployment, and front-end components. By integrating state-of-the-art IT solutions such as blockchain technology, cryptographic hashing, and role-based authentication, the proposed ITI enhances trust, security, and efficiency in digital product data management, paving the way for a robust and universally applicable DPP system.

6.2.1. ITI Architecture

The ITI architecture comprises four main modules, which function in synergy to manage DPPs throughout their entire lifecycle, including creation, consultation, and updates (Figure 30). These four modules are: the *Python Web Flask* platform (PWF), the *Python Graphical User Interface* (GUI) *Desktop Application* (GUIA), the *Smart Contract* implemented in Solidity (SCS), and the *Ethereum Blockchain* (EB). Essentially, the two Python-based modules enable users to interact with DPPs, whereas the EB and SCS manage transactions and ensure the integrity of passport identity data, such as the passport ID and cryptographic hash, stored immutably on the blockchain. The proposed architecture not only streamlines DPP management but also ensures a high level of security and transparency. It decentralizes the integrity process while maintaining a central reference point for DPP management, archiving, and XML file verification, thereby achieving an optimal balance between accessibility and security.

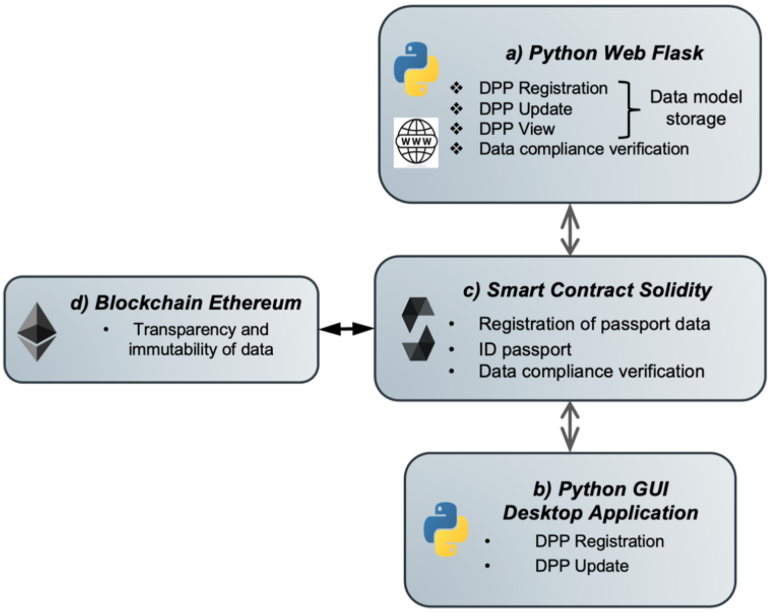

Figure 30 - DPP ITI modules

The PWF platform acts as the interface through which stakeholders interact with the DPP system to consult, verify, and archive passports. Additionally, it allows users to download a package containing specific instructions for the stakeholder, the XML (base version for creators, or the latest version with updated data for updaters), and the GUIA for managing the DPP. The platform, developed using the Flask web framework in Python, is designed to verify the information before registering it in the system. Specifically, it compares the input data, such as the passport ID and hash, by querying the SCS, thereby ensuring the integrity and authenticity of the DM. To enhance accessibility and security, the platform integrates Structure Query Language (SQL) Alchemy, a Python library facilitating database interactions, along with Flask-Migrate for handling database schema migrations. The front-end is developed using HyperText Markup Language (HTML) and Cascading Style Sheets (CSS) to provide a user-friendly interface, ensuring clarity and ease of navigation for stakeholders. Additionally, authentication is required via an Ethereum address, verified against a predefined list using Ganache, thereby simulating access control restrictions within the system. The platform also implements a role-based access system, distinguishing between different user categories such as passport owners, updaters, verifiers, and public or private stakeholders. This classification defines the level of interaction each user can have with the platform. Upon login, stakeholders can engage in three core functions: (i) uploading a new passport, which is then registered on the SCS, (ii) modifying an existing passport, and (iii) viewing a registered passport for verification purposes. Except for online consultation, both the creation and modification processes allow the download and upload of XML files, ensuring data consistency while minimizing redundancy. During passport creation, users access the "Generate a Passport" function to download a structured XML template, ensuring standardization across all entries. Upon completion, the system verifies the integrity of the uploaded file by comparing its hash with the stored value on the EB. If verified, the document is archived in the database under a standardized naming convention based on its passport ID, facilitating easy retrieval and traceability.

The GUIA, realized with Tkinter, provides a user-friendly tool for managing DPPs, enabling users to create, update, and verify passports directly on the EB. It simplifies the process by automating the communication with the SCS, ensuring that even non-experts can efficiently manage DPPs. The GUIA handles the input of the XML-based DM, and once the file is uploaded, it automatically generates the document's hash and transmits it to the SCS. To facilitate interaction, the user interface has been designed to be intuitive, requiring minimal technical expertise to operate the system. The application provides a graphical file selection feature, enabling users to upload the XML document without manual command-line operations. During the registration process, the system allows the owner to select the hashing algorithm via a dropdown menu, providing flexibility in cryptographic security. Conversely, for an updater, the system enforces the use of the pre-registered hash function to maintain consistency and avoid discrepancies in verification. If a new passport is being created, the SCS emits the "AddPassport" event, while for existing passports being updated, the "UpdatePassport" function is triggered. This ensures that any modification to the DPP is recorded transparently and immutably on the EB, enhancing traceability. The application also includes built-in error handling mechanisms that detect missing data, invalid XML formats, or incorrect passport identifiers before attempting EB registration. This entire process is handled seamlessly by the system, limiting human errors and barriers to use. Additionally, a verification step ensures that the registered hash corresponds with the document content before finalizing the update, preventing unauthorized or incorrect modifications from being stored in the EB.

The SCS, deployed on the EB, contains the rules for creating, updating, and verifying passports. Every time a passport is created, the SCS emits an event and generates an ID for the passport. This ID, along with the passport hash, the address of the passport creator or updater, and the hash function used, is permanently and immutably recorded on the EB. The system utilizes Secure Hash Algorithm (SHA)-256 as the primary cryptographic hash function, ensuring a robust, deterministic mechanism for securing and verifying passport integrity. To optimize the costs associated with EB transactions and ensure accountability among stakeholders, the system converts the XML DM into a hash function, minimizing the amount of data stored. SCS execute pre-defined functions autonomously when specific conditions are met, eliminating intermediaries and reducing operational inefficiencies. By leveraging Ethereum's Solidity language, the contract ensures secure and verifiable interactions between actors, preventing unauthorized modifications. Furthermore, each transaction requires authentication via a private key, guaranteeing that only authorized users can execute updates or register new passports. The contract is also structured to emit key events such as "AddPassport" and "UpdatePassport," allowing external applications to track passport lifecycle changes in real-time, further reinforcing transparency and traceability within the EB ecosystem.

The EB functions as a decentralized and immutable ledger, recording all transactions related to DPPs to ensure data integrity and prevent unauthorized modifications. Unlike traditional centralized databases, which are vulnerable to data tampering, the EB leverages cryptographic hashing and consensus mechanisms to validate every transaction before it is permanently recorded. The EB operates through a Peer-to-Peer (P2P) network, where each node maintains a copy of the distributed ledger and validates new transactions using the underlying consensus algorithm. This ensures that once a transaction is added to the EB, it cannot be altered or removed without modifying all subsequent blocks—a process that is computationally infeasible. To enhance security and efficiency, each transaction within the DPP system is recorded as a cryptographic hash, reducing on-chain data storage requirements while maintaining verifiability. Specifically, only the passport ID, hash of the XML document, and the cryptographic hash function used are stored on the EB, while the full document remains archived in an off-chain database. This approach significantly optimizes gas costs associated with Ethereum transactions while ensuring an efficient and scalable architecture. Additionally, the EB supports role-based access control mechanisms. Stakeholders, such as manufacturers, regulators, and recyclers, can interact with DPPs through their respective Ethereum accounts linked to predefined access permissions. Public and private users are distinguished, with verifiers and regulatory bodies having read-only access, while authorized stakeholders can perform updates. The system leverages the Ethereum Virtual Machine (EVM) to ensure that SCSs execute in a decentralized and deterministic manner, following predefined rules for creating, updating, and verifying DPPs. This mechanism guarantees that all modifications to a passport are permanently recorded on the EB, making them auditable, transparent, and immutable over time, thereby enhancing trust and compliance among stakeholders.

6.2.2. IT Infrastructure Workflow and Use Scenarios

The DPP management system is utilized by various stakeholders throughout the entire product lifecycle, each with distinct roles and access privileges. Figure 31 illustrates how different actors interact with the ITI modules at different stages, depending on their specific operational needs and system permissions. Stakeholders are categorized into three main roles: Owners, Updaters, and Viewers.

- Owners are responsible for the initial creation and registration of a DPP. Typically, this role is assumed by manufacturers, who input fundamental product details such as battery chemistry, capacity, and production date into the system.
- Updaters modify and expand upon existing DPPs as the product moves through its lifecycle. This includes suppliers updating material sourcing details, maintenance technicians logging servicing records, or recyclers adding end-of-life processing data.
- Viewers (or Verifiers) have read-only access, typically comprising regulatory bodies, market surveillance authorities, or consumers, who consult the DPP to verify compliance, assess sustainability parameters, or ensure traceability.

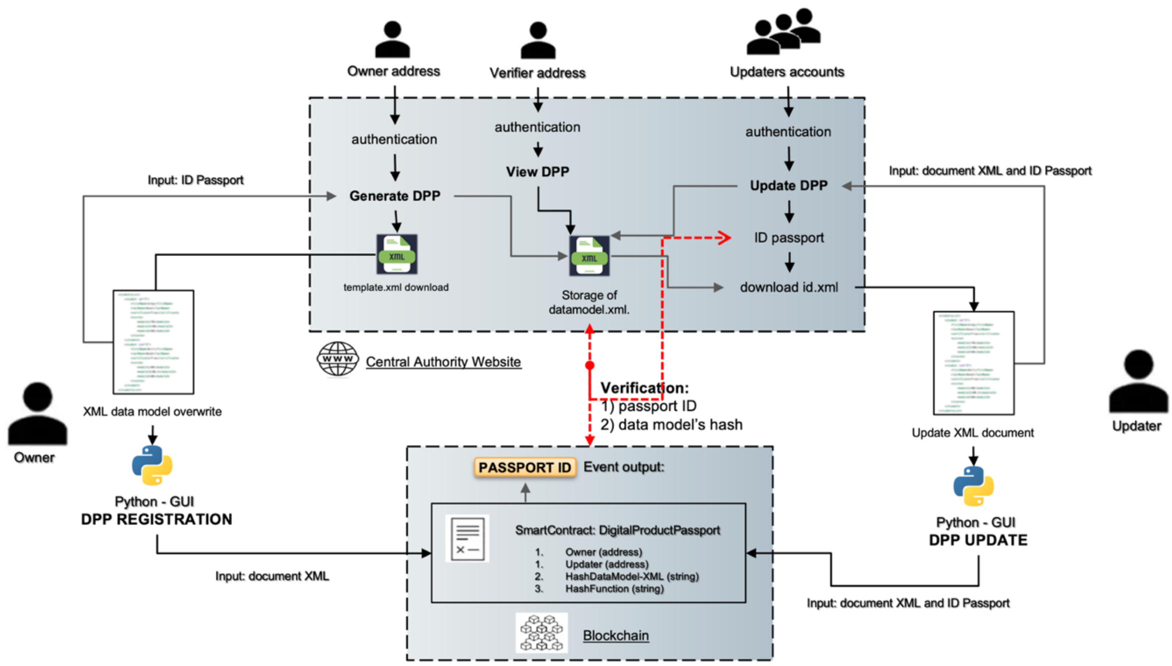

Figure 31 - DPP Use Scenario Workflow

The ITI is designed around three main functions that govern the lifecycle of DPPs: Generate DPP, Update DPP, and View DPP.

The first function of the DPP system is the generation of a new DPP (Figure 32). This process begins with the manufacturer or another designated stakeholder (referred to as the Owner). The Owner must first authenticate through the PWF platform, which serves as the gateway for managing DPPs. Once authenticated, the system grants access to a downloadable package containing the XML DM empty (template.xml), the GUIA (.py) to launch it locally, and a set of structured guidelines to assist the user in correctly inputting the necessary data. With the required files in place, the Owner modifies the XML DM by entering product-specific information, and part-specific details if internally manufactured, ensuring compliance with both technical and regulatory requirements. After completing this step, the user interacts with the GUIA, which automates the EB registration process and minimizes the complexity of interacting with the SCS. Within the GUIA, the user must input the contract ID and select the updated XML document. The application then computes the document's hash using a cryptographic function, ensuring a unique digital fingerprint of the DPP. Following this, the GUIA initiates an EB transaction, transmitting the computed hash, the applied hash function, and the owner's EB address to the SCS. The transaction is securely recorded on the EB, guaranteeing immutability and traceability. At this stage, the SCS triggers the "AddPassport" event, which automatically generates a unique Passport ID. This identifier is essential for future interactions with the DPP, such as updates or verifications. The final step involves archiving the registered DM. Upon successful authentication, the PWF platform verifies the integrity of the newly created passport by cross-checking the passport ID and hash against the EB records. Once validated, the DM is securely stored in the web platform’s database, ensuring that all information is readily accessible for future reference or updates.

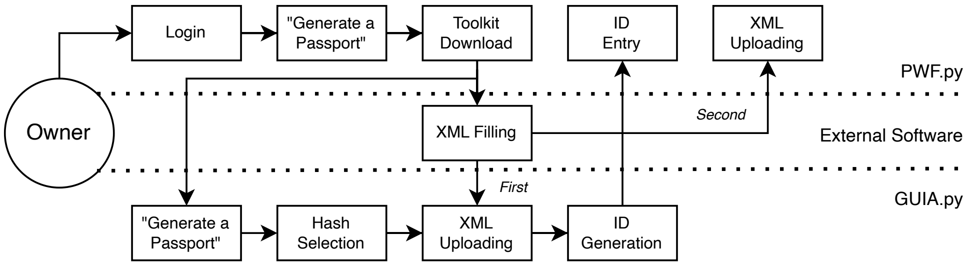

Figure 32 - DPP Generation procedure workflow

Updating a DPP is a critical function that allows authorized stakeholders to modify an existing DPP while maintaining data integrity and compliance with regulatory standards (Figure 33). The update process begins with the Updater authenticating through the PWF platform. Once authenticated, the system prompts the user to input the Passport ID, which uniquely identifies the passport requiring modification. The platform then retrieves the most recent version of the XML DM, allowing the Updater to download it along with the GUI and guide, and modify it. After obtaining the XML file, the Updater proceeds with entering updated product- or part-specific information. These modifications may include performance updates, maintenance records, compliance adjustments, or any other relevant amendments required for the product's lifecycle, specifically related to the activities performed by the designated Updater. Once the DM has been adjusted, the Updater utilizes the GUIA to facilitate the EB update process. Through the GUIA, the Updater selects the corresponding Passport ID, uploads the modified XML document, and triggers a cryptographic hashing function to generate a unique digital fingerprint of the updated DPP. Following the hash computation, the GUIA automatically initiates an EB transaction via the SCS, transmitting the newly generated hash alongside key metadata, including the Passport ID, the address of the entity performing the update, and the cryptographic function used. The SCS then processes this update and emits the "UpdatePassport" event, confirming that the new version of the DPP has been securely logged onto the EB. This step ensures that any modification is immutable, permanently recorded, and available for verification at any point. As the final step, the updated XML DM is archived within the PWF platform's centralized database. Before finalizing the update, the system performs an automatic integrity verification by cross-referencing the newly computed hash with the one stored on the EB. If the validation is successful, the previous version of the XML file is replaced with the updated one, ensuring consistency across the system. Additionally, a comprehensive update log is maintained, preserving a traceable record of all modifications made to the DPP.

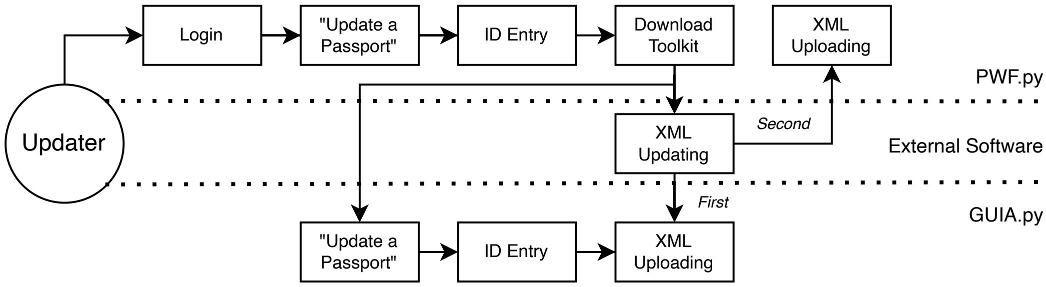

Figure 33 - DPP Updating procedure workflow

The View DPP function is designed to provide authorized stakeholders, such as regulatory bodies, auditors, or other verifiers, with secure and seamless access to DPPs for compliance verification and data integrity checks (Figure 34). The process begins with the Verifier authenticating through the PWF platform. Upon successful authentication, the Verifier is required to enter the Passport ID, which uniquely identifies the digital passport they wish to consult. The system then queries its centralized database to retrieve the corresponding XML DM. Once retrieved, the platform displays the DPP's structured data, allowing the Verifier to review its contents. To ensure the integrity and authenticity of the data, the system automatically performs an EB verification process. Additionally, the platform provides access to historical versions of the DPP, allowing Verifiers to track all modifications made over time. This version control functionality ensures a complete audit trail, enhancing transparency and accountability among stakeholders.

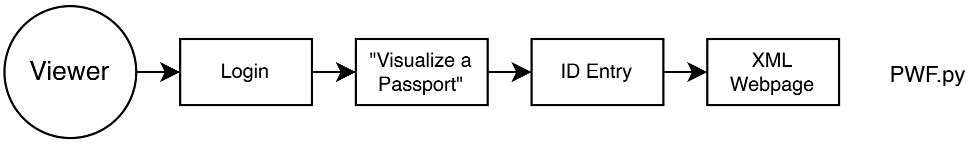

Figure 34 - DPP Visualization procedure workflow

6.3.3. Code Implementation of ITI Modules

This section details the core functionalities of the files composing the DPP prototype, developed and tested during the doctoral research. Each file contributes to the ITI architecture, managing data, user interaction, and EB integration. The implementation demonstrates the interaction between front-end and back-end components, along with SCS logic and EB-enabled verification processes. At the core of the backend, two Python scripts—GUIA.py and PWF.py—handle user interactions, data processing, and EB transactions. The specific roles and functionalities of each file are outlined below, while full implementation details, including complete source code, are provided in Annex V-VIII, covering backend scripts, front-end components, and the Smart Contract System (SCS) for DPP management.

The *GUIA.py* file functions as the core interface for interacting with the EB. It is designed to facilitate user interaction with the EB through SCS, enabling users to create and update DPPs. The script's functionality is achieved using the following libraries:

- web3: Central to enabling EB communication, this library connects to the Ethereum node (via Ganache in this implementation) and facilitates interactions with the SCS. It provides tools to query EB data, execute transactions, and validate accounts.
- tkinter: Powers the GUIA for users to interact with the system. Tasks such as file selection, data input, and process initiation are simplified through dialog boxes and buttons.
- hashlib: Handles cryptographic hashing operations, supporting algorithms like SHA-256, SHA3-256, and BLAKE2s. This ensures the security and integrity of the XML DM by generating unique digital fingerprints.
- os: Enables file operations, such as verifying file existence and handling file paths, which is critical during XML document upload and retrieval.
- re: Utilized for regular expressions, primarily for validating user inputs like Passport IDs and ensuring compliance with hexadecimal formatting rules.
- sys: Facilitates command-line argument parsing, enabling flexibility when specifying accounts and other configurations during execution.

The file adheres to a modular structure, beginning with configuration and EB setup to establish seamless communication with the Ethereum network. The core functions are the following:

- Configuration: The script first connects to the EB via the web3 library, verifying contract addresses and initializing parameters such as account indices and the Application Binary Interface (ABI) of the SCS. This initialization ensures that all subsequent interactions with the EB are properly authenticated and synchronized.
- upload_passport: This function orchestrates the process of creating new passports. Leveraging tkinter, it opens a GUIA for file selection and allows the user to specify a cryptographic hashing algorithm, such as SHA-256, provided by hashlib. The selected XML file is read, hashed, and securely transmitted to the EB through a transaction, ensuring immutability and traceability.
- update_passport: This function enables the modification of existing passports. It retrieves the passport's metadata from the SCS, including the original hash function, ensuring consistency during updates. Using the hashlib library, a new hash for the updated XML data is computed and transmitted via web3 to update the EB.
- main_window: Serving as the GUI, this function creates an intuitive interface with buttons for core operations, such as uploading or updating passports. The GUIA also incorporates error handling through dialog boxes, ensuring users are guided to resolve issues like invalid file paths or unsupported hash algorithms before proceeding.

The *PWF.py* file serves as the backend for the web platform, enabling users to interact with DPPs via a web-based interface. Its architecture is built upon several key libraries:

- flask: Acts as the framework for developing the web application. Flask enables routing, request handling, and rendering of HTML templates for various user interactions.
- SQLAlchemy: Implements database management for storing metadata about users and documents. This ensures efficient storage and retrieval of data, supporting relational structures.
- hashlib: Similar to *GUIA.py*, this library generates cryptographic hashes of XML documents to ensure data integrity during uploads and updates.

- xml.etree.ElementTree (ET): Parses XML documents to extract and verify their structure and content, enabling detailed inspection of uploaded files.
- os: Manages file handling operations, such as saving uploaded XML documents and retrieving stored files for further processing.
- web3: Establishes connections to the EB and interacts with the SCS, ensuring secure and verifiable data transactions.
- werkzeug: Provides utilities for securing uploaded files and managing file paths.
- functools: Facilitates role-based access control through decorators, ensuring that only authenticated users with the appropriate roles can access specific functionalities.

The file follows a structured implementation focusing on key functionalities:

- Routing: Flask's @app.route decorators define key Application Programming Interface (API) endpoints, such as /generate_passport, /update_passport, and /view_passport. These routes enable interaction with DPPs, allowing users to submit, modify, or retrieve XML-based passport.
- Database Management: SQLAlchemy is utilized to manage user authentication and document metadata. The User and Document classes define relational structures, storing Ethereum addresses linked to uploaded files, ensuring controlled access and efficient data retrieval.
- EB Integration: The web3 library is employed to interact with the SCS, allowing passport data hashes to be securely stored on the ET. Transactions such as passport creation and updates are managed through contract function calls, logging immutable changes.
- Verification: Uploaded XML files are validated by computing their cryptographic hash via hashlib and cross-referencing it with the stored EB value. This guarantees data integrity by ensuring that no unauthorized modifications have occurred.

To enhance backend functionality, the DPP system incorporates structured front-end elements for user interaction. The system utilizes HTML templates and CSS for styling:

- style.css: Defines the visual design and layout of the web platform, ensuring a consistent and responsive user experience.

- HTML Templates: The system includes multiple templates:
    - login.html: Manages user authentication and role verification.
    - dashboard.html: Provides an overview of available functionalities.
    - generate_passport.html: Facilitates the process of creating a new DPP.
    - update_passport.html: Supports the modification of existing passports.
    - upload_passport.html: Manages the submission of XML passport files with integrated hash validation.
    - view_passport.html: Enables authorized stakeholders to consult stored DPPs.

These front-end components work in conjunction with Flask's rendering engine to dynamically update and display relevant content. The HTML templates incorporate JavaScript for client-side validation, such as ensuring correct file types and computing hash values before submission.

Finally, the implementation of the SCS is required to govern the creation, updating, and verification of DPPs on the EB. The contract defines a PassportData structure that stores essential metadata, including the owner's address, the last updater's address, the cryptographic hash of the passport, and the hashing function used. Moreover, the contract leverages Ethereum's immutable ledger. The SCS was developed and tested using the Remix IDE, a browser-based development environment optimized for Solidity, and deployed on a local EB network using Ganache. Remix provided real-time compilation, debugging, and execution capabilities, whereas Ganache simulated a local Ethereum network, allowing controlled efficient contract deployment and testing. The SCS provides two primary functions:

- addPassport: This function generates a new passport ID using a keccak256 hash derived from the timestamp, the document hash, and the block number. It records the owner's address and hash metadata before emitting an AddPassport event, notifying the EB of the new registration.
- updatePassport: This function allows an authorized user to modify the passport hash by referencing the unique passport ID. The updater's address is logged to maintain a verifiable history of modifications, ensuring that each update is auditable.

Chapter 7.

Case Study: Framework application to an LFP EV Battery

This chapter presents the application of the proposed framework to a real-world case study involving an LFP EVB. Given the constraints of conducting a full-scale industrial validation, the study is based on a simulated industrial scenario, replicating the key phases of the battery lifecycle while leveraging data from literature and structured assumptions [10], [142]–[145]. The goal of this application was to systematically test key phases of the framework, evaluating its feasibility, tool interactions, and limitations. The activities performed on the battery in this case study are structured into four phases, which define the core sections of this chapter and of the framework presented in Chapter 4:

- *Plan (7.2):* Identification of design constraints and modeling of the battery pack using BatPaC-LCA, defining key technical, economic, and environmental parameters.
- *Do (7.3):* Implementation of lifecycle tracking through the DPP, collecting production, usage, and end-of-life data.
- *Check (7.4):* Generation of cradle-to-grave LCA using DPP's LCI data.
- *Act (7.5):* Discrepancy analysis between BatPaC-LCA results and the outcomes of the LCA conducted with DPP data, identifying key gaps and proposing improvements.

Since the case study does not involve a physically operational battery, certain phases have been adapted to fit the simulated context, as detailed in Section 7.1, which introduces the methodological assumptions and supply chain structure underlying the study.

7.1. Case Study Assumptions

7.1.1. Methodological Framework and Adaptation Rationale

To maintain coherence with the Framework, certain steps were fully implemented, while others were simplified or omitted. The main adaptations include:

- Plan: The battery pack design was generated using BatPaC-LCA, but without iterative refinements. Unlike a real-world industrial setting, where multiple design loops would be performed, this simulation was conducted as a single-cycle optimization, evaluating two battery configurations. Additionally, while tools such as SWOT analysis and QFD workshops were not fully integrated, their exclusion was justified by the focus on quantitative validation rather than stakeholder-driven optimization processes.
- Do: A full-scale Digital Twin was developed but has been omitted in the main text to avoid unnecessary repetition of code, as its implementation consists of integrating BatPaC simulation data directly into the DPP, detailed in Annex IV. Rather than presenting extensive code structure, the analysis directly compares BatPaC-LCA outputs with DPP-structured LCA outcomes in the Act phase, ensuring consistency in the final evaluation. Instead, the population of the Real DPP was simulated in a local blockchain network (Ganache), where various stakeholders were emulated, and lifecycle data were injected using values derived from literature-based analyses.
- Check: Given the simulated nature of the case, regulatory compliance could not be fully assessed against real-world certification processes.
- Act: a selection of analyses has been presented to demonstrate the capabilities of the framework, focusing on key discrepancies and areas for iterative refinement. The full report, while valuable

for an exhaustive assessment, has been excluded from this document to maintain conciseness and focus on the methodological demonstration.

7.1.2. Battery and Supply Chain Definition

To test the DPP functionality, a simulated supply chain was modeled, ensuring the integration of key lifecycle interactions across the battery value chain. This simulation replicates the flow of materials, manufacturing processes, and end-of-life management, allowing for structured data exchange between stakeholders within the DPP framework. The case study is a project for ENEA, serving as the basis for the development of a real battery within the IPCEI EuBatIn initiative. The battery is assembled at ENEA AB-Lab (Casaccia), relying on a network of European suppliers for key raw materials and components. The cathode is produced using Anhydrous Iron Phosphate from BASF (Germany), while Vulcan Energy (Germany) supplies Lithium Concentrate, processed into Lithium Carbonate by Green Lithium (UK). The electrolyte formulation consists of Dimethyl Carbonate (DMC) and Ethylene Carbonate (EC), sourced from Solvay (Belgium) and BASF (Germany). The separator is a Polypropylene membrane supplied by Freudenberg (Germany), while KME Group (Italy) and Slim Aluminium (Italy) provide Copper Foil and Aluminum Sheet & Shell for structural and conductive components. The Battery Management System (BMS), responsible for monitoring and optimizing battery performance, is manufactured by STMicroelectronics (France). Once assembled, the battery is integrated into EVs at the FCA Melfi plant (Italy). The BMS continuously tracks charging cycles, efficiency rates, and energy dissipation, transmitting this data to a centralized server for real-time monitoring. At 80% of its original capacity, the battery undergoes second-life assessment at ENEA, where its remaining lifespan is evaluated for remanufacturing and repurposing into stationary energy storage systems (ESS), used in photovoltaic energy storage at ENEA facilities, enhancing solar energy management. When the battery reaches 60% capacity, it enters the recycling phase, where ENEA oversees material recovery through hydrometallurgical processes. The BMS waste is processed by STMicroelectronics (Catania), while Aluminum and Copper are recovered by Slim

Aluminium (Verona) and KME Group (Fornaci di Barga). Plastic components, including the separator and casing, are handled by Sa.Ma Green Recycle (Santarcangelo di Romagna), and steel scrap is recovered by Acciaierie Venete (Padova), ensuring full reintegration of materials into the industrial loop.

7.2. Plan: Context Analyses and Design Identification

The battery design process follows the structured approach outlined in the sustainable lifecycle management framework, as detailed in Chapter 4. This phase—Plan—focuses on defining the constraints and specifications necessary for the simulation and assessment of battery performance, sustainability, and feasibility. As discussed in Section 4.2, the first step is Input Collection, where essential data is gathered to ensure that the battery configuration aligns with its intended application, regulatory requirements, and laboratory constraints. These parameters, derived from the framework described in Chapter 5, serve as the baseline for integrating BatPaC simulations and optimizing the battery lifecycle assessment, forming the foundation for subsequent modeling steps.

The battery under study is a conceptual design intended for EV propulsion and will be simulated for production at the Advanced Battery Laboratory (AB-Lab) at ENEA Casaccia, within the IPCEI EUBatIn initiative. This state-of-the-art research facility enables testing of next-generation battery configurations under realistic conditions, supporting the transition from theoretical design to industrial feasibility. The main characteristics are:

- Total capacity: 57 kWh
- Weight: 600 kg
- Energy density: 95 Wh/kg
- Configuration: 6 modules × 16 cells = 96 cells
- SOC at rated power: 90%
- Average discharge temperature: 298,15 K (25°C)

- Cycle life target: Equivalent to 200.000 km

The electrode composition and structural parameters are designed to ensure high efficiency and compliance with performance requirements:

- Positive electrode:
  - Material: LFP
  - Specific capacity: 137 mAh/g
  - Void volume fraction: 32,66%
  - Thickness: 95 µm
- Negative electrode:
  - Material: Graphite
  - Specific capacity: 726 mAh/g
  - Void volume fraction: 16,84%
  - Negative current collector thickness: 10 µm
  - N/P capacity ratio: 1.1
- To guarantee electrochemical stability, the separator is designed with thickness: 20 µm

Although the AB-Lab at ENEA Casaccia is a research facility rather than an industrial manufacturer, the design follows industrial-scale methodologies to ensure scalability. Furthermore, regarding End-of-Life strategies, the battery is designed for:

- Second-life application: energy storage system (from 80% to 60% of remaining capacity)
- Final recycling: hydrometallurgical process

The input parameters defining battery performance, material composition, and manufacturing constraints have been structured in BatPaC for simulation and assessment (Figure 35).

Inputs		
Chemistry		
	Current Selection	Choose
Default Electrode Couple	LFP-G (Energy)	LFP-G (Energy)
Positive Electrode: LiFePO4		Override
Positive active material specific capacity, mAh/g	157	
Void volume fraction, % of positive electrode	25	
Positive foil thickness, μm	15	
Maximum positive electrode thickness, μm	120	
Negative Electrode: Graphite		
Negative active material specific capacity, mAh/g	360	
N/P capacity ratio after formation	1,10	
Void volume fraction, % of negative electrode	25	
Negative current collector thickness, μm	10	
Separator thickness, μm	15	
Add silicon to graphite electrode?	No	No
Battery Design		
General		
	Current Selection	Choose
Vehicle Type	EV	EV
Mass or Cost Sensitive Pack Design (default = Cost)	Mass	Mass
Design electrodes to meet charging requirements? If Yes, see Dashboard Row 59	No	No
Storage		
Fill in value for either capacity or energy	Battery 1	Battery 2
Total pack capacity, 0-100% SOC (Ah)	57	57
Total pack energy, 0-100% SOC (kWh)		
Extras	Battery 1	Battery 2
To select time to recharge, fast charge must be enabled		
Optional positive electrode thickness override, μm		
Cell thickness, mm	20	20
Cell thickness override, mm		
Length to width ratio of the positive electrode	8	5
Length to width ratio of the positive electrode override		
Pack Configuration	Battery 1	Battery 2
Number of cells per module	16	16
Number of cells in parallel	1	1
Number of modules in row	6	3
Number of rows of modules per pack	1	2
Number of modules in parallel	1	1
Add set of default pack designs (power, energy, pack configurations)		

Name	Battery 1	Battery 2
Configuration Errors	None	None
Configuration Warnings	None	None
Battery system total energy, kWh	18,14	18,14
Battery system capacity, Ah	57,00	57,00
Battery system rated power, kW	300	300
Battery system nominal operating voltage, V	318	318
Pack power to energy ratio (with respect to rated power)	16,54	16,54
Pack energy density, Wh/L	170	180
Pack specific energy, Wh/kg	109	119
Number of modules per pack	6,00	6,00
Number of cells per pack	96,00	96,00
Pack volume, L	107	101
Pack total mass, kg	167	152
Cell capacity, Ah	57,00	57,00
Cell nominal operating voltage, V	3,32	3,32
Positive electrode thickness, μm	33,98	37,64
Positive electode areal capacity, mAh/cm²	1,28	1,41
Negative electrode thickness, μm	24,14	26,74
Negative electrode areal capacity, mAh/cm²	1,40	1,55
Cell energy density, Wh/L	369	370
Cell specific energy, Wh/kg	174	180
Pack cost, $/pack	$4.823	$4.513
Pack cost, $/kWh	$266	$249
Pack cost, $/kWh(Useable)	$313	$293
Cell cost, $/kWh	$136	$130
Plant Size, GWh	9,07	9,07
Packs manufactured per year (packs/year)	500000	500000
Pack length, mm	2053	1075
Pack width, mm	524	838
Pack height, mm	95,75	108

Figure 35 - BatPaC LFP EVB Configuration

In BatPaC, battery chemistry can be configured for either 'Energy' or 'Power' optimization. The LFP-G (Energy) variant was selected to maximize storage capacity and longevity, prioritizing extended cycle life over power output—an essential factor for EV applications. Additionally, several parameters have been overridden to better align with the design constraints and performance targets, as indicated above. In particular, two possible designs were considered, Battery 1 and Battery 2, where module and cell configurations were varied to ensure compliance with design constraints and manufacturing feasibility while maintaining optimal battery performance. Specifically, in Battery 1 the 16-1-6-1-1 configuration was adopted, where each module contains 16 cells, arranged in a single parallel string, with six modules in a row, forming one row per pack, and one module in parallel. This layout preserves a conventional structure, ensuring a streamlined integration into EV platforms while maintaining the intended voltage and energy density. Alternatively, in Battery 2 the 16-1-3-2-1 configuration introduces a variation by reducing the number of modules in a row from six to three and increasing the number of rows per pack from one to two, enhancing thermal management and structural flexibility. Once the input parameters were defined, the tool automatically generated midpoint indicators for the LCA assessment of the selected battery configurations. Figure 36 presents the overall LCA results, comparing the two battery designs. While the tool provides granular details for each component and lifecycle phase, a full breakdown of these results is included in the final comparison within the ACT phase (Section 7.5), where they are analyzed alongside real data from the DPP for a more comprehensive evaluation.

Life Cycle Assessment		
LCA - Cradle-to-Grave	Battery 1	Battery 2
Terrestrial Acidification Potential (TAP)(kg SO2-Eq)	4,93E-02	4,43E-02
Global Warming Potential (GWP100)(kg CO2-Eq)	1,10E+01	1,35E+01
Freshwater Ecotoxicity Potential (FETP)(kg 1,4-DCB-Eq)	2,03E+00	8,27E-01
Marine Ecotoxicity Potential (METP)(kg 1,4-DCB-Eq)	2,76E+00	1,27E+00
Terrestrial Ecotoxicity Potential (TETP)(kg 1,4-DCB-Eq)	1,74E+02	1,55E+02
Fossil Fuel Potential (FFP)(kg oil-Eq)	2,90E+00	3,56E+00
Freshwater Eutrophication Potential (FEP)(kg P-Eq)	5,84E-03	5,52E-03
Marine Eutrophication Potential (MEP)(kg N-Eq)	6,68E-04	1,12E-03
Human Toxicity Potential (HTPc)(kg 1,4-DCB-Eq)	1,00E+01	7,09E+00
Human Toxicity Potential (HTPnc)(kg 1,4-DCB-Eq)	3,79E+01	1,83E+01
Ionising Radiation Potential (IRP)(kBq Co-60-Eq)	1,02E+00	1,16E+00
Agricultural Land Occupation (LOP)(m2*a crop-Eq)	2,94E-01	2,98E-01
Surplus Ore Potential (SOP)(kg Cu-Eq)	1,37E+00	2,64E+00
Ozone Depletion Potential (ODPinfinite)(kg CFC-11-Eq)	3,62E-06	4,04E-06
Particulate Matter Formation Potential (PMFP)(kg PM2.5-Eq)	2,48E-02	2,57E-02
Photochemical Oxidant Formation Potential: Humans (HOFP)(kg NOx-Eq)	2,68E-02	3,23E-02
Photochemical Oxidant Formation Potential: Ecosystems (EOFP)(kg NOx-Eq)	2,78E-02	3,33E-02
Water Consumption Potential (WCP)(m3)	9,25E-02	1,01E-01
Other LCA Indicator		
Carbon Footprint (kg CO2-Eq) Battery Regulation 2023/1542 compliant	1,01E+02	1,13E+02

Figure 36 - LCA results of the two designed batteries in BatPaC

The comparative assessment of the two battery configurations highlighted the superior performance of Battery 2 in several key aspects. It exhibited higher energy density (180 Wh/L vs. 170 Wh/L) and better cost efficiency ($249/kWh vs. $266/kWh), making it a more optimized solution in terms of energy storage and economic viability. Additionally, Battery 2 had lower environmental impacts across multiple LCA categories, including ecotoxicity, human toxicity, and terrestrial acidification, indicating a reduced overall burden on ecosystems and health. However, until the specific CF thresholds are defined in the upcoming amendment to Battery Regulation 2023/1542, considering that the study is conducted within a semi-industrial laboratory context, Battery 1 is chosen as the preferred option. This decision is further supported by its lower impact in categories such as freshwater eutrophication, fossil fuel potential, and water consumption, making it a more balanced choice in terms of both regulatory alignment and resource efficiency.

After selecting the optimal configuration in BatPaC, the Plan phase would typically involve refining the battery pack design, translating simulation results into a detailed engineering model, and integrating a Digital Twin for lifecycle monitoring. However, in this case study, these steps were omitted to avoid redundancy, as the final design parameters were instead derived from literature sources and are fully detailed in Section 7.4 and Annex VIII. Rather than performing additional iterative simulations or real-time data initialization, the study directly adopts a finalized battery design, ensuring consistency with established benchmarks. This approach maintains the methodological structure of the framework while streamlining the validation process for the simulated industrial scenario.

7.3. Do: LFP Battery Lifecycle Tracking

Once the battery is designed in the Plan phase, the Do phase begins, encompassing the entire lifecycle of the battery from cradle to grave. In parallel, all data and information are tracked through the DPP, which is the primary focus of this section. This phase ensures comprehensive monitoring and traceability across the different stages of the battery's life, involving multiple stakeholders who serve different roles in updating the DPP. ENEA acts as the owner of the DPP, being responsible for the production of the battery and the creation of its DPP. All other actors in the value chain, described in 7.1.2., function as updaters, responsible for adding relevant data throughout the battery's lifecycle. Additionally, an independent super partes entity that functions as a viewer, a neutral entity that manages the platform and monitors the compliance of various actions oversees the platform, managing the overall integrity of the DPP system.

Throughout every stage of this lifecycle, each actor is responsible for updating the DPP. Their roles and corresponding duties are summarized in Table 20.

Table 20 - Roles and Responsibilities in the DPP Process

Role	Company Name	Activities	Updated DPP Nodes
Owner	ENEA	Battery production, refurbishing, second use, and end-of-life recycling	ALL
Updater	BASF (Germany)	Raw material supply (Anhydrous Iron Phosphate)	CATHODE/MATERIAL
Updater	Vulcan Energy (Germany)	Raw material supply (Lithium Concentrate)	CATHODE/MATERIAL
Updater	Green Lithium (UK)	Lithium Carbonate production & supply	CATHODE/MATERIAL
Updater	Solvay (Belgium)	Electrolyte component supply (Dimethyl Carbonate)	ELECTROLYTE/MATERIAL
Updater	Freudenberg (Germany)	Separator production & supply	SEPARATOR/MATERIAL
Updater	KME Group (Italy)	Copper foil production & supply	CELL/MATERIAL, MODULE/MATERIAL
Updater	Slim Aluminium (Italy)	Aluminum sheet production & supply	CELL/MATERIAL, MODULE/MATERIAL, PACK/MATERIAL
Updater	STMicroelectronics (France & Italy)	BMS production and EoL recycling	BMS/MATERIAL, BMS/END OF LIFE
Updater	Sa.Ma Green Recycle (Italy)	Plastic component recycling	BATTERY/END OF LIFE
Updater	Acciaierie Venete (Italy)	Steel scrap recycling	BATTERY/END OF LIFE
Viewer	Independent Regulatory Entity	DPP platform management, compliance monitoring	-

To test the interaction of each actor within the DPP system, the system must first be initialized and the SCS activated. This setup is a necessary step during the testing phase, while in the final implementation, it will be executed only once by the designated authority responsible for platform management. The first procedure was to connect Ganache v2.7.1 to the SCS. This was achieved by uploading the SCS to Remix, selecting a stable Solidity compiler version 0.7.6+commit.7338295f, and compiling it. Then, in the Deploy & Run Transactions tab, the “Dev - Ganache provider” environment was selected, and server http://127.0.0.1:7545 was entered before proceeding with the deployment. On Ganache, it is then verified that the transaction has been successfully processed by checking the Blocks page (Figure 37).

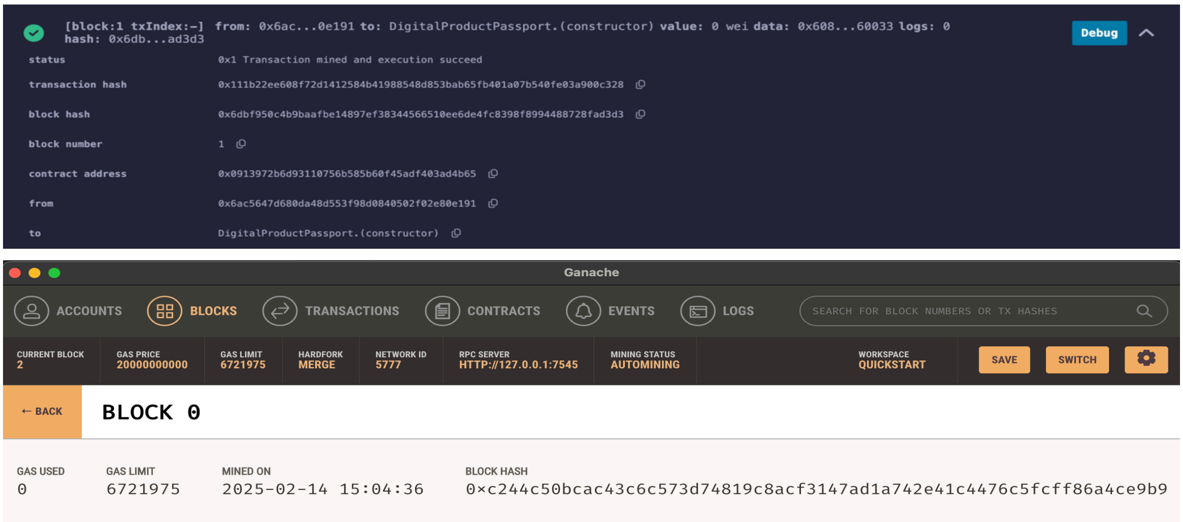

Figure 37 - Successful transaction on SCS using Ganache local server

Once the SCS is activated, the contract address 0x0913972b6d93110756b585b60f45adf403ad4b65 must be inserted into GUIA.py and PWF.py in the lines: *contract_address = Web3.to_checksum_address()*. Additionally, the ABI needs to be included, which can be copied from the bottom of the Solidity Compiler page and added to the lines: *contract_abi = json.loads()*. At this stage, the created system is now fully connected to the SCS and the EB, making it fully operational.

Before starting the process, Ethereum addresses were assigned to the respective actors involved in updating the DPP, as shown in Table 21. This step is necessary for accessing the platform initiated via PWF.py. In a future development, this process will be replaced by a username and password authentication system, along with a pre-approval mechanism managed by the super partes regulatory entity to ensure controlled and secure access. It was assumed that all mentioned companies would interact with the DPP, except for Vulcan Energy, which supplies lithium concentrate along with documentation that Green Lithium uses to extract information and input into the DPP. Similarly, Solvay provides ENEA with the necessary data regarding Dimethyl Carbonate, which is then recorded in the DPP as part of the cell composition.

Table 21 - Company Ethereum addresses for platform login

Company Name	**Ethereum Address**	**Index**
ENEA	0x6AC5647d680DA48d553f98D0840502f02E80e191	0
BASF	0x2EC615421B14aCDd76F387781b3d1F488aCB8325	1
Green Lithium	0xe47d3928Bf32beb8748dBdbD472dd06D70FA1925	2
Freudenberg	0xf840b241508A500Dfd7db2d9f3852029A4B6290C	3
KME Group	0xdD7ce790C7CdC21A9701Ffc9a64ab298157f4878	4
Slim Aluminium	0xdcee9ee0b4cB1800034b1d98bdbe87274B25aE41	5
STMicroelectronics	0x177d03DdD0550E143B9d956dE3ac2A3aa42796c3	6
Sa.Ma GreenRecycle	0xA2b05d1f09Ef4C6be4F9Bd2A1BC3E773FABc3BEa	7
Acciaierie Venete	0x45aD527560094ddCdd72737c19C46370ee7837D1	8
Regulatory Entity	0x4b710C42Db3989fc852a041fbEF37743C322d1c6	9

These address assignments are reflected in the PWF.py script, where they have been substituted in the following function:

```python
def get_user_role_by_index(address):
    index = get_account_index(address)
    roles = {
        0: 'ENEA',
        1: 'BASF',
        2: 'Green Lithium',
        3: 'Freudenberg',
        4: 'KME Group',
        5: 'Slim Aluminium',
        6: 'STMicroelectronics',
        7: 'Sa.Ma GreenRecycle',
        8: 'Acciaierie Venete',
        9: 'Regulatory Entity',
    }
    return roles.get(index, 'Unknown')
```

Additionally, these roles were integrated into dashboard.html to manage access permissions based on the actor's role as an owner, updater, or viewer in the DPP system. As a final setup detail, the system package of the software includes the *template.xml* file, which serves as the pre-configured DM for batteries. This XML is the tailored version of the FDM for batteries, as described in Section 6.1.3, and was structured using the population framework outlined in Section 6.1.2. For different product types, the process would require starting from the FDM, populating it accordingly, and replacing the *template.xml* file in the system package with the appropriate tailored model.

The first step in the DPP management system is the creation of a new DPP by the Owner ENEA. As described in Section 6.2.2 and illustrated in Figure 38, the process involves a series of structured steps. ENEA accesses the PWF platform and performs authentication using its assigned Ganache account 0, as specified in Table 21 (Step 1). Upon successful authentication, ENEA is redirected to the home screen of the platform, which provides various functionalities related to DPP management. From the home screen, ENEA selects the option "Generate a Passport" to initiate the DPP generation process (Step 2). The system provides ENEA with the ability to download the necessary files to facilitate the DPP creation process (Step 3). ENEA then fills in the DM template with the required data, including BATTERY/ATTRIBUTE, BATTERY/MANUFACTURING, and the PART sections related to CATHODE, ANODE, CELL, MODULE, and PACK (Step 4). The detailed data entries for each of these sections are outlined in Annex IV. After completing the DM, ENEA launches GUIA.py and selects the option "Generate a Passport" (Step 5). It then chooses SHA-256 as the cryptographic hash function and uploads the filled DM template (template.xml) (Step 6). The system processes the blockchain transaction via the SCS, generating a unique Passport ID. ENEA copies this ID, which uniquely identifies the DPP (Step 7). Returning to the PWF platform, ENEA enters the generated Passport ID (Step 8) and uploads the finalized DM file (Step 9), receiving confirmation that the DPP has been successfully created and recorded. At this stage, the DPP is officially recorded, and its metadata is stored immutably on the EB. The DPP is now available for future updates by updaters and can be accessed for verification by the regulatory entity.

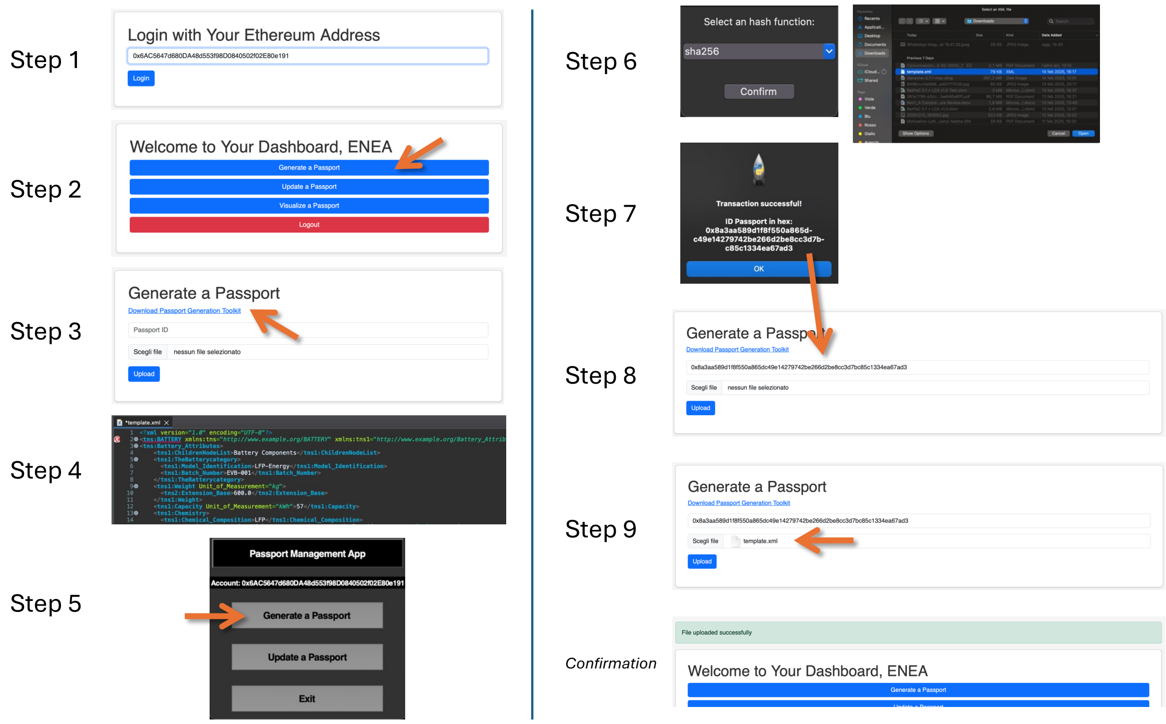

Figure 38 – DPP creation procedure by the Owner

As outlined in Section 6.2.2 and depicted in Figure 39, once the DPP has been created, it can be updated both by the Owner and by the Updaters listed in Table 21. Taking STMicroelectronics as an example, the company, acting as an Updater, must access the PWF platform using its Ethereum Address with Index 6 (Table 21) (Step 1). Upon successful authentication, STMicroelectronics is redirected to the platform's Dashboard, where it selects the option "Update a Passport" (Step 2). The system then prompts the Updater to enter the DPP ID previously generated by the Owner (Step 3) and click on Verify. If the verification is successful, the platform grants access to the DPP Update Toolkit, which includes GUIA.py, a user guide, and the most recently updated version of the DPP (Step 4). STMicroelectronics proceeds to modify the XML file, adding a new PART node corresponding to the BMS. The company updates all relevant details within the ATTRIBUTE, MATERIAL, and MANUFACTURING sub-nodes (Step 5). Additionally, at the end of the battery's lifecycle, STMicroelectronics will also be responsible for adding information about end-of-life treatments within the END OF LIFE node of the BMS. Following these modifications, STMicroelectronics launches GUIA.py and selects "Update a Passport" (Step 6). The system prompts the Updater to enter the DPP ID (Step 7) and upload the updated XML file (Step 8). If the SCS successfully registers the transaction on the EB, a confirmation message appears, displaying the updated DPP information within the SCS. To finalize the update, the Updater must return to the PWF web interface, upload the new DPP file (Step 9), and receive a final confirmation that the DPP has been successfully updated and stored on the platform.

The procedure described for STMicroelectronics follows the same process for all stakeholders involved, occurring sequentially along the battery lifecycle. Each actor, whose responsibilities are summarized in Table 20, has performed updates corresponding to their role in the value chain. For instance, Slim Aluminium updated the MANUFACTURING node, integrating data on the aluminum rolling process, energy consumption, and associated emissions from sheet production. Similarly, Freudenberg, as the supplier of the polypropylene separator, modified the MATERIAL node, detailing the separator’s chemical composition, thickness, and surface treatment processes. Throughout the lifecycle, ENEA played a dual role—first as an Owner and later as an Updater in phases such as refurbishing and recycling. These types of updates were accounted for during the experimental validation; however, for brevity and to avoid redundancy, the complete set of recorded updates has been documented within the Battery DM included in Annex IV.

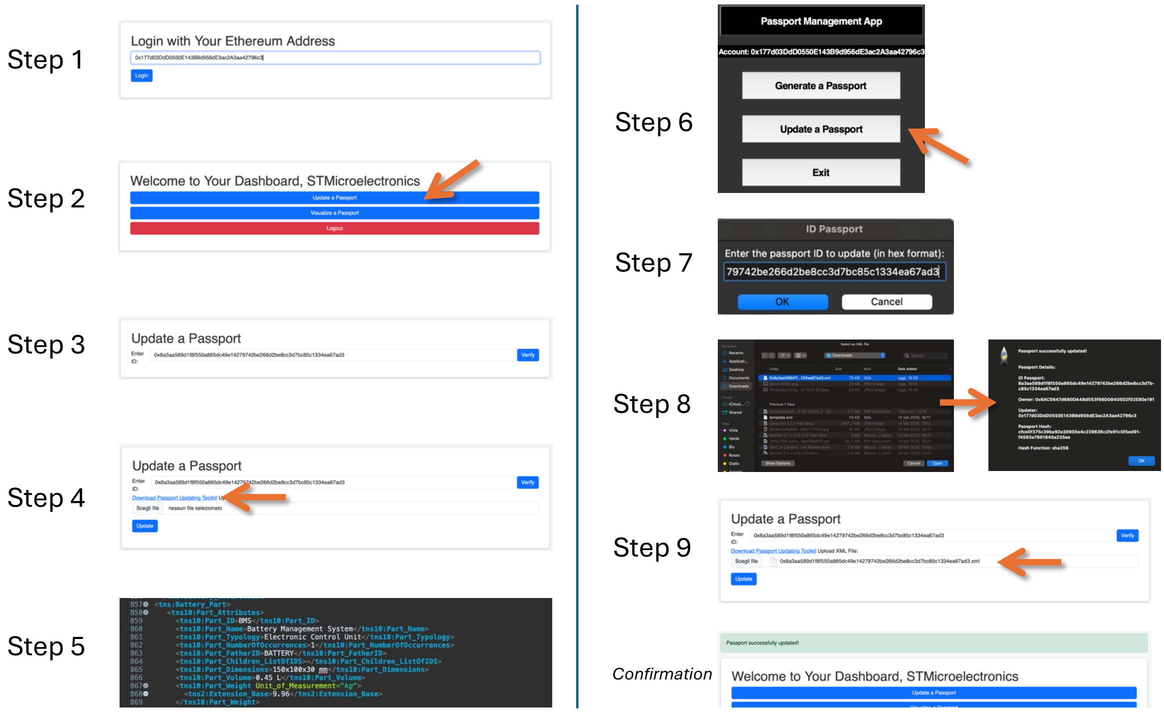

Figure 39 - DPP updating procedure by the Updater

For the Viewer, as illustrated in Figure 40, the process is more straightforward and takes place entirely within the platform. For example, the Regulatory Entity, acting as a Viewer, logs into the platform using its Ethereum Address with Index 9 (Step 1). Once authenticated, it is redirected to the home screen, where it selects "Visualize a Passport" (Step 2). The system then prompts the Viewer to enter the DPP ID and click on "View Passport" (Step 3). Upon validation, the platform retrieves the corresponding DPP, and an interface displaying the full XML document opens on the screen (Step 4), allowing the Viewer to inspect all recorded information.

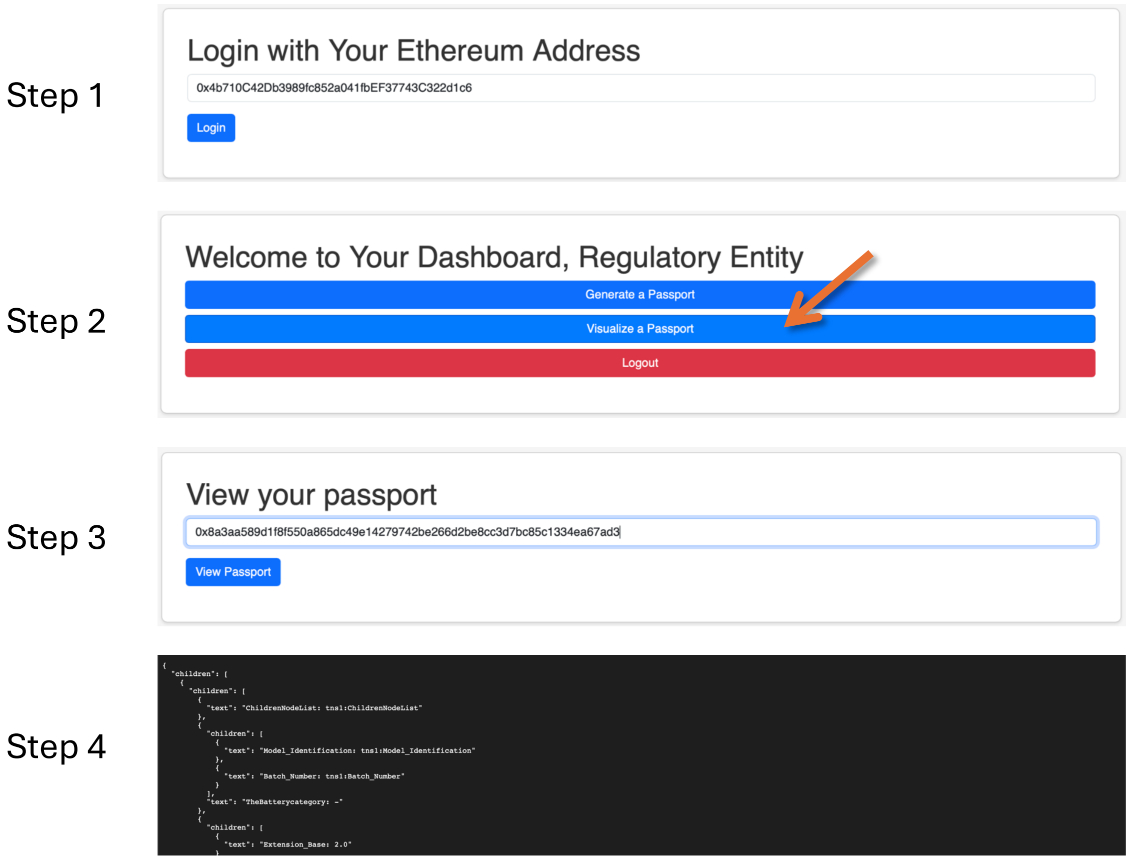

Figure 40 - DPP visualization procedure by the Viewer

7.4. Check: LCI extrapolation and utilization

Once all data has been collected within the DPP, the next step is to extract information from the ATTRIBUTE nodes, in the dedicated LCI section present at each level, to build the LCI in an external LCA software. For this study, the LCI was compiled and analyzed using SimaPro, in combination with the ecoinvent v3.10 database and the ReCiPe 2016 Hierarchy impact assessment method. This setup ensures comparability in the Act phase with the preliminary results extrapolated from BatPaC. The following tables (Tables 22–25) outline the process of constructing the LCI from the DPP to SimaPro, specifying inputs, outputs, their units of measure, number of occurrences of the material considered, indicated in the DPP, values recorded in the DPP, transformation of the previous value into quantities per FU, reference datasets utilized for LCIA, and their respective positions and the sources where the information was retrieved within the DPP. The complete dataset and additional inventory details are provided in Annex VIII. The FU chosen for this study is 1 kg of LFP battery. Table 22 presents the manufacturing phase of the LCI for cell, module, and pack. The cell and module constitute two PART nodes, while elements marked as "New" represent additional PART nodes specifically created based on data provided by the actors. The pack, instead, is registered as the BATTERY node. Materials for which only the weight is known have been categorized as MATERIAL nodes within the PROCESS sections of their respective parent nodes. The remaining components of manufacturing have been included in Annex VIII.

Table 22 - Cell, Module, and Pack LCI

Component (n° occurences)	**Units**	**DPP Value**	**LCI Value**	**Reference Dataset**	**DPP Position**
Inputs					
Electricity	kWh	2,15E+00	4,99E-01	electricity, medium voltage	BATTERY / CELL / MANUFACTURING / PROCESS / LCI / ENERGY
Natural Gas	m3	7,70E-01	1,79E-01	heat, district or industrial, natural gas	
Cathode	kg	1,41E+00	3,27E-01	New	BATTERY / PART (Specific, e.g. CATHODE) / ATTRIBUTE
Anode	kg	7,26E-01	1,68E-01	New	
Copper Foil	kg	5,99E-01	1,39E-01	New	
Aluminum Foil	kg	3,25E-01	7,54E-02	New	
Electrolyte: Ethylene Carbonate	kg	4,06E-01	9,41E-02	New	
Electrolyte: Dimethyl Carbonate	kg	4,06E-01	9,41E-02	New	

Separator: Polypropylene	kg	5,75E-02	1,33E-02	New	
Carbon black	kg	9,49E-02	2,20E-02	carbon black	BATTERY / CELL / PROCESS / MATERIAL / ATTRIBUTE
Binder (PVDF)	kg	1,17E-01	2,72E-02	polyvinylfluoride	
Electrolyte: LiPF6	kg	1,45E-01	3,37E-02	lithium hexafluorophosphate	
Separator: Polyethylene	kg	1,28E-02	2,98E-03	polyethylene, high density, granulate	
Separator: Polyethylene Terephthalate	kg	1,31E-02	3,05E-03	polyethylene terephthalate, granulate	
Outputs					
Cell (n°: 96)	kg	4,31E+00	1,00E+00		
Inputs					
Electricity	kWh	4,63E-03	7,30E-04	electricity, medium voltage	BATTERY / MODULE / MANUFACTURING / PROCESS / LCI / ENERGY
Cells	kg	6,90E+01	9,16E-01	New	BATTERY / PART (Specific, e.g. CELL) / ATTRIBUTE
Copper Foil	kg	2,41E-02	3,79E-03	New	
Aluminum Foil	kg	4,43E-01	6,98E-02	New	
Plastic: Polyethylene	kg	8,50E-03	1,34E-03	polyethylene, high density, granulate	BATTERY / MODLE / PROCESS / MATERIAL / ATTRIBUTE
Insulation (Fiberglass)	kg	6,14E-03	9,67E-04	glass fibre reinforced plastic, polyamide	
Electronic part	kg	5,29E-02	8,33E-03	electronic component, passive, unspecified	
Outputs					

Module (n°: 6)	kg	7,53E+01	1,00E+00		
Inputs					
Electricity	kWh	4,21E-01	2,84E-03	electricity, medium voltage	BATTERY / MANUFACTURING / PROCESS / LCI / ENERGY
Modules	kg	4,52E+02	7,53E-01	New	BATTERY / PART (Specific, e.g. MODULE) / ATTRIBUTE
Copper	kg	9,13E-02	6,16E-04	New	
Shell: Aluminum	kg	2,19E+01	1,48E-01	New	
BMS	kg	2,46E+00	1,66E-02	New	
Shell: Steel	kg	1,20E+00	8,07E-03	Steel, electric, low-alloyed	BATTERY / PROCESS / MATERIAL / ATTRIBUTE
Insulation	kg	6,81E-01	4,59E-03	glass fibre reinforced plastic, polyamide	
Coolant	kg	8,59E+00	5,80E-02	ethylene glycol	
Electronic part	kg	1,71E+00	1,16E-02	electronic component, passive, unspecified	
Outputs					
Pack	kg	6,00E+02	1,00E+00		

Although BatPaC did not take it into account, as it follows the system boundaries set by the Battery Regulation, the BMS tracked energy losses, a key distinguishing factor among different batteries and the only factor considered in the use phase. The studied battery was utilized in an EV until reaching 80% of its capacity, after which it underwent a refurbishing process and was repurposed as an ESS in another ENEA facility, until reaching 60% of its capacity, which is considered end-of-life. The LCI of both the use phases and the refurbishing process, constructed using data extracted from the DPP, is detailed in Table 23.

Table 23 - First Life, Refurbishing, and Second Life Phases LCI

Component	Units	DPP Value	LCI Value	Reference Dataset	DPP Position
Inputs					
Electricity	kWh	6,85E+03	1,14E+01	electricity, low voltage	BATTERY / USE / USE SCENARIO / ENERGY / ATTRIBUTE
Outputs					
First Use Phase (EV)	kg		1,00E+00		
Inputs					
Cables (Cooper)	kg	7,26E+00	1,21E-02	cable, unspecified	BATTERY / END-OF-LIFE / TREATMENT / PROCESS (REFURBISHING) / MATERIAL / ATTRIBUTE
Casing (Steel)	kg	1,94E+01	3,23E-02	Steel, low-alloyed, hot rolled	
BMS	kg	4,85E+00	8,08E-03	New	
Nickel (Metal)	kg	2,42E+00	4,04E-03	smelting and refining of nickel concentrate, 16% Ni	
Electricity	kWh	4,04E+01	6,74E-02	electricity, medium voltage	
Outputs					
Refurbishing Phase	kg		1,00E+00		
Scrap metal casing	kg	2,14E+01	3,57E-02	ferrous metal, in mixed metal scrap	BATTERY / END-OF-LIFE / TREATMENT / PROCESS (REFURBISHING) / ATTRIBUTE / LCI / PRODUCT
Scrap plastic	kg	1,54E+00	2,56E-03	waste plastic, WEEE, unsorted, Recycled Content cut-off	
Scrap cables	kg	2,91E+00	4,85E-03	copper scrap, sorted, pressed, Recycled Content cut-off	
Scrap BMS circuit boards	kg	1,46E+00	2,43E-03	electronics scrap, Recycled Content cut-off	
Inputs					

Electricity	kWh	8,77E+03	1,46E+01	electricity, low voltage	BATTERY / USE / USE SCENARIO (II) / ENERGY / ATTRIBUTE
Outputs					
Second Use Phase (ESS)	kg		1,00E+00		

Finally, end-of-life information was collected from the DPP. Specifically, Table 24 presents the hydrometallurgical process, while Annex VIII includes all recycling processes for various output scraps generated from hydrometallurgy. Additionally, it is important to consider that two different accounting methods can be used for end-of-life impacts: the cut-off method and system expansion. To showcase the potential of the DPP and ensure a comparison with the LCA provided by BatPaC, the system expansion method was applied.

Table 24 - Hydrometallurgy recycling LCI

Component	**Units**	**DPP Value**	**LCI Value**	**Reference Dataset**	**DPP Position**
Inputs					
HCl (30%)	kg	2,06E+01	3,43E-02	hydrochloric acid, without water, in 30% solution state	BATTERY / END-OF-LIFE / TREATMENT / PROCESS (HYDROMETALLURGY) / MATERIAL / ATTRIBUTE
H2O2 (7.5%)	kg	5,72E+01	9,54E-02	hydrogen peroxide, without water, in 50% solution state	
NaOH (32%)	kg	5,24E+01	8,73E-02	sodium hydroxide, without water, in 50% solution state	
CaCl2	kg	2,14E+02	3,57E-01	calcium chloride	
Fresh water	kg	3,19E+02	5,31E-01	tap water	
Electricity	kWh	2,91E+02	4,85E-01	electricity, medium voltage	
Outputs					
Hydrometallurgy Treatment	kg		1,00E+00		
Lithium brine	k	2,14E+02	3,57E-01	Lithium brine, 6.7 % Li	

Plastic scrap	kg	1,50E+02	2,50E-01	New	BATTERY / END-OF-LIFE / TREATMENT / PROCESS (HYDROMETALLURGY) / ATTRIBUTE / LCI / PRODUCT
Waste BMS	kg	1,80E+01	3,00E-02	New	
Copper scrap	kg	6,00E+01	1,00E-01	New	
Aluminium scrap shell	kg	2,11E+01	3,51E-02	New	
Aluminium scrap foil	kg	1,49E+01	2,49E-02	New	
Waste graphite	kg	9,00E+01	1,50E-01	New	
Dust	kg	1,06E-01	1,76E-04	particulates, air, unspecified // (>2.5, <10)	BATTERY / END-OF-LIFE / TREATMENT / PROCESS (HYDROMETALLURGY) / ATTRIBUTE / LCI / EMISSION
Hydrogen fluoride	kg	1,43E-03	2,39E-06	Hydrogen fluoride, air, unspecified	
VOC	kg	7,92E-02	1,32E-04	VOC, volatile organic compounds, air, unspecified	
Hydrochloric acid mist	kg	2,41E-03	4,01E-06	Hydrochloric acid, air, unspecified	

In each black box, all transportation processes were included, considering material transported, distance, vehicle type, and kilometres travelled. Each of these elements corresponds to a Route node within the DPP and is summarized in Table 25.

Table 25 - LCI Data for transport accounting

Process/Material	From-To	Transport Type	Range (Km)
Anhydrous Iron Phosphate	BASF (DE) - ENEA Casaccia (IT)	lorry, 16-32 metric ton, diesel, EURO 5	1200
Lithium Carbonate	Green Lithium (UK) - ENEA Casaccia (IT)	lorry, 7.5-16 metric ton, diesel, EURO 6	1600
Lithium Concentrate	Vulcan Energy (DE) - Green Lithium (UK)	lorry, 16-32 metric ton, diesel, EURO 5	1100

Dimethyl Carbonate	Solvay (BE) - ENEA Casaccia (IT)	lorry, 7.5-16 metric ton, diesel, EURO 6	1300
Ethylene Carbonate	BASF (DE) - ENEA Casaccia (IT)	lorry, >32 metric ton, diesel, EURO 5	1200
Separator in Polypropylene	Freudenberg (DE) - ENEA Casaccia (IT)	lorry, 16-32 metric ton, diesel, EURO 6	1100
Copper Foil	KME Group (IT) - ENEA Casaccia (IT)	lorry, 7.5-16 metric ton, diesel, EURO 6	200
Aluminium Foil and Shell	Slim Aluminium (IT) - ENEA Casaccia (IT)	lorry, 16-32 metric ton, diesel, EURO 5	300
BMS	STMicroelectronics (FR) - ENEA Casaccia (IT)	lorry, 16-32 metric ton, diesel, EURO 6	1000
First Use Phase	ENEA Casaccia (IT) - Stabilimento FCA Melfi (IT)	lorry, 16-32 metric ton, diesel, EURO 6	400
Refurbishing Phase	Stabilimento FCA Melfi (IT) - ENEA Casaccia (IT)	lorry, 7.5-16 metric ton, diesel, EURO 6	400
Second Use Phase	ENEA Casaccia (IT) - ENEA Portici (IT)	lorry, 16-32 metric ton, diesel, EURO 6	250
Hydrometallurgy Recycling	ENEA Portici (IT) - ENEA Casaccia (IT)	lorry, 16-32 metric ton, diesel, EURO 6	250
BMS Waste Recycling	ENEA Casaccia (IT) - STMicroelectronics Catania (IT)	lorry, 7.5-16 metric ton, diesel, EURO 6	800
Aluminium Scrap Recycling	ENEA Casaccia (IT) - Slim Aluminium Verona (IT)	lorry, 16-32 metric ton, diesel, EURO 5	500
Copper Scrap Recycling	ENEA Casaccia (IT) - KME Fornaci di Barga (IT)	lorry, 16-32 metric ton, diesel, EURO 5	600
Plastic Scrap Recycling	ENEA Casaccia (IT) - Plastic Recycling Center Rimini (IT)	lorry, 7.5-16 metric ton, diesel, EURO 6	450

Steel Scrap Recycling	ENEA Casaccia (IT) - Acciaierie Venete Padova (IT)	lorry, 16-32 metric ton, diesel, EURO 6	600

To complete the Check phase, the LCA was performed (Figure 41), and the resulting data (Figure 42) were reinserted into the DPP, finalizing and closing it. The LCA results will be presented in the next section, where they will be compared with those obtained from BatPaC.

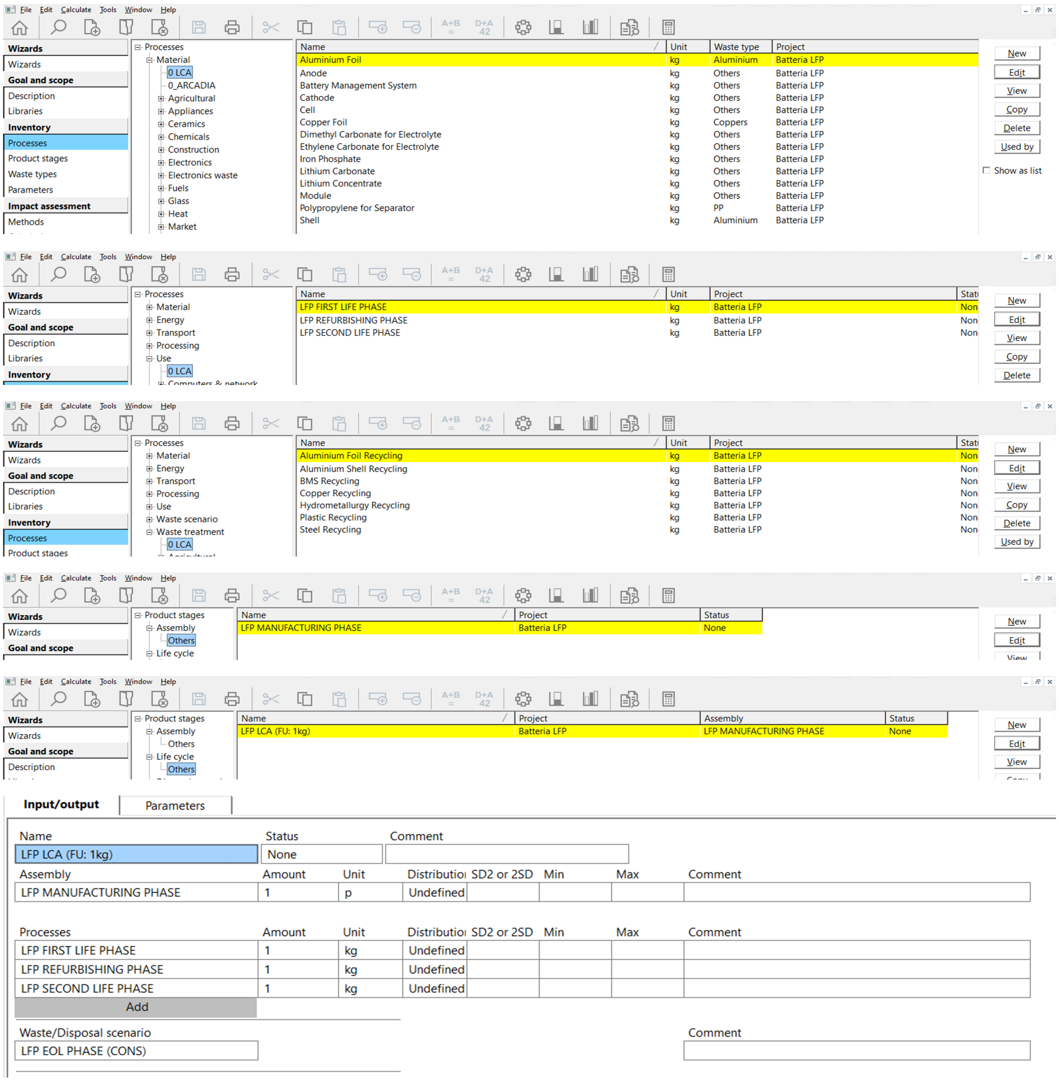

Figure 41 - LCI development in SimaPro

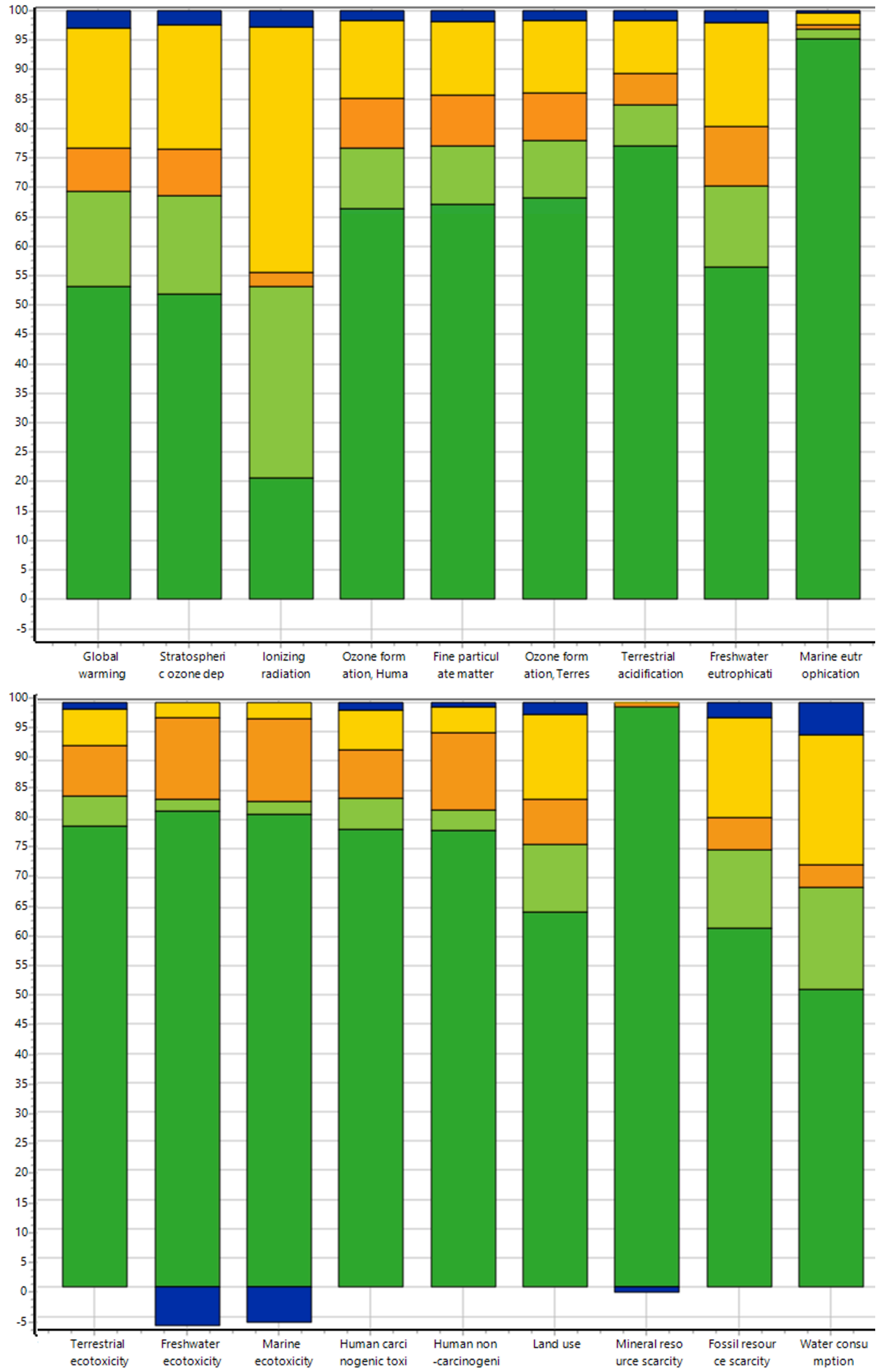

Figure 42 - LCIA, Midpoint indicators chart

7.4. Act: Discrepancy Analysis and Final Report Insights

Once the DPP is finalized and the LCA has been processed, including the necessary considerations regarding compliance with the Battery Regulation by verifying the entries listed in Table 19, the next step is to conduct a Discrepancy Analysis. This analysis allows for identifying key differences and insights that can be incorporated into the final report and leveraged to enhance the BatPaC model in the next iteration.

The analysis was conducted using a bottom-up approach, starting with an evaluation of the fundamental material components: cathode, anode, and electrolyte (Table 26).

Table 26 - LCIA MidPoint Indicators of Cathode, Anode, and Electrolyte from DPP and BatPaC

Impact category	Unit	Cathode (DPP)	Cathode (BatPaC)	Anode (DPP)	Anode (BatPaC)	Electro-lyte (DPP)	Electrolyte (BatPaC)
Global warming	kg CO2 eq	2,19E+00	2,21E+00	4,34E-02	4,73E-02	7,69E-01	8,05E-01
Stratospheric ozone depletion	kg CFC11 eq	1,28E-06	1,31E-06	1,93E-08	1,80E-08	1,83E-07	1,87E-07
Ionizing radiation	kBqCo-60 eq	2,69E-01	2,78E-01	2,11E-02	2,27E-02	5,84E-02	6,05E-02
Ozone formation, Human health	kg NOx eq	4,86E-03	5,07E-03	1,05E-04	1,08E-04	1,69E-03	1,74E-03
Fine particulate matter formation	kg PM2.5 eq	5,22E-03	5,57E-03	8,55E-05	8,83E-05	1,55E-03	1,61E-03
Ozone formation, Terrestrial	kg NOx eq	5,11E-03	5,32E-03	1,09E-04	1,12E-04	1,79E-03	1,84E-03
Terrestrial acidification	kg SO2 eq	1,56E-02	1,58E-02	1,57E-04	1,58E-04	4,13E-03	4,22E-03
Freshwater eutrophication	kg P eq	1,40E-03	1,46E-03	3,41E-05	3,52E-05	3,43E-04	3,47E-04

Marine eutrophication	kg N eq	1,47E-02	1,41E-02	2,77E-06	2,93E-06	1,03E-04	1,06E-04
Terrestrial ecotoxicity	kg 1,4-DCB	3,08E+01	3,09E+01	3,06E-01	3,12E-01	8,54E+00	8,73E+00
Freshwater ecotoxicity	kg 1,4-DCB	2,68E-01	2,74E-01	1,79E-03	1,89E-03	7,60E-02	7,92E-02
Marine ecotoxicity	kg 1,4-DCB	3,77E-01	3,89E-01	2,63E-03	2,70E-03	1,04E-01	1,07E-01
Human carcinogenic	kg 1,4-DCB	2,06E+00	2,11E+00	6,51E-03	6,75E-03	1,35E-01	1,40E-01
Human non-carcinogenic	kg 1,4-DCB	5,39E+00	5,32E+00	5,02E-02	5,16E-02	1,55E+00	1,50E+00
Land use	m2a crop eq	2,33E-01	2,43E-01	1,65E-03	1,79E-03	2,77E-02	2,91E-02
Mineral resource scarcity	kg Cu eq	1,18E+01	1,20E+01	2,23E-02	2,30E-02	1,33E-02	1,36E-02
Fossil resource scarcity	kg oil eq	7,75E-01	8,07E-01	1,43E-02	1,48E-02	2,37E-01	2,59E-01
Water consumption	m3	8,69E-02	8,97E-02	7,80E-04	8,49E-04	9,17E-03	9,57E-03

By systematically comparing the primary LCA data with BatPaC's standardized estimations, discrepancies were identified in key impact categories. These differences stem from variations in production methodologies, material refinement processes, and energy consumption patterns. The details of these discrepancies, their root causes, and the necessary modifications to BatPaC parameters are presented in Table 27, which provides a structured comparison of the key findings.

Table 27 - Discrepancy Analysis of fundamental components and BatPaC updating solutions

Impact Category	Component	Discrepancy	Cause of Discrepancy	BatPaC Parameters to Update
Global Warming	Anode	+9,01%	Primary LCA shows synthetic graphite production requiring	Adjust Energy Consumption framework, modify baseline

			higher energy use than the natural graphite assumed in BatPaC.	Energy Input, recalibrate Cost Input energy mix assumptions
	Electrolyte	+4,64%	Primary LCA considers solvent synthesis requiring additional energy compared to BatPaC assumptions.	Refine Electrolyte Composition assumptions, adjust Processing Impact parameters, improve Energy Efficiency factors
Stratospheric Ozone Depletion	Anode	-6,88%	BatPaC overestimates fluorinated gas emissions, while the real-world process uses lower-impact solvents.	Redefine solvent impact models, revise coating process datasets, and update emission factors
Ionizing Radiation	Anode	+7,32%	Real-world lithium sourcing involves higher nuclear energy use compared to BatPaC's assumed supply chain.	Adjust lithium sourcing methodology, refine supply chain dependencies, integrate nuclear energy factors
Fine Particulate Matter	Cathode	+6,65%	Primary LCA reveals higher metal refining emissions not fully captured in BatPaC's standard processes.	Adjust cathode metal processing parameters, refine refining impact calculations, and recalibrate emission intensity factors
Terrestrial Acidification	Electrolyte	+2,23%	Variations in precursor materials and their associated sulfur dioxide emissions.	Reevaluate electrolyte base source data, refine electrolyte additive impact, and enhance emission control modeling
Marine Eutrophication	Anode	+5,70%	Real-world sludge treatment emits more nitrogen than BatPaC's default waste assumptions.	Refine waste treatment methodologies, update waste disposal impact assessment, and restructure waste stream categorization
Freshwater Ecotoxicity	Cathode	+2,15%	BatPaC assumes lower toxicity emissions from cathode metal production.	Enhance cathode raw material extraction data precision and adjust heavy metal content evaluation

Human Carcinogenic Toxicity	Electrolyte	+3,68%	Differences in solvent purification levels between primary and secondary data.	Refine electrolyte component purity models, optimize solvent recovery efficiency, and improve contaminant level tracking
Land Use	Anode	+8,19%	BatPaC does not fully account for land-intensive mining impacts in real-world anode material sourcing.	Adjust anode composition assumptions, improve mining impact assessments, and update land use efficiency factors
Fossil Resource Scarcity	Electrolyte	+9,39%	BatPaC assumes lower fossil fuel dependency in electrolyte production.	Refine electrolyte solvent sourcing data, reassess fossil fuel dependency metrics, and enhance feedstock sourcing models
Water Consumption	Anode	+8,79%	The primary LCA accounts for high water usage in synthetic graphite extraction, while BatPaC assumes dry mining.	Update water usage assumptions, incorporate real extraction parameters, and refine water intensity calculation models

At the level of assembly and manufacturing, these differences become even more pronounced, as evidenced by the aggregated impacts presented in Table 28.

Table 28 - MidPoint Indicators of Manufacturing Phase from DPP and BatPaC

Manufacturing Phase	Unit	Value (DPP)	Value (BatPaC)	Discrepancy
Global warming	kg CO2 eq	1,27E+01	1,43E+01	12,50%
Stratospheric ozone depletion	kg CFC11 eq	5,54E-06	5,09E-06	-8,20%
Ionizing radiation	kBq Co-60 eq	1,45E+00	1,60E+00	10,10%
Ozone formation, Human health	kg NOx eq	4,33E-02	4,52E-02	4,40%
Fine particulate matter formation	kg PM2,5 eq	3,69E-02	3,98E-02	7,80%
Ozone formation, Terrestrial ecosystems	kg NOx eq	4,89E-02	5,13E-02	4,90%
Terrestrial acidification	kg SO2 eq	1,45E-01	1,54E-01	6,50%
Freshwater eutrophication	kg P eq	1,42E-02	1,49E-02	4,90%

Marine eutrophication	kg N eq	1,53E-02	1,67E-02	8,90%
Terrestrial ecotoxicity	kg 1,4-DCB	3,17E+02	3,45E+02	8,80%
Freshwater ecotoxicity	kg 1,4-DCB	6,86E+00	7,27E+00	5,90%
Marine ecotoxicity	kg 1,4-DCB	8,90E+00	9,61E+00	8,00%
Human carcinogenic toxicity	kg 1,4-DCB	7,32E+00	7,82E+00	6,80%
Human non-carcinogenic toxicity	kg 1,4-DCB	1,10E+02	1,21E+02	10,40%
Land use	m2a crop eq	8,13E-01	8,72E-01	7,20%
Mineral resource scarcity	kg Cu eq	1,22E+01	1,26E+01	2,70%
Fossil resource scarcity	kg oil eq	4,94E+00	5,50E+00	11,10%
Water consumption	m3	2,13E-01	2,31E-01	8,30%

A key aspect of this discrepancy lies in the significantly higher energy consumption reported in BatPaC. While the DPP data indicates an average energy usage of 2.73 kWh per kg of battery, BatPaC estimates a considerably higher consumption. By calculating the various energy consumption components in BatPaC, it results that the model utilizes approximately 35% more energy compared to the real-world data in DPP. This variance can be attributed to the fact that BatPaC applies standardized processing assumptions across all battery types, whereas in the DPP, industrial actors have aggregated energy consumption data, making further breakdowns and attributions difficult. Therefore, BatPaC must allow for greater flexibility in modifying energy input parameters, enabling users to manually adjust production energy values or derive process-specific consumption figures based on real-world aggregated industry data provided by manufacturers. Energy input parameters must be adapted to allow regional differentiation, prioritizing European data over global averages, or even national-level data where possible. In particular, the majority of battery manufacturing takes place in Italy, where the share of renewable energy in the grid mix is significantly higher than the global average.

In addition to energy consumption, another crucial factor influencing discrepancies in BatPaC is the end-of-life modeling. BatPaC incorporates hydrometallurgical processes for material recovery, with predefined recovery percentages for key materials. The recovery percentages currently implemented in BatPaC must be recalibrated to align with the values reported in the DPP, ensuring that the model reflects real-world recycling efficiencies and material loop closure rates.

7.5. Discussion

The case study confirms the validity of the framework across three key aspects: the feasibility of understanding the impacts at the moment of design choice and making more informed decisions, the successful implementation of data traceability across the entire supply chain, and the comparison between LCA results derived from BatPaC and those extracted from real-world data. The integration of BatPaC with LCA has proven effective in identifying the optimal battery design while maintaining a balance between environmental impact and technical performance. Furthermore, despite the simplification to a limited set of parameters in this initial implementation, including constraints on design options such as module and cell arrangement, the BatPaC structure allows for extensive customization, ensuring that in real-world scenarios with increased constraints and a broader range of design options, it retains the capability to accommodate these complexities.

The framework has also demonstrated the feasibility of tracking and verifying data along the supply chain using EB-based DPPs. The case study, performed with local Ethereum accounts provided by Ganache, successfully simulated access by different stakeholders, each with a specific access profile and limited permissions for creating, modifying, and visualize the DPP. Additionally, the comparison between LCA results obtained from BatPaC predictions and those reconstructed from the traced supply chain data has revealed minimal but significant deviations. These discrepancies arise primarily from differences in methodological approach: BatPaC employs a standardized material and process structure, whereas industrial actors tend to simplify data capture processes, generally aggregating information such as energy consumption, while increasing variability in material choices. Despite these variations, the overall consistency of results suggests that the BatPaC model could be further refined to incorporate a more comprehensive representation of industrial practices.

The results of the case study provide valuable insights into how the proposed framework aligns with, and in some cases challenges, current European regulatory requirements, particularly those outlined in the Battery Regulation 2023/1542. One key observation concerns the exclusion of the use phase from the system boundaries of the CF calculation mandated by the Battery Regulation. The LCA results derived from the DPP indicate that the use phase, which includes first life, refurbishment, and second life, contributes between 0,77% (Mineral Resource Scarcity) and 76,43% (Ionizing Radiation) to the overall environmental impact (Table 29). This finding suggests that current regulatory methodologies may underestimate the true lifecycle impact of batteries. Given the high variability in energy losses and maintenance needs across different battery types, it is imperative to incorporate these aspects into regulatory assessments to ensure a more accurate representation of environmental burdens.

Table 29 - MidPoint Indicator of Use Phase and its impact share

Impact category	Unit	Total	Use Phase	Impact Share
Global warming	kg CO2 eq	2,39E+01	1,05E+01	43,91%
Stratospheric ozone depletion	kg CFC11 eq	1,07E-05	4,87E-06	45,68%
Ionizing radiation	kBq Co-60 eq	7,01E+00	5,36E+00	76,43%
Ozone formation, Human health	kg NOx eq	6,53E-02	2,08E-02	31,87%
Fine particulate matter formation	kg PM2.5 eq	5,50E-02	1,71E-02	31,03%
Ozone formation, Terrestrial ecosystems	kg NOx eq	7,16E-02	2,15E-02	30,06%
Terrestrial acidification	kg SO2 eq	1,88E-01	4,01E-02	21,33%
Freshwater eutrophication	kg P eq	2,52E-02	1,05E-02	41,62%
Marine eutrophication	kg N eq	1,61E-02	7,19E-04	4,47%
Terrestrial ecotoxicity	kg 1,4-DCB	4,02E+02	8,05E+01	20,00%
Freshwater ecotoxicity	kg 1,4-DCB	7,88E+00	1,57E+00	19,93%

Marine ecotoxicity	kg 1,4-DCB	1,04E+01	2,11E+00	20,36%
Human carcinogenic toxicity	kg 1,4-DCB	9,35E+00	1,91E+00	20,42%
Human non-carcinogenic toxicity	kg 1,4-DCB	1,40E+02	2,96E+01	21,10%
Land use	m2a crop eq	1,27E+00	4,29E-01	33,86%
Mineral resource scarcity	kg Cu eq	1,22E+01	9,36E-02	0,77%
Fossil resource scarcity	kg oil eq	8,06E+00	2,90E+00	36,01%
Water consumption	m3	4,19E-01	1,82E-01	43,54%

Additionally, the impact of other midpoint indicators reveals gaps in current regulatory approaches. The values obtained after normalization using SimaPro show that while the GWP remains relatively low at 0,299%, Human Carcinogenic Toxicity reaches 90,8%, Freshwater Ecotoxicity 31,3%, and Marine Ecotoxicity 23,8% (Figure 43). Values approaching 100% signify a highly significant impact relative to the total annual environmental burden per capita in the reference region, as defined by ReCiPe 2016 H, indicating that emissions or resource use in that category disproportionately contribute to the overall environmental impact. For this reason, it is crucial that the regulation does not focus solely on CF but extends reporting requirements and restrictions to other environmental indicators. This issue is further highlighted by BatPaC, where, in the case study, one design solution was chosen over another based exclusively on its CF impact, despite having higher environmental burdens across multiple other impact categories. While the Battery Regulation includes provisions for limiting hazardous substances, it does not fully address their broader impacts, which are also relevant to the CLP and REACH regulations. A more integrated approach to chemical risk management across multiple regulatory frameworks would strengthen efforts to mitigate adverse environmental and health consequences.

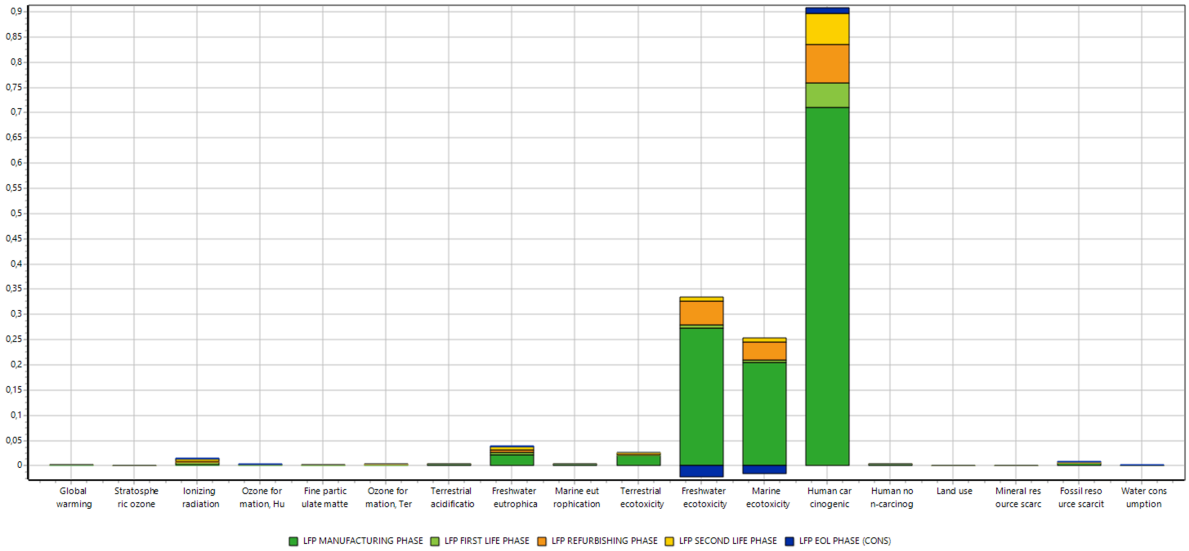

Figure 43 - Normalization of Midpoint Indicators for LFP Battery

Moreover, the regulation mandates the disclosure of critical raw materials present above 0.1% but does not provide sufficient synergy with the objectives of the CRMA. At the same time, the structured data population methodology demonstrated by the framework suggests that the proposed solution could serve as a viable candidate for a universal DPP within the ESPR framework. While further regulatory developments must be monitored, the hierarchical, modular structure of the FDM has proven adaptable to different supply chain actors, enhancing interoperability and data standardization beyond the battery sector.

For battery manufacturers and supply chain stakeholders, adopting the proposed framework will require significant advancements in data management and integration practices. The implementation of DPP, as well as the framework as a whole, demands a more collaborative approach to data sharing, necessitating clear agreements on data accessibility and protection among all participants. Additionally, effective collaboration is required in the design phase within BatPaC, given its need for a substantial volume of high-quality input data to optimize battery configurations. From an operational perspective, manufacturers will need to invest in automated data collection systems to ensure accurate and consistent information flows. Integration between DPPs and existing enterprise resource planning, manufacturing execution systems, and LCA tools will be essential to prevent redundancy and streamline data exchange. While decentralized architectures offer enhanced data security and traceability, this particular infrastructure has been designed to minimize blockchain-related costs, making it more feasible for widespread industrial adoption while still overcoming implementation challenges.

Based on the case study, the findings discussed, and the work carried out over years of research, it is possible to conclude this section by outlining the limitations observed in the tools used within the framework and possible future developments. In this synthetic analysis, these two aspects have been explored in detail for BatPaC integrated with LCA and for the DPP, divided into DM and ITI, as shown in Table 30.

Table 30 - Limitations and future developments of framework tools

Tool	Limitations	Future Developments
BatPac LCA	• Requires a paid LCA database, restricting accessibility, or the use of free LCA databases that may lack reliability and completeness. • Battery chemistries and production processes are limited to pre-measured configurations, reducing applicability to emerging technologies. • EoL scenarios rely on literature data, potentially reducing LCA accuracy. • The model does not incorporate battery use-phase impacts.	• Expanding the database by integrating more LCA datasets, incorporating multiple selection options for regionality and quality, particularly when real-world data is available, will enhance result accuracy. • Refining end-of-life modeling incorporating more structured processes will improve results. • Integrating a macro that allows the addition of new battery chemistries and the modification of production processes to increase flexibility. • Industrial-scale testing. • Including battery use-phase with energy losses and refurbishing phase to a more comprehensive LCA.
DM	• Ensuring reliable data collection from all supply chain actors is challenging due to variability in data quality and completeness.	• Implementing AI-driven automation to enhance data collection accuracy and reduce human errors.

	• Stakeholder resistance, lack of technical knowledge, and data-sharing concerns hinder collaboration. • Time-consuming and, therefore, cost burden. Small and medium enterprises (SMEs) may face challenges due to limited financial and technical resources. • Manual XML data entry increases risk of errors and security vulnerabilities. • Broader stakeholder engagement is necessary for successful adoption. • Ensuring data security requires advanced measures. • High data granularity complicates consistent LCI data collection.	• Expanding the model to additional industries, such as textiles and electronics, will facilitate wider adoption. • Improving interoperability with existing IT systems to ensure seamless integration across various platforms. • Maintaining compliance with evolving EU regulations requires continuous updates to the data model. • Conducting real-world validation through industrial testing in different industries. • Collaborating with international organizations to standardize DMs for DPPs at both European and global levels. • Strengthening data security mechanisms to ensure sensitive information is accessible only to authorized parties.
ITI	• A central oversight is required to ensure infrastructure integrity and security. • Managing sensitive data requires more granular access controls. • DPP tests on EB-based infrastructures remain untested. • Multiple steps between the website and the desktop application are still necessary, increasing complexity and reducing efficiency. • Effective communication between different actors is required to ensure the proper sharing of DPP IDs. • The current system is developed across multiple Python, HTML, and CSS files and needs to be transitioned to a more advanced software and graphical development level.	• Developing a dedicated application or integrating XML management within the webpage will streamline data handling and improve efficiency. • Enhancing user interfaces to improve accessibility for different stakeholders. • Utilizing AI for data management to increase efficiency and adaptability to evolving data needs. • Conducting pilot tests on real EB-based networks to provide insights into the infrastructure's feasibility, scalability, and long-term viability. • Integrating all developed files into a unified environment to streamline workflow and improve system efficiency.

Conclusions

The present research work investigated methods and tools able to address key challenges in battery eco-design, data traceability, and regulatory compliance. A multidisciplinary approach was adopted, integrating expertise from environmental engineering, materials science, data science, blockchain technology, and regulatory analysis, to develop an integrated framework for sustainable battery lifecycle management.

The thesis initially analyzed the state of the art in relevant technological fields, including advancements and limitations in battery materials, manufacturing techniques, digital traceability solutions, and regulatory compliance mechanisms. Furthermore, the research examined the European regulatory and industrial landscape, leading to the development of a structured strategy for a sustainable European battery market by 2030, outlining key policy drivers and industry actions required to enhance circularity and reduce dependency on critical raw materials. Among the key outcomes, the study highlighted the hazardous nature of black mass from battery recycling, underscoring the necessity of classifying it as hazardous waste and implementing stringent traceability mechanisms. From these analyses, a common factor emerged: the necessity for a structured and integrated framework capable of addressing technological and regulatory gaps while fostering sustainable battery lifecycle based on eco-design and data traceability. Subsequently, the research focused on developing the proposed framework, which led to the following key outcomes:

- *Integrated Methodology for Battery Lifecycle Management:* Developed a structured framework integrating predictive environmental impact analysis and real-time traceability to enhance battery eco-design and sustainability. This supports manufacturers and policymakers in adopting a data-driven approach for sustainable battery design, accelerating compliance with Battery Regulation requirements.

- *Implementation of Automated LCA within Battery Design Software:* Enhanced BatPaC with LCA integration, enabling instant sustainability assessments during the design phase. This opens pathways for eco-design optimization across battery and adjacent industries, demonstrating that LCI data can be extracted directly from design tools.
- *Universal DPP:* The implementation of an FDM and a structured framework for its population and customization enables potential standardization of the DPP across industries, accelerating its adoption and facilitating compliance with ESPR requirements.
- *Fully Decentralized Blockchain Solution for Cost-Effective Traceability:* Developed a fully decentralized hash-based data-sharing method to reduce blockchain storage costs, addressing scalability issues. This makes traceability systems more accessible, particularly for SMEs, encouraging wider industry adoption of DPP principles.
- *LCI-Ready DM for Seamless LCA Integration:* This approach could further support the widespread adoption of LCA practices and data standardization, fostering eco-design practices.
- Development of a functional DPP prototype tailored for battery applications: Tested in a local blockchain environment, this model is specifically designed for adoption within the Battery Regulation after further optimizations.

Despite its advantages, the framework presents some limitations that can be justified by the fact that the framework components currently reach a Technology Readiness Level (TRL) of 5-6, indicating that while they have been validated in relevant environments, further testing, particularly at an industry scale, is required before widespread adoption. BatPaC is currently limited to predefined chemistries and manufacturing processes, restricting its applicability to emerging battery technologies. Moreover, the developed version currently lacks integration of the use phase, aligned with system boundaries of Battery Regulation, and requires greater precision in modeling end-of-life scenarios to improve lifecycle assessment accuracy. Similarly, the EB-based DPP, while effective in data traceability, it remains complex for mass adoption, time-consuming, and thus prohibitive for SMEs.

Additionally, the hashing method was theorized and successfully applied to reduce costs; however, further research is needed to confirm and quantify the extent of its benefits.

Future research and industrial implementation should focus on several key areas, such as expanding BatPaC's macros to accommodate additional battery chemistries and allowing for customizable production processes, while continuously integrating real-world industrial data to enhance accuracy. Additionally, efforts should be directed towards automating data management and optimizing the DPP for a more streamlined 'one-entry access' system, simplifying stakeholder interactions and improving efficiency. While the improvement of these tools could lead to the adoption of the entire framework within a unified system, for now, the automation of LCA within BatPaC could open new research avenues in eco-design across multiple industries, demonstrating that LCA-relevant data can be directly extracted from design software. At the same time, if supported by international organizations, the DPP could facilitate the refinement of the DM toward a standardized structure, potentially elevating it to a truly universal version.

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Annex I.
World Battery Sector Forecast

Table 31 - World Battery CRMs 2030 Forecasting, overall data

	Li	Co	Ni	Mn	Graphite	Ti	Cu	Al	P	Si
Production										
2023 (t)	184680	229300	3566000	19890000	1587650	9062000	21550000	69560000	220050000	8983000
2030 (t)	564723	685302	8807616	30993606	5129622	16121860	33281728	189543629	371323499	23972655
CAGR 19-23	21%	12%	8%	1%	10%	4%	1%	2%	-1%	2%
CAGR 23-30	17%	17%	14%	7%	18%	9%	6%	15%	8%	15%
Growth 23-30	206%	199%	147%	56%	223%	78%	54%	172%	69%	167%
Reserve										
2023 (t)	26590000	10529000	131040000	1908000000	263200000	901200000	1000600000		74222000000	
2030 (t)	24084668	7438502	88025204	1730112165	240605513	809200915	821586919		72262941538	
Depletion 23-30	9%	29%	33%	9%	9%	10%	18%		3%	
Depletion Time (y)	43	11	10	56	47	50	25		195	
HHI										
2023	31%	56%	29%	21%	61%	18%	12%	37%	21%	55%
2030	9%	72%	51%	50%	75%	30%	16%	55%	20%	74%
FSI										
1st producer 2023	19,6 - Australia	106,7 - Congo	63,7 - Indonesia	69,6 - South Africa	64,4 - China	64,4 - China	41,1 - Chile	64,4 - China	64,4 - China	64,4 - China
1st producer 2030	41,1 - Chile	106,7 - Congo	63,7 - Indonesia	69,6 - South Africa	64,4 - China	64,4 - China	106,7 - Congo	64,4 - China	68,8 - Morocco	64,4 - China

Table 32 - Primary CRM-producing countries, forecast and model reliability metrics

	Prod. '23 (t)	Res. '23 (t)	Prod. '30 (t)	Share '30	Res. 2030 (t)	Depl. 23-30	Correlation	R^2	P-Value
Li									
Chile	44000	3000000	824969	61%	2317225	23%	0,992	0,984	0,001
Argentina	9600	6200000	31972	12%	6058326	2%	0,859	0,738	0,062
Canada	3400	9300000	23355	9%	9217079	1%	0,859	0,738	0,062
Brazil	4900	930000	17496	7%	854235	8%	0,856	0,733	0,064
Australia	86000	390000	0	0%	0	100%	0,983	0,968	0,002
China	33000	60000	0	0%	0	100%	0,978	0,957	0,004
Co									
Congo	170000	6000000	576199	84%	3461602	42%	0,998	0,995	0,001
Indonesia	17000	500000	56895	8%	248299	50%	0,988	0,976	0,002
Philippines	3800	260000		3%				0,479	0,195
Turkey	2800	91000	8077	1%	53427	41%	0,857	0,735	0,063

Canada	2100	230000		<1%				0,546	0,154
Cuba	3200	500000		<1%				0,648	0,100
Ni									
Indonesia	1800000	55000000	6142273	70%	28001141	49%	0,980	0,961	0,003
Brazil	89000	16000000	279093	3%	14738102	8%	0,845	0,714	0,071
Australia	160000	24000000		1%				0,071	0,665
Mn									
South Africa	7200000	600000000	19982667	64%	505796593	16%	0,757	0,572	0,139
Graphite									
China	1230000	78000000	4415867	86%	58911235	24%	0,947	0,896	0,015
Korea Republic of	27000	1800000	99576	2%	1373313	24%	0,971	0,942	0,006
Tanzania	6000	18000000	44610	1%	17845057	1%	0,902	0,813	0,036
P Rock									
Morocco	35000000	50000000000	134919523	36%	49430077847	1%	0,872	0,761	0,128
China	90000000	3800000000		17%			-0,128	0,016	0,838
Jordan	12000000	1000000000	52986134	14%	785598289	21%	0,984	0,969	0,002
Ti mineral concentrate									
Australia	600000	215000					-0,741	0,549	0,152
China	3100000	210000					0,568	0,322	0,318
Al									
China	41000000		139027595	73%			0,918	0,843	0,028
Si Metal									
China	6600000		20500089	86%			0,864	0,747	0,059
Cu									
Congo	2500000	80000000	9108713	27%	40814309	49%	0,962	0,925	0,009
Chile	5000000	190000000	528957	2%	178183253	6%	-0,995	0,989	0,001

Annex II.
EU Battery Sector Forecast

Table 33 - Best, Base, and Worst 2030 EU Scenarios analysis

CRM	Battery Supply Needs 2030 (t)	Battery Application (%)	Other Sector Supply Needs (t)	CRM Demand 2030 (t)	Internal production (t)	Shortage (t)	Shortage (%)
Best Scenario							
Li	75989	44,80%	23407	91865	170358	No	No
Co	75133	56,00%	14758	66024	11308	54716	82,9%
Ni	229192	7,00%	761245	914283	6066777	No	No
Mn	59150	1,05%	1393546	1433067	5461674	No	No
Graphite	733600	18,20%	824292	1557892	591529	966364	62,0%
Ti		0,21%			10405800		
Cu	612267	6,09%	2360345	2851462	6790117	No	No
P		2,10%			492481736		
Al	313425	0,21%	37234144	37488227	36452262	1035965	3,0%
Si		3,15%			20974071		
Base Scenario							
Li	75989	32,00%	80738	149196	59267	89928	60,3%
Co	75133	40,00%	56350	107616	8077	99539	92,5%
Ni	229192	5,00%	2177324	2330362	575522	1754840	75,3%
Mn	59150	0,75%	3913758	3953279	536350	3416929	86,4%
Graphite	733600	13,00%	2454738	3188338	170606	3017732	94,6%
Ti		0,15%			987141		
Cu	612267	4,35%	6731418	7222535	826452	6396083	88,6%
P		1,50%			233432291		
Al	313425	0,15%	104318288	104572371	3458026	101114345	96,7%
Si		2,25%			1989695		
Worst Scenario							
Li	75989	19,20%	239840	308298	26770	281528	91,3%
Co	75133	24,00%	178441	229707	4846	224861	97,9%
Ni	229192	3,00%	5557906	5710944	16111	5694833	99,0%
Mn	59150	0,45%	9813971	9853492	25635	9827857	99,7%
Graphite	733600	7,80%	6503646	7237246	71470	7165776	99,0%
Ti		0,09%			27634		
Cu	612267	2,61%	17134679	17625796	129337	17496459	99,3%
P		0,90%			115300507		
Al	313425	0,09%	260952431	261206515	96803	261109712	99,0%
Si		1,35%			55699		

Annex III.
Comparative LCAs

Table 34 - Comparative LCA of CRMs

Midpoint Indicator	LCE	Ni	Mn	Co	Al	P	Ti	Graphite	Si
TAP (kg SO2-Eq)	4,89E-02	1,51E+00	2,55E-02	3,56E-01	9,80E-02	4,50E-02	2,08E-01	3,30E-04	4,06E-02
GWP100 (kg CO2-Eq)	8,11E+00	1,86E+01	5,65E+00	4,85E+01	2,28E+01	1,36E+01	5,05E+01	7,43E-02	1,17E+01
FETP (kg 1,4-DCB-Eq)	7,04E-01	9,92E+00	4,77E+00	1,81E+01	7,16E-01	4,18E-01	5,73E+00	2,37E-03	2,27E-01
METP (kg 1,4-DCB-Eq)	9,63E-01	1,38E+01	7,11E+00	2,53E+01	1,07E+00	6,29E-01	8,39E+00	4,17E-03	1,64E+00
TETP (kg 1,4-DCB-Eq)	7,93E+01	2,80E+03	2,60E+01	2,58E+03	7,38E+01	8,48E+01	3,91E+02	1,20E+00	1,14E+03
FFP (kg oil-Eq)	2,05E+00	5,19E+00	1,20E+00	1,56E+01	4,71E+00	3,95E+00	1,15E+01	2,01E-02	2,57E+00
FEP (kg P-Eq)	4,68E-03	1,56E-02	2,44E-03	2,85E-02	6,37E-03	6,88E-03	2,31E-02	1,76E-05	3,39E-03
MEP (kg N-Eq)	6,21E-03	3,06E-03	1,46E-04	1,15E-02	4,89E-04	8,58E-04	1,41E-03	1,75E-06	2,69E-04
HTPc (kg 1,4-DCB-Eq)	1,70E+00	4,86E+00	3,66E+02	1,74E+01	1,35E+01	1,91E+00	6,88E+01	1,64E-02	9,16E-01
HTPnc (kg 1,4-DCB-Eq)	1,57E+01	1,68E+02	1,02E+01	6,13E+02	2,28E+01	1,31E+01	5,95E+01	6,44E-02	6,80E+00
IRP (kBq Co-60-Eq)	2,85E-01	2,61E+00	4,22E-01	1,42E+01	1,46E-01	1,66E+00	2,38E+00	4,28E-03	7,36E-01
LOP (m2*a crop-Eq)	2,36E-01	6,39E-01	1,70E-01	1,78E+00	2,37E-01	8,22E-01	1,71E+00	2,59E-03	8,54E-01
SOP (kg Cu-Eq)	2,68E+01	5,72E+00	2,47E-01	1,66E+01	3,22E-01	7,73E-01	2,69E+00	2,03E-01	5,62E-02
ODPinfinite (kg CFC-11-Eq)	2,36E-06	1,38E-05	1,36E-06	3,75E-05	4,29E-06	4,18E-06	1,33E-05	2,62E-08	3,52E-06
PMFP (kg PM2.5-Eq)	1,88E-02	4,47E-01	2,14E-02	1,26E-01	4,41E-02	2,58E-02	9,60E-02	1,50E-04	1,94E-02
HOFP (kg NOx-Eq)	2,83E-02	8,10E-02	2,33E-02	1,54E-01	5,93E-02	3,60E-02	1,27E-01	3,82E-04	2,81E-02
EOFP (kg NOx-Eq)	2,91E-02	8,38E-02	2,38E-02	1,61E-01	6,01E-02	3,70E-02	1,31E-01	3,94E-04	2,88E-02
WCP (m3)	8,78E-02	1,75E+00	2,36E-02	9,53E+00	7,31E-02	1,05E-01	2,07E-01	2,34E-04	1,12E-01

Table 35 – Comparative LCA of LCE from spodumene and brine sources, with percentage reductions

Midterm Indicator	LCE - Spondumene	LCE - Brine	Reduction (using brine)
TAP (kg SO2-Eq)	6,31E-02	1,26E-02	80%
GWP100 (kg CO2-Eq)	1,01E+01	2,24E+00	78%
FETP (kg 1,4-DCB-Eq)	9,10E-01	1,92E-01	79%
METP (kg 1,4-DCB-Eq)	1,25E+00	2,73E-01	78%
TETP (kg 1,4-DCB-Eq)	1,02E+02	2,94E+01	71%

FFP (kg oil-Eq)	2,77E+00	5,67E-01	79%
FEP (kg P-Eq)	6,71E-03	1,78E-03	73%
MEP (kg N-Eq)	8,65E-03	1,57E-03	82%
HTPc (kg 1,4-DCB-Eq)	1,63E+00	1,44E+00	12%
HTPnc (kg 1,4-DCB-Eq)	1,93E+01	5,72E+00	70%
IRP (kBq Co-60-Eq)	5,94E-01	1,04E-01	82%
LOP (m2*a crop-Eq)	2,58E-01	1,69E-01	35%
SOP (kg Cu-Eq)	4,00E+01	1,40E+00	97%
ODPinfinite (kg CFC-11-Eq)	3,26E-06	6,46E-07	80%
PMFP (kg PM2.5-Eq)	2,57E-02	4,66E-03	82%
HOFP (kg NOx-Eq)	3,31E-02	8,45E-03	74%
EOFP (kg NOx-Eq)	3,42E-02	8,72E-03	74%
WCP (m3)	1,18E-01	4,05E-02	66%

Table 36 – Comparative LCA of Energy EU Country Mix

Country	GWP100 (kg CO2-Eq)	CED (MJ-Eq)	TETP (kg 1,4-DCB-Eq)
Austria	2,23E-01	6,62E+00	1,31E+00
Belgium	2,07E-01	9,91E+00	1,28E+00
Bulgaria	4,99E-01	1,27E+01	1,67E+00
Croatia	3,91E-01	9,07E+00	1,63E+00
Cyprus	1,12E+00	1,42E+01	6,32E+00
Czechia	6,37E-01	1,20E+01	2,13E+00
Denmark	1,53E-01	6,29E+00	1,57E+00
Estonia	3,70E-01	9,99E+00	1,84E+01
Finland	1,49E-01	8,89E+00	1,47E+00
France	7,88E-02	1,21E+01	1,03E+00
Germany	4,26E-01	8,57E+00	1,65E+00
Greece	6,49E-01	1,14E+01	2,85E+00
Hungary	3,79E-01	1,19E+01	1,77E+00
Iceland	5,34E-02	1,08E+01	1,26E+00
Ireland	3,31E-01	7,54E+00	1,59E+00
Italy	3,84E-01	8,67E+00	1,96E+00

Latvia	3,88E-01	9,54E+00	6,38E+00
Lithuania	4,10E-01	1,03E+01	3,85E+00
Luxembourg	3,65E-01	9,60E+00	1,73E+00
Malta	5,12E-01	8,90E+00	2,41E+00
Netherlands	4,23E-01	8,50E+00	1,99E+00
Norway	1,87E-02	4,14E+00	5,50E-01
Poland	9,16E-01	1,21E+01	2,99E+00
Portugal	2,69E-01	7,35E+00	1,86E+00
Romania	3,69E-01	1,04E+01	1,51E+00
Slovak Republic	3,92E-01	1,20E+01	1,59E+00
Slovenia	3,42E-01	9,42E+00	1,11E+00
Spain	2,06E-01	8,99E+00	1,57E+00
Sweden	3,02E-02	7,05E+00	8,88E-01
Switzerland	2,42E-02	6,03E+00	6,89E-01
United Kingdom	2,55E-01	9,46E+00	1,42E+00

Table 37 – Comparative LCA of End of Life processes, with net environmental savings projected for 2023 and 2030.

MidTerm Indicators	Direct Impacts			Net environmental savings 2023		Net environmental savings 2030	
	Pyrometallurgy	Hydrometallurgy	Landfill	Pyrometallurgy	Hydrometallurgy	Pyrometallurgy	Hydrometallurgy
TAP (kg SO2-Eq)	5,00E-03	7,09E-03	2,78E-05	-1,65E-01	-1,60E-01	-6,53E-02	-6,10E-02
GWP100 (kg CO2-Eq)	1,55E+00	9,46E-01	7,33E-03	-4,44E+00	-4,24E+00	-1,85E+00	-1,50E+00
FETP (kg 1,4-DCB-Eq)	7,87E-02	1,14E-01	5,30E-02	-2,93E+00	-2,92E+00	-1,46E+00	-1,42E+00
METP (kg 1,4-DCB-Eq)	1,13E-01	1,54E-01	6,54E-02	-3,89E+00	-3,89E+00	-1,91E+00	-1,87E+00
TETP (kg 1,4-DCB-Eq)	9,61E+00	9,94E+00	1,07E-01	-3,51E+02	-3,55E+02	-1,36E+02	-1,36E+02
FFP (kg oil-Eq)	3,47E-01	1,76E-01	3,43E-03	-1,12E+00	-1,22E+00	-3,86E-01	-4,60E-01
FEP (kg P-Eq)	5,78E-04	3,54E-04	7,08E-07	-3,98E-03	-4,18E-03	-1,80E-03	-1,94E-03
MEP (kg N-Eq)	3,21E-04	1,65E-04	1,26E-07	-3,91E-04	-7,01E-04	2,29E-05	-2,11E-04
HTPc (kg 1,4-DCB-Eq)	3,11E-01	2,03E-01	2,16E-02	-1,09E+01	-1,11E+01	-4,34E+00	-4,26E+00
HTPnc (kg 1,4-DCB-Eq)	2,26E+00	2,40E+00	7,11E-03	-4,76E+01	-4,87E+01	-2,12E+01	-2,13E+01
IRP (kBq Co-60-Eq)	1,42E-01	6,81E-02	1,19E-04	-5,63E-01	-6,78E-01	-1,40E-01	-2,27E-01
LOP (m2*a crop-Eq)	2,52E-02	2,18E-02	3,57E-03	-1,78E-01	-1,82E-01	-7,79E-02	-7,81E-02

SOP (kg Cu-Eq)	7,48E-02	3,13E-02	1,39E-04	-1,10E+00	-1,76E+00	-4,15E-01	-7,98E-01
ODPinf (kg CFC-11-Eq)	5,35E-07	4,31E-07	2,22E-09	-2,65E-06	-2,78E-06	-9,07E-07	-9,79E-07
PMFP (kg PM2.5-Eq)	3,30E-03	2,88E-03	1,35E-05	-4,98E-02	-4,92E-02	-1,91E-02	-1,86E-02
HOFP (kg NOx-Eq)	3,70E-03	1,94E-03	5,10E-05	-1,77E-02	-1,80E-02	-7,61E-03	-7,50E-03
EOFP (kg NOx-Eq)	3,77E-03	1,99E-03	5,32E-05	-1,83E-02	-1,86E-02	-7,82E-03	-7,71E-03
WCP (m3)	1,04E-02	1,12E-02	1,51E-05	-4,48E-01	-4,74E-01	-1,70E-01	-1,79E-01

Annex IV.
Battery Data Model XML Code

```xml
<?xml version="1.0" encoding="UTF-8"?>
<tns:BATTERY
    xmlns:tns="http://www.example.org/BATTERY"
    xmlns:tns1="http://www.example.org/Battery_Attributes"
    xmlns:tns2="http://www.example.org/Weight"
    xmlns:tns3="http://www.example.org/ManufacturingREV1"
    xmlns:tns4="http://www.example.org/Battery_Manufacturing"
    xmlns:tns5="http://www.example.org/Material"
    xmlns:tns6="http://www.example.org/EnvironmentNode"
    xmlns:tns7="http://www.example.org/Battery_Transport"
    xmlns:tns8="http://www.example.org/Battery_Use"
    xmlns:tns9="http://www.example.org/End_Of_Life"
    xmlns:tns10="http://www.example.org/PART_Node"
    xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
    xsi:schemaLocation="http://www.example.org/BATTERY BATTERY.xsd ">

  <tns:Battery_Attributes>

    <tns1:TheBatterycategory>
      <tns1:Model_Identification>EV_LFP_Pack_Gen1</tns1:Model_Identification>
      <tns1:Batch_Number>EV-001</tns1:Batch_Number>
      <tns1:Configuration>6 modules × 16 cells = 96 cells</tns1:Configuration>
      <tns1:SoC_At_Rated_Power>90%</tns1:SoC_At_Rated_Power>
      <tns1:Average_Discharge_Temperature>298.15 K (25°C)</tns1:Average_Discharge_Temperature>
      <tns1:Cycle_Life_Target>200,000 km</tns1:Cycle_Life_Target>
      <tns1:First_Life_Application>EV battery</tns1:First_Life_Application>
      <tns1:Second_Life_Application>Energy storage system (80%–60%)</tns1:Second_Life_Application>
      <tns1:Final_Recycling>Hydrometallurgical process</tns1:Final_Recycling>
    </tns1:TheBatterycategory>

    <tns1:Weight Unit_of_Measurement="kg">
      <tns2:Extension_Base>600</tns2:Extension_Base>
    </tns1:Weight>

    <tns1:Capacity>57 kWh</tns1:Capacity>
    <tns1:Energy_Density>95 Wh/kg</tns1:Energy_Density>

    <tns1:Manufacturer>ENEA (Casaccia)</tns1:Manufacturer>

    <tns1:StatusOfBattery>ORIGINAL</tns1:StatusOfBattery>

  </tns:Battery_Attributes>

  <tns:Battery_manufacturing>

    <tns3:Process>
      <tns4:ProcessAttributes>
        <tns4:ProcessID>ASSEMBLY-001</tns4:ProcessID>
        <tns4:ProcessName>Battery Pack Assembly</tns4:ProcessName>
        <tns4:ProcessTypology>Assembly</tns4:ProcessTypology>
        <tns4:ListOfAssemblyParameters>Standard EV line</tns4:ListOfAssemblyParameters>

        <tns4:LCAProcessParameters>
          <tns4:Material_ID_List>Modules;Copper;AlShell;BMS;SteelShell;Insulation;Coolant;ElectronicPart</tns4:Material_ID_List>
          <tns4:Water>
            <tns4:Value>0.0</tns4:Value>
            <tns4:Unit_of_Measurement>kg</tns4:Unit_of_Measurement>
          </tns4:Water>
          <tns4:Energy>
            <tns4:Value>4.21E-01</tns4:Value>
            <tns4:Unit_of_Measurement>kWh</tns4:Unit_of_Measurement>
          </tns4:Energy>
          <tns4:Renevable_Content>
            <tns4:Value>0</tns4:Value>
            <tns4:Percentage>0%</tns4:Percentage>
          </tns4:Renevable_Content>

          <tns4:Product_Semi_Product>Pack (600 kg)</tns4:Product_Semi_Product>
          <tns4:Emissions>None</tns4:Emissions>
        </tns4:LCAProcessParameters>

        <tns4:ManufacturerIdentification>
          <tns4:Manufacturer_Name>ENEA (Casaccia)</tns4:Manufacturer_Name>
          <tns4:Registered_Trade_Name>ENEA Lab</tns4:Registered_Trade_Name>
          <tns4:Postal_address>Rome, Italy</tns4:Postal_address>
          <tns4:Web_Address>https://www.enea.it</tns4:Web_Address>
```

```xml
    <tns4:EmailAddress>info@enea.it</tns4:EmailAddress>
  </tns4:ManufacturerIdentification>
  <tns4:Manufacturering_Place>ENEA Pilot Line</tns4:Manufacturering_Place>
  <tns4:Manufacturing_Date>2025-01-01</tns4:Manufacturing_Date>
</tns4:ProcessAttributes>

<tns4:Material>
  <tns5:MaterialAttributes>
    <tns5:Raw_Material_Name>Modules</tns5:Raw_Material_Name>
    <tns5:Raw_Material_ID>M001</tns5:Raw_Material_ID>
    <tns5:Raw_Material_Typology>New</tns5:Raw_Material_Typology>
    <tns5:Weight Unit_of_Measurement="kg">
      <tns2:Extension_Base>4.52E+02</tns2:Extension_Base>
    </tns5:Weight>
  </tns5:MaterialAttributes>
  <tns5:Environment/>
</tns4:Material>

<tns4:Material>
  <tns5:MaterialAttributes>
    <tns5:Raw_Material_Name>Copper</tns5:Raw_Material_Name>
    <tns5:Raw_Material_ID>Cu-001</tns5:Raw_Material_ID>
    <tns5:Raw_Material_Typology>New</tns5:Raw_Material_Typology>
    <tns5:Weight Unit_of_Measurement="kg">
      <tns2:Extension_Base>9.13E-02</tns2:Extension_Base>
    </tns5:Weight>
  </tns5:MaterialAttributes>
  <tns5:Environment/>
</tns4:Material>

<tns4:Material>
  <tns5:MaterialAttributes>
    <tns5:Raw_Material_Name>Shell: Aluminum</tns5:Raw_Material_Name>
    <tns5:Raw_Material_ID>Al-001</tns5:Raw_Material_ID>
    <tns5:Raw_Material_Typology>New</tns5:Raw_Material_Typology>
    <tns5:Weight Unit_of_Measurement="kg">
      <tns2:Extension_Base>2.19E+01</tns2:Extension_Base>
    </tns5:Weight>
  </tns5:MaterialAttributes>
  <tns5:Environment/>
</tns4:Material>

<tns4:Material>
  <tns5:MaterialAttributes>
    <tns5:Raw_Material_Name>BMS</tns5:Raw_Material_Name>
    <tns5:Raw_Material_ID>BMS-001</tns5:Raw_Material_ID>
    <tns5:Raw_Material_Typology>New</tns5:Raw_Material_Typology>
    <tns5:Weight Unit_of_Measurement="kg">
      <tns2:Extension_Base>2.46E+00</tns2:Extension_Base>
    </tns5:Weight>
  </tns5:MaterialAttributes>
  <tns5:Environment/>
</tns4:Material>

<tns4:Material>
  <tns5:MaterialAttributes>
    <tns5:Raw_Material_Name>Shell: Steel</tns5:Raw_Material_Name>
    <tns5:Raw_Material_ID>Steel-001</tns5:Raw_Material_ID>
    <tns5:Raw_Material_Typology>Steel, electric, low-alloyed</tns5:Raw_Material_Typology>
    <tns5:Weight Unit_of_Measurement="kg">
      <tns2:Extension_Base>1.20E+00</tns2:Extension_Base>
    </tns5:Weight>
  </tns5:MaterialAttributes>
  <tns5:Environment/>
</tns4:Material>

<tns4:Material>
  <tns5:MaterialAttributes>
    <tns5:Raw_Material_Name>Insulation</tns5:Raw_Material_Name>
    <tns5:Raw_Material_Typology>glass fibre reinforced plastic</tns5:Raw_Material_Typology>
    <tns5:Weight Unit_of_Measurement="kg">
      <tns2:Extension_Base>6.81E-01</tns2:Extension_Base>
    </tns5:Weight>
  </tns5:MaterialAttributes>
  <tns5:Environment/>
</tns4:Material>

<tns4:Material>
  <tns5:MaterialAttributes>
    <tns5:Raw_Material_Name>Coolant</tns5:Raw_Material_Name>
    <tns5:Raw_Material_Typology>ethylene glycol</tns5:Raw_Material_Typology>
    <tns5:Weight Unit_of_Measurement="kg">
      <tns2:Extension_Base>8.59E+00</tns2:Extension_Base>
    </tns5:Weight>
  </tns5:MaterialAttributes>
  <tns5:Environment/>
</tns4:Material>

<tns4:Material>
  <tns5:MaterialAttributes>
    <tns5:Raw_Material_Name>Electronic part</tns5:Raw_Material_Name>
```

```xml
        <tns5:Raw_Material_Typology>electronic component, passive</tns5:Raw_Material_Typology>
        <tns5:Weight Unit_of_Measurement="kg">
          <tns2:Extension_Base>1.71E+00</tns2:Extension_Base>
        </tns5:Weight>
      </tns5:MaterialAttributes>
      <tns5:Environment/>
    </tns4:Material>

  </tns3:Process>
</tns:Battery_manufacturing>

<tns:Battery_Use>

  <tns8:UseScenario>
    <tns8:UseScenarioAttributes>
      <tns8:Use_Scenario_Application>First Use Phase (EV)</tns8:Use_Scenario_Application>
      <tns8:Number_of_the_Use>1</tns8:Number_of_the_Use>
    </tns8:UseScenarioAttributes>
    <tns8:UseScenarioEnergy>
      <tns8:EnergyAttributes>
        <tns8:Energy_Source_Origin>electricity, low voltage</tns8:Energy_Source_Origin>
        <tns8:Energy_Source_Specification>6.85E+03 kWh</tns8:Energy_Source_Specification>
      </tns8:EnergyAttributes>
    </tns8:UseScenarioEnergy>
  </tns8:UseScenario>

  <tns8:UseScenario>
    <tns8:UseScenarioAttributes>
      <tns8:Use_Scenario_Application>Second Use Phase (ESS)</tns8:Use_Scenario_Application>
      <tns8:Number_of_the_Use>2</tns8:Number_of_the_Use>
    </tns8:UseScenarioAttributes>
    <tns8:UseScenarioEnergy>
      <tns8:EnergyAttributes>
        <tns8:Energy_Source_Origin>electricity, low voltage</tns8:Energy_Source_Origin>
        <tns8:Energy_Source_Specification>8.77E+03 kWh</tns8:Energy_Source_Specification>
      </tns8:EnergyAttributes>
    </tns8:UseScenarioEnergy>
  </tns8:UseScenario>
</tns:Battery_Use>

<tns:Battery_EOL>
  <tns9:EndOfLifeAttributes>
    <tns9:EndOfLifeScenarioParameters>Refurbishing, then final hydrometallurgical recycling</tns9:EndOfLifeScenarioParameters>
  </tns9:EndOfLifeAttributes>

  <tns9:EndOfLifeTreatment>
    <tns4:ProcessAttributes>
      <tns4:ProcessID>REFURB-001</tns4:ProcessID>
      <tns4:ProcessName>Refurbishing Phase</tns4:ProcessName>
      <tns4:ProcessTypology>Refurbishing</tns4:ProcessTypology>
      <tns4:ListOfAssemblyParameters>Remove old parts, new BMS, etc.</tns4:ListOfAssemblyParameters>

      <tns4:LCAProcessParameters>
        <tns4:Material_ID_List>Cables;SteelCasing;BMS;Nickel;Electricity</tns4:Material_ID_List>
        <tns4:Water>
          <tns4:Value>0.0</tns4:Value>
          <tns4:Unit_of_Measurement>kg</tns4:Unit_of_Measurement>
        </tns4:Water>
        <tns4:Energy>
          <tns4:Value>4.04E+01</tns4:Value>
          <tns4:Unit_of_Measurement>kWh</tns4:Unit_of_Measurement>
        </tns4:Energy>
        <tns4:Renevable_Content>
          <tns4:Value>0</tns4:Value>
          <tns4:Percentage>0%</tns4:Percentage>
        </tns4:Renevable_Content>

        <tns4:Waste>Scrap metal, plastic, cables, old BMS</tns4:Waste>
        <tns4:Product_Semi_Product>Refurbished Battery (1 eq.)</tns4:Product_Semi_Product>
        <tns4:Emissions>No direct gas emission</tns4:Emissions>
      </tns4:LCAProcessParameters>
    </tns4:ProcessAttributes>

    <tns4:Material>
      <tns5:MaterialAttributes>
        <tns5:Raw_Material_Name>Cables (Copper)</tns5:Raw_Material_Name>
        <tns5:Raw_Material_ID>Cable-001</tns5:Raw_Material_ID>
        <tns5:Raw_Material_Typology>cable, unspecified</tns5:Raw_Material_Typology>
        <tns5:Weight Unit_of_Measurement="kg">
          <tns2:Extension_Base>7.26E+00</tns2:Extension_Base>
        </tns5:Weight>
      </tns5:MaterialAttributes>
      <tns5:Environment/>
    </tns4:Material>

  </tns9:EndOfLifeTreatment>

  <tns9:EndOfLifeTreatment>
    <tns4:ProcessAttributes>
      <tns4:ProcessID>HYDRO-001</tns4:ProcessID>
      <tns4:ProcessName>Hydrometallurgy</tns4:ProcessName>
```

```xml
      <tns4:ProcessTypology>Recycling</tns4:ProcessTypology>
      <tns4:ListOfAssemblyParameters>Chemical leaching, neutralization, etc.</tns4:ListOfAssemblyParameters>

      <tns4:LCAProcessParameters>
        <tns4:Material_ID_List>HCl(30%);H2O2(7.5%);NaOH(32%);CaCl2;FreshWater;Electricity</tns4:Material_ID_List>
        <tns4:Water>
          <tns4:Value>0.0</tns4:Value>
          <tns4:Unit_of_Measurement>kg</tns4:Unit_of_Measurement>
        </tns4:Water>
        <tns4:Energy>
          <tns4:Value>2.91E+02</tns4:Value>
          <tns4:Unit_of_Measurement>kWh</tns4:Unit_of_Measurement>
        </tns4:Energy>
        <tns4:Renevable_Content>
          <tns4:Value>0</tns4:Value>
          <tns4:Percentage>0%</tns4:Percentage>
        </tns4:Renevable_Content>
        <tns4:Waste>Sludge, etc.</tns4:Waste>
        <tns4:Product_Semi_Product>Recovered Materials (1 eq.)</tns4:Product_Semi_Product>
        <tns4:Emissions>Dust=1.06E-01; HF=1.43E-03; VOC=7.92E-02; HCl mist=2.41E-03</tns4:Emissions>
      </tns4:LCAProcessParameters>
    </tns4:ProcessAttributes>
  </tns9:EndOfLifeTreatment>
</tns:Battery_EOL>

<tns:Battery_Transport>
  <tns7:TransportRoute>
    <tns7:RouteAttribute>
      <tns7:Origin>ENEA Casaccia (IT)</tns7:Origin>
      <tns7:Destination>Stabilimento FCA Melfi (IT)</tns7:Destination>
      <tns7:Life_Cycle_Phase>Manufacturing to Use</tns7:Life_Cycle_Phase>
    </tns7:RouteAttribute>
    <tns7:TransportScenario>
      <tns7:Means_Of_Transport>transport, freight, lorry, 16-32 metric ton, diesel, EURO 6</tns7:Means_Of_Transport>
      <tns7:Distance>
        <tns7:Value>400</tns7:Value>
        <tns7:Unit_of_Measurement>km</tns7:Unit_of_Measurement>
      </tns7:Distance>
    </tns7:TransportScenario>
    <tns7:Environment/>
  </tns7:TransportRoute>

  <tns7:TransportRoute>
    <tns7:RouteAttribute>
      <tns7:Origin>Stabilimento FCA Melfi (IT)</tns7:Origin>
      <tns7:Destination>ENEA Casaccia (IT)</tns7:Destination>
      <tns7:Life_Cycle_Phase>Use to Refurbishing</tns7:Life_Cycle_Phase>
    </tns7:RouteAttribute>
    <tns7:TransportScenario>
      <tns7:Means_Of_Transport>transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 6</tns7:Means_Of_Transport>
      <tns7:Distance>
        <tns7:Value>400</tns7:Value>
        <tns7:Unit_of_Measurement>km</tns7:Unit_of_Measurement>
      </tns7:Distance>
    </tns7:TransportScenario>
    <tns7:Environment/>
  </tns7:TransportRoute>

  <tns7:TransportRoute>
    <tns7:RouteAttribute>
      <tns7:Origin>ENEA Casaccia (IT)</tns7:Origin>
      <tns7:Destination>ENEA Portici (IT)</tns7:Destination>
      <tns7:Life_Cycle_Phase>Refurbishing to 2nd Use</tns7:Life_Cycle_Phase>
    </tns7:RouteAttribute>
    <tns7:TransportScenario>
      <tns7:Means_Of_Transport>transport, freight, lorry, 16-32 metric ton, diesel, EURO 6</tns7:Means_Of_Transport>
      <tns7:Distance>
        <tns7:Value>250</tns7:Value>
        <tns7:Unit_of_Measurement>km</tns7:Unit_of_Measurement>
      </tns7:Distance>
    </tns7:TransportScenario>
    <tns7:Environment/>
  </tns7:TransportRoute>

  <tns7:TransportRoute>
    <tns7:RouteAttribute>
      <tns7:Origin>ENEA Portici (IT)</tns7:Origin>
      <tns7:Destination>ENEA Casaccia (IT)</tns7:Destination>
      <tns7:Life_Cycle_Phase>2nd Use to Recycling</tns7:Life_Cycle_Phase>
    </tns7:RouteAttribute>
    <tns7:TransportScenario>
      <tns7:Means_Of_Transport>transport, freight, lorry, 16-32 metric ton, diesel, EURO 6</tns7:Means_Of_Transport>
      <tns7:Distance>
        <tns7:Value>250</tns7:Value>
        <tns7:Unit_of_Measurement>km</tns7:Unit_of_Measurement>
      </tns7:Distance>
    </tns7:TransportScenario>
    <tns7:Environment/>
  </tns7:TransportRoute>

</tns:Battery_Transport>
```

```xml
<tns10:PART>

    <tns10:Part_Attributes>

      <tns10:PartID>CATHODE-001</tns10:PartID>
      <tns10:PartName>LFP Cathode (Lithium Iron Phosphate)</tns10:PartName>
      <tns10:Weight Unit_of_Measurement="kg">
        <tns2:Extension_Base>1.41E+00</tns2:Extension_Base>
      </tns10:Weight>
      <tns10:Manufacturer>ENEA Casaccia (IT)</tns10:Manufacturer>
      <tns10:DateOfProduction>2025-02-01</tns10:DateOfProduction>
      <tns10:Composition>LFP-based, 99% purity</tns10:Composition>
      <tns10:Responsible_Sourcing>
        <tns10:Policy_Link>http://example.org/responsible_sourcing_policy</tns10:Policy_Link>
        <tns10:Year_of_Update>2025</tns10:Year_of_Update>
        <tns10:Compliance>true</tns10:Compliance>
      </tns10:Responsible_Sourcing>

    </tns10:Part_Attributes>

    <tns4:Process>
      <tns4:ProcessAttributes>
        <tns4:ProcessID>SF1-LiConcentrates</tns4:ProcessID>
        <tns4:ProcessName>Production of Lithium Concentrates</tns4:ProcessName>
        <tns4:ProcessTypology>Cathode_SemiFinished_I</tns4:ProcessTypology>
        <tns4:ListOfAssemblyParameters>Extraction + basic refining of Li ore</tns4:ListOfAssemblyParameters>

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          <tns4:Manufacturer_Name>Vulcan Energy (DE)</tns4:Manufacturer_Name>
          <tns4:Registered_Trade_Name>Vulcan Energy</tns4:Registered_Trade_Name>
          <tns4:Postal_address>Germany</tns4:Postal_address>
          <tns4:Web_Address>https://www.vulcanenergy.eu</tns4:Web_Address>
        </tns4:ManufacturerIdentification>

        <tns4:LCAProcessParameters>
          <tns4:Material_ID_List>LithiumOre,Na2CO3,NaOH,ParaffinSoap,Electricity,Diesel</tns4:Material_ID_List>
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            <tns4:Unit_of_Measurement>kg</tns4:Unit_of_Measurement>
          </tns4:Water>
          <tns4:Energy>
            <tns4:Value>0</tns4:Value>
            <tns4:Unit_of_Measurement>kWh</tns4:Unit_of_Measurement>
          </tns4:Energy>
          <tns4:Renewable_Content>
            <tns4:Value>0</tns4:Value>
            <tns4:Percentage>0%</tns4:Percentage>
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          <tns4:Product_Semi_Product>Lithium concentrates n°96, 2.71E+00 kg</tns4:Product_Semi_Product>
          <tns4:Emissions>None</tns4:Emissions>
        </tns4:LCAProcessParameters>
      </tns4:ProcessAttributes>

      <tns4:Material>
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          <tns5:Raw_Material_Name>Lithium ore</tns5:Raw_Material_Name>
          <tns5:Raw_Material_Typology>Lithium, in ground</tns5:Raw_Material_Typology>
          <tns5:Weight Unit_of_Measurement="kg">
            <tns2:Extension_Base>1.52E+01</tns2:Extension_Base>
          </tns5:Weight>
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    <tns4:Process>
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        <tns4:ProcessID>SF2-Li2CO3</tns4:ProcessID>
        <tns4:ProcessName>Production of Lithium Carbonate</tns4:ProcessName>
        <tns4:ProcessTypology>Cathode_SemiFinished_II</tns4:ProcessTypology>
        <tns4:ListOfAssemblyParameters>Puri. + reaction to get Li2CO3</tns4:ListOfAssemblyParameters>

        <tns4:ManufacturerIdentification>
          <tns4:Manufacturer_Name>Green Lithium (UK)</tns4:Manufacturer_Name>
          <tns4:Postal_address>United Kingdom</tns4:Postal_address>
          <tns4:Web_Address>https://www.greenlithium.com</tns4:Web_Address>
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        <tns4:LCAProcessParameters>
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          <tns4:Waste>Some sludge</tns4:Waste>
          <tns4:Product_Semi_Product>Li2CO3(n°96), 3.35E-01 kg</tns4:Product_Semi_Product>
          <tns4:Emissions>SO2=5.26E-04; Dust=2.65E-03; COD=1.41E-04; etc.</tns4:Emissions>
        </tns4:LCAProcessParameters>
      </tns4:ProcessAttributes>
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    <tns4:Process>
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          <tns4:Web_Address>https://www.basf.com</tns4:Web_Address>
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        <tns4:LCAProcessParameters>
          <tns4:Material_ID_List>FeSO4,H3O4P,H2O2,NaOH,Water,Electricity,NatGas</tns4:Material_ID_List>
          <tns4:Product_Semi_Product>Iron phosphate(n°96), 1.37E+00 kg</tns4:Product_Semi_Product>
          <tns4:Emissions>COD=1.56E-03; NH3=8.19E-06; etc.</tns4:Emissions>
        </tns4:LCAProcessParameters>
      </tns4:ProcessAttributes>

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    <tns4:Process>
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          <tns4:Web_Address>https://www.enea.it</tns4:Web_Address>
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        <tns4:LCAProcessParameters>
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          <tns4:Product_Semi_Product>LFP cathode material(n°96), 1.41E+00 kg</tns4:Product_Semi_Product>
          <tns4:Emissions>Dust=4.11E-04; WaterVap=4.48E+00; N2=3.06E-01; CO2=2.39E-01</tns4:Emissions>
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        <tns7:Destination>ENEA Casaccia (IT)</tns7:Destination>
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        <tns4:Registered_Trade_Name>ENEA Lab</tns4:Registered_Trade_Name>
        <tns4:Postal_address>Rome, IT</tns4:Postal_address>
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      <tns4:LCAProcessParameters>
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          NonMethaneHC=5.16E-04; Dust=3.03E-04; Benzoapyrene=1.02E-09; Soot=1.22E-04
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        <tns5:Raw_Material_Typology>heat, district or industrial</tns5:Raw_Material_Typology>
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```

```xml
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      &lt;/tns4:ManufacturerIdentification&gt;

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        &lt;/tns5:Weight&gt;
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        &lt;tns4:Emissions&gt;NMVOC=1.19E-06&lt;/tns4:Emissions&gt;
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    &lt;/tns4:ProcessAttributes&gt;

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        &lt;tns5:Raw_Material_Typology&gt;ethylene oxide&lt;/tns5:Raw_Material_Typology&gt;
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        &lt;tns5:Raw_Material_Typology&gt;carbon dioxide, in chemical industry&lt;/tns5:Raw_Material_Typology&gt;
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        &lt;/tns5:Weight&gt;
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        &lt;tns5:Raw_Material_Typology&gt;electricity, medium voltage&lt;/tns5:Raw_Material_Typology&gt;
        &lt;tns5:Weight Unit_of_Measurement="kWh"&gt;
          &lt;tns2:Extension_Base&gt;8.88E-03&lt;/tns2:Extension_Base&gt;
```

```xml
          </tns5:Weight>
        </tns5:MaterialAttributes>
      </tns4:Material>

      <tns4:Material>
        <tns5:MaterialAttributes>
          <tns5:Raw_Material_Name>Steam</tns5:Raw_Material_Name>
          <tns5:Raw_Material_Typology>steam, in chemical industry</tns5:Raw_Material_Typology>
          <tns5:Weight Unit_of_Measurement="kg">
            <tns2:Extension_Base>1.09E+00</tns2:Extension_Base>
          </tns5:Weight>
        </tns5:MaterialAttributes>
      </tns4:Material>

    </tns4:Process>
  </tns10:PART>

  <tns10:PART>
    <tns10:Part_Attributes>
      <tns10:PartID>CUFOIL-001</tns10:PartID>
      <tns10:PartName>Copper Foil (for Battery)</tns10:PartName>
      <tns10:Description>Battery-grade copper foil (n°96)</tns10:Description>

      <tns10:Weight Unit_of_Measurement="kg">
        <tns2:Extension_Base>7.14E-01</tns2:Extension_Base>
      </tns10:Weight>

      <tns10:Manufacturer>KME Group (Italy)</tns10:Manufacturer>
      <tns10:DateOfProduction>2025-05-01</tns10:DateOfProduction>
    </tns10:Part_Attributes>

    <tns4:Process>
      <tns4:ProcessAttributes>
        <tns4:ProcessID>CUFOIL-PROC-001</tns4:ProcessID>
        <tns4:ProcessName>Copper foil production</tns4:ProcessName>
        <tns4:ProcessTypology>Foil_Production</tns4:ProcessTypology>

        <tns4:ManufacturerIdentification>
          <tns4:Manufacturer_Name>KME Group</tns4:Manufacturer_Name>
          <tns4:Postal_address>Italy</tns4:Postal_address>
          <tns4:Web_Address>https://www.kme.com</tns4:Web_Address>
        </tns4:ManufacturerIdentification>

        <tns4:LCAProcessParameters>

          <tns4:Material_ID_List>Electricity,NatGas,Copper,ConcSulfuric,HCl,TartaricAcid,ActiveCarbon,CoSO4,ZnSO4,CarboxyEthylCell,Carboxy-
PropSulfonate,Water</tns4:Material_ID_List>

          <tns4:Product_Semi_Product>Copper foil (n°96), 7.14E-01 kg</tns4:Product_Semi_Product>

          <tns4:Emissions>
            SulfuricAcidMist=5.04E-01 g; Cu=2.67E-04 g; Co=3.53E-05 g
          </tns4:Emissions>
        </tns4:LCAProcessParameters>
      </tns4:ProcessAttributes>

      <tns4:Material>
        <tns5:MaterialAttributes>
          <tns5:Raw_Material_Name>Electricity</tns5:Raw_Material_Name>
          <tns5:Raw_Material_Typology>electricity, medium voltage</tns5:Raw_Material_Typology>
          <tns5:Weight Unit_of_Measurement="kWh">
            <tns2:Extension_Base>8.85E+00</tns2:Extension_Base>
          </tns5:Weight>
        </tns5:MaterialAttributes>
      </tns4:Material>

      <tns4:Material>
        <tns5:MaterialAttributes>
          <tns5:Raw_Material_Name>Natural gas</tns5:Raw_Material_Name>
          <tns5:Raw_Material_Typology>heat, district or industrial</tns5:Raw_Material_Typology>
          <tns5:Weight Unit_of_Measurement="m3">
            <tns2:Extension_Base>2.46E-04</tns2:Extension_Base>
          </tns5:Weight>
        </tns5:MaterialAttributes>
      </tns4:Material>

      <tns4:Material>
        <tns5:MaterialAttributes>
          <tns5:Raw_Material_Name>Copper</tns5:Raw_Material_Name>
          <tns5:Raw_Material_Typology>copper, cathode</tns5:Raw_Material_Typology>
          <tns5:Weight Unit_of_Measurement="kg">
            <tns2:Extension_Base>7.14E-01</tns2:Extension_Base>
          </tns5:Weight>
        </tns5:MaterialAttributes>
      </tns4:Material>

      <tns4:Material>
        <tns5:MaterialAttributes>
          <tns5:Raw_Material_Name>Water</tns5:Raw_Material_Name>
          <tns5:Raw_Material_Typology>tap water</tns5:Raw_Material_Typology>
          <tns5:Weight Unit_of_Measurement="kg">
```

```xml
          <tns2:Extension_Base>7.98E+00</tns2:Extension_Base>
        </tns5:Weight>
      </tns5:MaterialAttributes>
    </tns4:Material>

  </tns4:Process>

  <tns9:EndOfLifeTreatment>
    <tns4:ProcessAttributes>
      <tns4:ProcessID>CUFOIL-EOL-001</tns4:ProcessID>
      <tns4:ProcessName>Copper foil recycling</tns4:ProcessName>
      <tns4:ProcessTypology>Recycling</tns4:ProcessTypology>

      <tns4:ManufacturerIdentification>
        <tns4:Manufacturer_Name>KME Group Recycling</tns4:Manufacturer_Name>
        <tns4:Postal_address>Italy</tns4:Postal_address>
      </tns4:ManufacturerIdentification>

      <tns4:LCAProcessParameters>
        <tns4:Material_ID_List>CopperScrap,Electricity</tns4:Material_ID_List>
        <tns4:Product_Semi_Product>Secondary copper, 5.40E+01 kg</tns4:Product_Semi_Product>
        <tns4:Emissions>None</tns4:Emissions>
      </tns4:LCAProcessParameters>
    </tns4:ProcessAttributes>

    <tns4:Material>
      <tns5:MaterialAttributes>
        <tns5:Raw_Material_Name>Copper scrap</tns5:Raw_Material_Name>
        <tns5:Raw_Material_Typology>copper scrap, sorted, pressed</tns5:Raw_Material_Typology>
        <tns5:Weight Unit_of_Measurement="kg">
          <tns2:Extension_Base>6.00E+01</tns2:Extension_Base>
        </tns5:Weight>
      </tns5:MaterialAttributes>
    </tns4:Material>

    <tns4:Material>
      <tns5:MaterialAttributes>
        <tns5:Raw_Material_Name>Electricity</tns5:Raw_Material_Name>
        <tns5:Raw_Material_Typology>electricity, medium voltage</tns5:Raw_Material_Typology>
        <tns5:Weight Unit_of_Measurement="kWh">
          <tns2:Extension_Base>4.09E+01</tns2:Extension_Base>
        </tns5:Weight>
      </tns5:MaterialAttributes>
    </tns4:Material>

  </tns9:EndOfLifeTreatment>
</tns10:PART>

<tns10:PART>
  <tns10:Part_Attributes>
    <tns10:PartID>ALFOIL-001</tns10:PartID>
    <tns10:PartName>Aluminium Foil (for Battery)</tns10:PartName>
    <tns10:Description>Battery-grade aluminum sheet/foil</tns10:Description>

    <tns10:Weight Unit_of_Measurement="kg">
      <tns2:Extension_Base>1.02E+00</tns2:Extension_Base>
    </tns10:Weight>

    <tns10:Manufacturer>Slim Aluminium (Italy)</tns10:Manufacturer>
    <tns10:DateOfProduction>2025-06-01</tns10:DateOfProduction>
  </tns10:Part_Attributes>

  <tns4:Process>
    <tns4:ProcessAttributes>
      <tns4:ProcessID>ALFOIL-PROC-001</tns4:ProcessID>
      <tns4:ProcessName>Aluminium foil production</tns4:ProcessName>
      <tns4:ProcessTypology>Foil_Production</tns4:ProcessTypology>

      <tns4:ManufacturerIdentification>
        <tns4:Manufacturer_Name>Slim Aluminium</tns4:Manufacturer_Name>
        <tns4:Postal_address>Italy</tns4:Postal_address>
        <tns4:Web_Address>https://www.slimaluminium.com</tns4:Web_Address>
      </tns4:ManufacturerIdentification>

      <tns4:LCAProcessParameters>
        <tns4:Material_ID_List>ElectrolyticAl,Water,Diatomite,RollingOil</tns4:Material_ID_List>

        <tns4:Product_Semi_Product>Aluminium foil (n°96), 1.02E+00 kg</tns4:Product_Semi_Product>

        <tns4:Emissions>
          NMHC=2.28E+00; COD=3.80E-02; SuspSolids=7.57E-04; NH3=7.48E-04
        </tns4:Emissions>
      </tns4:LCAProcessParameters>
    </tns4:ProcessAttributes>

    <tns4:Material>
      <tns5:MaterialAttributes>
        <tns5:Raw_Material_Name>Electrolytic aluminum</tns5:Raw_Material_Name>
        <tns5:Raw_Material_Typology>Aluminium, primary, liquid, prebake</tns5:Raw_Material_Typology>
        <tns5:Weight Unit_of_Measurement="kg">
          <tns2:Extension_Base>1.02E+00</tns2:Extension_Base>
```

```
      </tns5:Weight>
    </tns5:MaterialAttributes>
  </tns4:Material>

  <tns4:Material>
    <tns5:MaterialAttributes>
      <tns5:Raw_Material_Name>Water</tns5:Raw_Material_Name>
      <tns5:Raw_Material_Typology>tap water</tns5:Raw_Material_Typology>
      <tns5:Weight Unit_of_Measurement="kg">
        <tns2:Extension_Base>2.19E+00</tns2:Extension_Base>
      </tns5:Weight>
    </tns5:MaterialAttributes>
  </tns4:Material>

  <tns4:Material>
    <tns5:MaterialAttributes>
      <tns5:Raw_Material_Name>Diatomite</tns5:Raw_Material_Name>
      <tns5:Raw_Material_Typology>silica sand</tns5:Raw_Material_Typology>
      <tns5:Weight Unit_of_Measurement="kg">
        <tns2:Extension_Base>3.16E+00</tns2:Extension_Base>
      </tns5:Weight>
    </tns5:MaterialAttributes>
  </tns4:Material>

  <tns4:Material>
    <tns5:MaterialAttributes>
      <tns5:Raw_Material_Name>Rolling Oil</tns5:Raw_Material_Name>
      <tns5:Raw_Material_Typology>lubricating oil</tns5:Raw_Material_Typology>
      <tns5:Weight Unit_of_Measurement="kg">
        <tns2:Extension_Base>1.00E+01</tns2:Extension_Base>
      </tns5:Weight>
    </tns5:MaterialAttributes>
  </tns4:Material>

</tns4:Process>

<tns9:EndOfLifeTreatment>
  <tns4:ProcessAttributes>
    <tns4:ProcessID>ALFOIL-EOL-001</tns4:ProcessID>
    <tns4:ProcessName>Aluminium foil recycling</tns4:ProcessName>
    <tns4:ProcessTypology>Recycling</tns4:ProcessTypology>

    <tns4:ManufacturerIdentification>
      <tns4:Manufacturer_Name>Slim Aluminium Recycling</tns4:Manufacturer_Name>
      <tns4:Postal_address>Italy</tns4:Postal_address>
    </tns4:ManufacturerIdentification>

    <tns4:LCAProcessParameters>
      <tns4:Material_ID_List>AluminumScrap,Water2,Inorganic,Electricity,Gas</tns4:Material_ID_List>

      <tns4:Product_Semi_Product>Secondary aluminum=1.27E+01 kg</tns4:Product_Semi_Product>
      <tns4:Emissions>
        PM=8.10E-03; Chlorides=2.41E-03; Fluorides=5.38E-04; Petroleum=2.94E-06; SS=3.20E-05; MSW=2.66E+00
      </tns4:Emissions>
    </tns4:LCAProcessParameters>
  </tns4:ProcessAttributes>

  <tns4:Material>
    <tns5:MaterialAttributes>
      <tns5:Raw_Material_Name>Aluminum scrap</tns5:Raw_Material_Name>
      <tns5:Raw_Material_Typology>aluminium scrap, post-consumer</tns5:Raw_Material_Typology>
      <tns5:Weight Unit_of_Measurement="kg">
        <tns2:Extension_Base>1.49E+01</tns2:Extension_Base>
      </tns5:Weight>
    </tns5:MaterialAttributes>
  </tns4:Material>

  <tns4:Material>
    <tns5:MaterialAttributes>
      <tns5:Raw_Material_Name>Water</tns5:Raw_Material_Name>
      <tns5:Raw_Material_Typology>tap water</tns5:Raw_Material_Typology>
      <tns5:Weight Unit_of_Measurement="kg">
        <tns2:Extension_Base>1.11E+01</tns2:Extension_Base>
      </tns5:Weight>
    </tns5:MaterialAttributes>
  </tns4:Material>

  <tns4:Material>
    <tns5:MaterialAttributes>
      <tns5:Raw_Material_Name>Inorganic chemical</tns5:Raw_Material_Name>
      <tns5:Raw_Material_Typology>chemical, inorganic</tns5:Raw_Material_Typology>
      <tns5:Weight Unit_of_Measurement="kg">
        <tns2:Extension_Base>7.59E-02</tns2:Extension_Base>
      </tns5:Weight>
    </tns5:MaterialAttributes>
  </tns4:Material>

  <tns4:Material>
    <tns5:MaterialAttributes>
      <tns5:Raw_Material_Name>Electricity</tns5:Raw_Material_Name>
      <tns5:Raw_Material_Typology>electricity, medium voltage</tns5:Raw_Material_Typology>
```

```xml
        <tns5:Weight Unit_of_Measurement="kWh">
          <tns2:Extension_Base>4.03E+00</tns2:Extension_Base>
        </tns5:Weight>
      </tns5:MaterialAttributes>
    </tns4:Material>

    <tns4:Material>
      <tns5:MaterialAttributes>
        <tns5:Raw_Material_Name>Natural gas</tns5:Raw_Material_Name>
        <tns5:Raw_Material_Typology>heat, district or industrial</tns5:Raw_Material_Typology>
        <tns5:Weight Unit_of_Measurement="m3">
          <tns2:Extension_Base>1.27E+00</tns2:Extension_Base>
        </tns5:Weight>
      </tns5:MaterialAttributes>
    </tns4:Material>

  </tns9:EndOfLifeTreatment>
</tns10:PART>

<tns10:PART>

  <tns10:Part_Attributes>
    <tns10:PartID>BMS-001</tns10:PartID>
    <tns10:PartName>Battery Management System</tns10:PartName>
    <tns10:Description>BMS (n°: 1)</tns10:Description>

    <tns10:Weight Unit_of_Measurement="kg">
      <tns2:Extension_Base>4.85E+00</tns2:Extension_Base>
    </tns10:Weight>

    <tns10:Manufacturer>STMicroelectronics (France &_Italy)</tns10:Manufacturer>
    <tns10:DateOfProduction>2025-07-01</tns10:DateOfProduction>
  </tns10:Part_Attributes>

  <tns4:Process>
    <tns4:ProcessAttributes>
      <tns4:ProcessID>BMS-PROC-001</tns4:ProcessID>
      <tns4:ProcessName>BMS Production</tns4:ProcessName>
      <tns4:ProcessTypology>Assembly_Electronic</tns4:ProcessTypology>

      <tns4:ManufacturerIdentification>
        <tns4:Manufacturer_Name>STMicroelectronics</tns4:Manufacturer_Name>
        <tns4:Postal_address>France & Italy</tns4:Postal_address>
        <tns4:Web_Address>https://www.st.com</tns4:Web_Address>
      </tns4:ManufacturerIdentification>

      <tns4:LCAProcessParameters>
        <tns4:Material_ID_List>
          PrintedWiringBoard,IntegratedCircuit,ABS,ElectronicComponent,Steel,Aluminium,
          SyntheticRubber,PET,Nylon66,Connector,Cable,Brass,CopperPrimary,PPS,Sn
        </tns4:Material_ID_List>

        <tns4:Product_Semi_Product>BMS (n°: 1), 4.85E+00 kg</tns4:Product_Semi_Product>
        <tns4:Emissions>None</tns4:Emissions>
      </tns4:LCAProcessParameters>
    </tns4:ProcessAttributes>

    <tns4:Material>
      <tns5:MaterialAttributes>
        <tns5:Raw_Material_Name>Printed wiring board</tns5:Raw_Material_Name>
        <tns5:Raw_Material_Typology>printed wiring board, Pb-free</tns5:Raw_Material_Typology>
        <tns5:Weight Unit_of_Measurement="kg">
          <tns2:Extension_Base>6.87E-01</tns2:Extension_Base>
        </tns5:Weight>
      </tns5:MaterialAttributes>
    </tns4:Material>

  </tns4:Process>

  <tns9:EndOfLifeTreatment>
    <tns4:ProcessAttributes>
      <tns4:ProcessID>BMS-EOL-001</tns4:ProcessID>
      <tns4:ProcessName>Waste BMS Recycling</tns4:ProcessName>
      <tns4:ProcessTypology>Electronics_Recycling</tns4:ProcessTypology>

      <tns4:ManufacturerIdentification>
        <tns4:Manufacturer_Name>STMicroelectronics</tns4:Manufacturer_Name>
        <tns4:Postal_address>Catania (IT)</tns4:Postal_address>
      </tns4:ManufacturerIdentification>

      <tns4:LCAProcessParameters>
        <tns4:Material_ID_List>WasteBMS</tns4:Material_ID_List>
        <tns4:Product_Semi_Product>Al, Cu, Steel, Plastic, WasteCircuitBoards</tns4:Product_Semi_Product>
        <tns4:Emissions>None</tns4:Emissions>
      </tns4:LCAProcessParameters>
    </tns4:ProcessAttributes>

    <tns4:Material>
      <tns5:MaterialAttributes>
        <tns5:Raw_Material_Name>Waste BMS</tns5:Raw_Material_Name>
        <tns5:Raw_Material_Typology>electronics scrap, Recycled Content cut-off</tns5:Raw_Material_Typology>
```

```xml
        <tns5:Weight Unit_of_Measurement="kg">
          <tns2:Extension_Base>1.80E+01</tns2:Extension_Base>
        </tns5:Weight>
      </tns5:MaterialAttributes>
    </tns4:Material>

  </tns9:EndOfLifeTreatment>

  <tns7:TransportRoute>
    <tns7:RouteAttribute>
      <tns7:Origin>ENEA Casaccia (IT)</tns7:Origin>
      <tns7:Destination>STMicroelectronics Catania (IT)</tns7:Destination>
      <tns7:Life_Cycle_Phase>Riciclo BMS Waste</tns7:Life_Cycle_Phase>
    </tns7:RouteAttribute>
    <tns7:TransportScenario>
      <tns7:Means_Of_Transport>transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 6</tns7:Means_Of_Transport>
      <tns7:Distance>
        <tns7:Value>800</tns7:Value>
        <tns7:Unit_of_Measurement>km</tns7:Unit_of_Measurement>
      </tns7:Distance>
    </tns7:TransportScenario>
    <tns7:Environment/>
  </tns7:TransportRoute>

</tns10:PART>

<tns10:PART>
  <tns10:Part_Attributes>
    <tns10:PartID>CELL-001</tns10:PartID>
    <tns10:PartName>Li-ion Cell</tns10:PartName>
    <tns10:Description>Cell (n°96)</tns10:Description>

    <tns10:Weight Unit_of_Measurement="kg">
      <tns2:Extension_Base>4.31E+00</tns2:Extension_Base>
    </tns10:Weight>

    <tns10:Manufacturer>ENEA Casaccia (Italy)</tns10:Manufacturer>
    <tns10:DateOfProduction>2025-08-01</tns10:DateOfProduction>
  </tns10:Part_Attributes>

  <tns4:Process>
    <tns4:ProcessAttributes>
      <tns4:ProcessID>CELL-PROC-001</tns4:ProcessID>
      <tns4:ProcessName>Cell Assembly</tns4:ProcessName>
      <tns4:ProcessTypology>Cell_Production</tns4:ProcessTypology>

      <tns4:ManufacturerIdentification>
        <tns4:Manufacturer_Name>ENEA</tns4:Manufacturer_Name>
        <tns4:Postal_address>Rome, Italy</tns4:Postal_address>
      </tns4:ManufacturerIdentification>

      <tns4:LCAProcessParameters>
        <tns4:Material_ID_List>
          Electricity,NaturalGas,Cathode,Anode,CopperFoil,AluminumFoil,
          EC,DMC,SeparatorPP,CarbonBlack,BinderPVDF,LiPF6,
          SepPolyethylene,SepPET
        </tns4:Material_ID_List>
        <tns4:Product_Semi_Product>Cell (n°96), 4.31E+00 kg</tns4:Product_Semi_Product>
        <tns4:Emissions>None</tns4:Emissions>
      </tns4:LCAProcessParameters>
    </tns4:ProcessAttributes>

    <tns4:Material>
      <tns5:MaterialAttributes>
        <tns5:Raw_Material_Name>Electricity</tns5:Raw_Material_Name>
        <tns5:Raw_Material_Typology>electricity, medium voltage</tns5:Raw_Material_Typology>
        <tns5:Weight Unit_of_Measurement="kWh">
          <tns2:Extension_Base>2.15E+00</tns2:Extension_Base>
        </tns5:Weight>
      </tns5:MaterialAttributes>
    </tns4:Material>

    <tns4:Material>
      <tns5:MaterialAttributes>
        <tns5:Raw_Material_Name>Natural Gas</tns5:Raw_Material_Name>
        <tns5:Raw_Material_Typology>heat, district or industrial</tns5:Raw_Material_Typology>
        <tns5:Weight Unit_of_Measurement="m3">
          <tns2:Extension_Base>7.70E-01</tns2:Extension_Base>
        </tns5:Weight>
      </tns5:MaterialAttributes>
    </tns4:Material>

    <tns4:Material>
      <tns5:MaterialAttributes>
        <tns5:Raw_Material_Name>Cathode (LFP)</tns5:Raw_Material_Name>
        <tns5:Raw_Material_Typology>New</tns5:Raw_Material_Typology>
        <tns5:Weight Unit_of_Measurement="kg">
          <tns2:Extension_Base>1.41E+00</tns2:Extension_Base>
        </tns5:Weight>
      </tns5:MaterialAttributes>
    </tns4:Material>
```

```xml
    <tns4:Material>
      <tns5:MaterialAttributes>
        <tns5:Raw_Material_Name>Anode (Graphite)</tns5:Raw_Material_Name>
        <tns5:Raw_Material_Typology>New</tns5:Raw_Material_Typology>
        <tns5:Weight Unit_of_Measurement="kg">
          <tns2:Extension_Base>7.26E-01</tns2:Extension_Base>
        </tns5:Weight>
      </tns5:MaterialAttributes>
    </tns4:Material>

    <tns4:Material>
      <tns5:MaterialAttributes>
        <tns5:Raw_Material_Name>Copper Foil</tns5:Raw_Material_Name>
        <tns5:Raw_Material_Typology>New</tns5:Raw_Material_Typology>
        <tns5:Weight Unit_of_Measurement="kg">
          <tns2:Extension_Base>5.99E-01</tns2:Extension_Base>
        </tns5:Weight>
      </tns5:MaterialAttributes>
    </tns4:Material>

    <tns4:Material>
      <tns5:MaterialAttributes>
        <tns5:Raw_Material_Name>Carbon black</tns5:Raw_Material_Name>
        <tns5:Raw_Material_Typology>carbon black</tns5:Raw_Material_Typology>
        <tns5:Weight Unit_of_Measurement="kg">
          <tns2:Extension_Base>9.49E-02</tns2:Extension_Base>
        </tns5:Weight>
      </tns5:MaterialAttributes>
    </tns4:Material>

  <tns7:TransportRoute>
    <tns7:RouteAttribute>
      <tns7:Origin>Solvay (Belgium)</tns7:Origin>
      <tns7:Destination>ENEA Casaccia (IT)</tns7:Destination>
      <tns7:Life_Cycle_Phase>Cell_DMC_Supply</tns7:Life_Cycle_Phase>
    </tns7:RouteAttribute>
    <tns7:TransportScenario>
      <tns7:Means_Of_Transport>freight, lorry, 7.5-16 metric ton, diesel, EURO 6</tns7:Means_Of_Transport>
      <tns7:Distance>
        <tns7:Value>1300</tns7:Value>
        <tns7:Unit_of_Measurement>km</tns7:Unit_of_Measurement>
      </tns7:Distance>
    </tns7:TransportScenario>
  </tns7:TransportRoute>

  <tns7:TransportRoute>
    <tns7:RouteAttribute>
      <tns7:Origin>BASF (Germany)</tns7:Origin>
      <tns7:Destination>ENEA Casaccia (IT)</tns7:Destination>
      <tns7:Life_Cycle_Phase>Cell_EC_Supply</tns7:Life_Cycle_Phase>
    </tns7:RouteAttribute>
    <tns7:TransportScenario>
      <tns7:Means_Of_Transport>freight, lorry, >32 metric ton, diesel, EURO 5</tns7:Means_Of_Transport>
      <tns7:Distance>
        <tns7:Value>1200</tns7:Value>
        <tns7:Unit_of_Measurement>km</tns7:Unit_of_Measurement>
      </tns7:Distance>
    </tns7:TransportScenario>
  </tns7:TransportRoute>

  <tns7:TransportRoute>
    <tns7:RouteAttribute>
      <tns7:Origin>Freudenberg (Germany)</tns7:Origin>
      <tns7:Destination>ENEA Casaccia (IT)</tns7:Destination>
      <tns7:Life_Cycle_Phase>Cell_PP_Separator_Supply</tns7:Life_Cycle_Phase>
    </tns7:RouteAttribute>
    <tns7:TransportScenario>
      <tns7:Means_Of_Transport>freight, lorry, 16-32 metric ton, diesel, EURO 6</tns7:Means_Of_Transport>
      <tns7:Distance>
        <tns7:Value>1100</tns7:Value>
        <tns7:Unit_of_Measurement>km</tns7:Unit_of_Measurement>
      </tns7:Distance>
    </tns7:TransportScenario>
  </tns7:TransportRoute>

</tns10:PART>

<tns10:PART>
  <tns10:Part_Attributes>
    <tns10:PartID>MODULE-001</tns10:PartID>
    <tns10:PartName>Battery Module</tns10:PartName>
    <tns10:Description>Module (n°:6)</tns10:Description>

    <tns10:Weight Unit_of_Measurement="kg">
      <tns2:Extension_Base>7.53E+01</tns2:Extension_Base>
    </tns10:Weight>

    <tns10:Manufacturer>ENEA Casaccia</tns10:Manufacturer>
    <tns10:DateOfProduction>2025-09-01</tns10:DateOfProduction>
  </tns10:Part_Attributes>
```

```xml
    <tns4:Process>
      <tns4:ProcessAttributes>
        <tns4:ProcessID>MODULE-PROC-001</tns4:ProcessID>
        <tns4:ProcessName>Module Assembly</tns4:ProcessName>
        <tns4:ProcessTypology>Module_Production</tns4:ProcessTypology>

        <tns4:ManufacturerIdentification>
          <tns4:Manufacturer_Name>ENEA</tns4:Manufacturer_Name>
          <tns4:Postal_address>Italy</tns4:Postal_address>
        </tns4:ManufacturerIdentification>

        <tns4:LCAProcessParameters>
          <tns4:Material_ID_List>Electricity,Cells,CopperFoil,AlFoil,PlasticPE,InsulationFiberglass,ElectronicPart</tns4:Material_ID_List>
          <tns4:Product_Semi_Product>Module (n°:6), 7.53E+01 kg</tns4:Product_Semi_Product>
          <tns4:Emissions>None</tns4:Emissions>
        </tns4:LCAProcessParameters>
      </tns4:ProcessAttributes>

      <tns4:Material>
        <tns5:MaterialAttributes>
          <tns5:Raw_Material_Name>Electricity</tns5:Raw_Material_Name>
          <tns5:Raw_Material_Typology>electricity, medium voltage</tns5:Raw_Material_Typology>
          <tns5:Weight Unit_of_Measurement="kWh">
            <tns2:Extension_Base>4.63E-03</tns2:Extension_Base>
          </tns5:Weight>
        </tns5:MaterialAttributes>
      </tns4:Material>

      <tns4:Material>
        <tns5:MaterialAttributes>
          <tns5:Raw_Material_Name>Cells</tns5:Raw_Material_Name>
          <tns5:Raw_Material_Typology>New</tns5:Raw_Material_Typology>
          <tns5:Weight Unit_of_Measurement="kg">
            <tns2:Extension_Base>6.90E+01</tns2:Extension_Base>
          </tns5:Weight>
        </tns5:MaterialAttributes>
      </tns4:Material>

      <tns4:Material>
        <tns5:MaterialAttributes>
          <tns5:Raw_Material_Name>Copper Foil</tns5:Raw_Material_Name>
          <tns5:Raw_Material_Typology>New</tns5:Raw_Material_Typology>
          <tns5:Weight Unit_of_Measurement="kg">
            <tns2:Extension_Base>2.41E-02</tns2:Extension_Base>
          </tns5:Weight>
        </tns5:MaterialAttributes>
      </tns4:Material>

      <tns4:Material>
        <tns5:MaterialAttributes>
          <tns5:Raw_Material_Name>Polyethylene</tns5:Raw_Material_Name>
          <tns5:Raw_Material_Typology>high density, granulate</tns5:Raw_Material_Typology>
          <tns5:Weight Unit_of_Measurement="kg">
            <tns2:Extension_Base>8.50E-03</tns2:Extension_Base>
          </tns5:Weight>
        </tns5:MaterialAttributes>
      </tns4:Material>

    </tns4:Process>
  </tns10:PART>


</tns:BATTERY>
```

Annex V.
GUIA.py Code

```
import tkinter as tk
from tkinter import filedialog, messagebox, simpledialog, ttk
import hashlib
import os
from web3 import Web3
import re
import sys

if len(sys.argv) < 2:
    print("Error: Please enter at least one account number as an argument")
    sys.exit(1)

try:
    account_numbers = [int(arg) for arg in sys.argv[1:]]
except ValueError:
    print("Error: All arguments must be valid integers")
    sys.exit(1)

node_url = "http://localhost:7545"


web3 = Web3(Web3.HTTPProvider(node_url))


if web3.is_connected():
    print("-" * 50)
    print("Connection Successful")
    print("-" * 50)
else:
    print("Connection Failed")
    exit()


accounts = web3.eth.accounts
if len(accounts) == 0:
    print("No accounts found on Ganache.")
    exit()


contract_address = Web3.to_checksum_ad-
dress('0x07ab35ae4d25879704eda2972d0b0df4b9479ef3')

if web3.is_address(contract_address) and web3.is_connected():
    print(f"The contract is accessible at the address {contract_address}")
else:
```

```
    print("Unable to access the contract. Please verify the address or node con-
nection.")

abi = '''[
    {
        "inputs": [
            {
                "internalType": "string",
                "name": "_hash",
                "type": "string"
            },
            {
                "internalType": "string",
                "name": "_hashFunction",
                "type": "string"
            }
        ],
        "name": "addPassport",
        "outputs": [
            {
                "internalType": "bytes32",
                "name": "",
                "type": "bytes32"
            }
        ],
        "stateMutability": "nonpayable",
        "type": "function"
    },
    {
        "anonymous": false,
        "inputs": [
            {
                "indexed": true,
                "internalType": "bytes32",
                "name": "passportId",
                "type": "bytes32"
            },
            {
                "indexed": true,
                "internalType": "address",
                "name": "owner",
                "type": "address"
            },
            {
                "indexed": false,
                "internalType": "string",
                "name": "passportHash",
                "type": "string"
            },
            {
                "indexed": false,
                "internalType": "string",
```

```
            "name": "hashFunction",
            "type": "string"
         }
      ],
      "name": "AddPassport",
      "type": "event"
   },
   {
      "inputs": [
         {
            "internalType": "bytes32",
            "name": "_passportId",
            "type": "bytes32"
         },
         {
            "internalType": "string",
            "name": "_newHash",
            "type": "string"
         }
      ],
      "name": "updatePassport",
      "outputs": [],
      "stateMutability": "nonpayable",
      "type": "function"
   },
   {
      "inputs": [
         {
            "internalType": "bytes32",
            "name": "",
            "type": "bytes32"
         }
      ],
      "name": "passports",
      "outputs": [
         {
            "internalType": "address",
            "name": "owner",
            "type": "address"
         },
         {
            "internalType": "address",
            "name": "updater",
            "type": "address"
         },
         {
            "internalType": "string",
            "name": "passportHash",
            "type": "string"
         },
         {
            "internalType": "string",
```

```
                "name": "hashFunction",
                "type": "string"
            }
        ],
        "stateMutability": "view",
        "type": "function"
    }
]'''

myContract = web3.eth.contract(address=contract_address, abi=abi)

def select_file():
    file_path = filedialog.askopenfilename(title="Select an XML file", file-
types=[("XML files", "*.xml")])
    return file_path

def hash_function_choice():
    def confirm():

        if hash_func_combo.get() in hash_functions:
            hash_var.set(hash_func_combo.get())
            hash_func_window.destroy()

    hash_func_window = tk.Toplevel()
    hash_func_window.title("Hash Function Selection")

    ttk.Label(hash_func_window, text="Select an hash function:").pack(pady=10)

    hash_functions = ['sha256', 'sha3_256', 'blake2s']
    hash_var = tk.StringVar()

    hash_func_combo = ttk.Combobox(hash_func_window, textvariable=hash_var, val-
ues=hash_functions)
    hash_func_combo.pack(pady=5)
    hash_func_combo.set("sha256")

    confirm_button = ttk.Button(hash_func_window, text="Confirm", command=con-
firm)
    confirm_button.pack(pady=20)

    hash_func_window.wait_window()

    return hash_var.get()

def get_passport_id():
    passport_id = simpledialog.askstring("ID Passport", "Enter the passport ID to
update (in hex format):")
    if passport_id:
        return passport_id.strip('0x')
    else:
        messagebox.showerror("Error", "Invalid or empty Passport ID.")
        return None
```

```python
accountNumber = int(sys.argv[1])
default_account = web3.eth.accounts[accountNumber]


def upload_passport():

    selected_hash_function = hash_function_choice()

    if not selected_hash_function:
        return

    file_path = select_file()
    if not file_path or not os.path.isfile(file_path):
        messagebox.showerror("Error", "File not found.")
        return

    with open(file_path, 'rb') as file:
        file_content = file.read()

    hash_object = hashlib.new(selected_hash_function)
    hash_object.update(file_content)

    hash_val = hash_object.hexdigest()

    try:
        tx_hash = myContract.functions.addPassport(hash_val, selected_hash_func-
tion).transact({'from': default_account})  #, 'nonce': nonce
        receipt = web3.eth.wait_for_transaction_receipt(tx_hash)
        if receipt.status == 1:

            passport_events = myContract.events.AddPassport().process_receipt(re-
ceipt)
            for event in passport_events:
                passport_id_bytes = event['args']['passportId']
                passport_id_hex = passport_id_bytes.hex()

            success_message = f"Transaction successful!\n\nID Passport in hex:
{'0x' + passport_id_hex}"
            messagebox.showinfo("Success", success_message)
            print(f"Passport ID in hex: {'0x' + passport_id_hex}")
        else:
            messagebox.showerror("Error", f"Transaction failed with status: {re-
ceipt.status}")
    except Exception as e:
        messagebox.showerror("Error", str(e))

def update_passport():

    passport_id_hex = re.sub('^0x', '', get_passport_id())
    if not passport_id_hex:
        messagebox.showerror("Error", "Passport ID not entered.")
```

```
        return

    try:
        passport_id_bytes = bytes.fromhex(passport_id_hex)
    except ValueError as v:
        messagebox.showerror("Error", "Invalid Passport ID. Make sure it is a
valid hexadecimal value.")
        print(v)
        return

    try:
        passport_data = myContract.functions.passports(passport_id_bytes).call()
        if not passport_data[0]:

            messagebox.showerror("Error", "Passport ID does not exist in the con-
tract.")
            return

        hash_function = passport_data[3]
        if hash_function not in hashlib.algorithms_available:
            messagebox.showerror("Error", "Incorrect passport ID.")
            return
    except Exception as e:
        messagebox.showerror("Error", "Incorrect passport ID.")
        return

    hash_function = passport_data[3]

    file_path = select_file()
    if not file_path or not os.path.isfile(file_path):
        messagebox.showerror("Error", "File not found.")
        return

    with open(file_path, 'rb') as file:
        file_content = file.read()

    hash_object = hashlib.new(hash_function)
    hash_object.update(file_content)
    new_hash = hash_object.hexdigest()

    try:
        tx_hash = myContract.functions.updatePassport(passport_id_bytes,
new_hash).transact({'from': default_account})
        receipt = web3.eth.wait_for_transaction_receipt(tx_hash)

        if receipt.status == 1:

            updated_passport_data = myContract.functions.passports(pass-
port_id_bytes).call()
            passport_details = f"ID Passport: {passport_id_hex}\n\nOwner: {up-
dated_passport_data[0]}\n\nUpdater: {updated_passport_data[1]}\n\nPassport Hash:
{updated_passport_data[2]}\n\nHash Function: {updated_passport_data[3]}"
```

```
            messagebox.showinfo("Success",
                                f"Passport successfully updated!\n\n\nPassport
Details:\n\n{passport_details}")
        else:
            messagebox.showerror("Error", f"Transaction failed with status: {re-
ceipt.status}")
    except Exception as e:
        messagebox.showerror("Error", str(e))

def main_window(account_number):
    window = tk.Tk()
    window.title("Passport Management")

    title_font = ('Helvetica', 16, 'bold')
    title_frame = tk.Frame(window, bg='black', bd=2, relief=tk.RAISED)
    title_frame.pack(fill=tk.X, padx=5, pady=5)
    title_label = tk.Label(title_frame, text="Passport Management App",
bg='black', fg='white', font=title_font)
    title_label.pack(padx=10, pady=10)
    bold_large_font = ('Helvetica', 12, 'bold')
    account_label = tk.Label(window, text=f"Account: {web3.eth.accounts[ac-
count_number]}",
                             font=bold_large_font, background='black')
    account_label.pack(pady=10)

    tk.Button(window, text="Generate a Passport", command=upload_passport,
width=25, height=2, font=("Helvetica", 16, "bold")).pack(pady=10)
    tk.Button(window, text="Update a Passport", command=update_passport,
width=25, height=2, font=("Helvetica", 16, "bold")).pack(pady=10)
    tk.Button(window, text="Exit", command=window.destroy, width=25, height=2,
font=("Helvetica", 16, "bold")).pack(pady=10)

    window.mainloop()

if __name__ == "__main__":

    accountNumber = int(sys.argv[1])
    main_window(accountNumber)
```

Annex VI.
PWF.py Code

```
from flask import Flask, request, redirect, url_for, render_template, session,
send_file, jsonify, flash
from flask_sqlalchemy import SQLAlchemy
from flask_migrate import Migrate
from web3 import Web3
from werkzeug.utils import secure_filename
import os
import json
import hashlib
from functools import wraps
from flask import jsonify
import re
import xml.etree.ElementTree as ET
import datetime
from flask import session
from uuid import uuid4

app = Flask(__name__, template_folder="templates")
app.config['SECRET_KEY'] = 'chiave_segreta'
app.config['SQLALCHEMY_DATABASE_URI'] = 'sqlite:///site.db'
app.config['UPLOAD_FOLDER'] = 'uploads'
db = SQLAlchemy(app)
migrate = Migrate(app, db)

w3 = Web3(Web3.HTTPProvider("http://127.0.0.1:7545"))
if not w3.is_connected():
    raise Exception("Cannot connect to Ganache. Check if Ganache is running.")

contract_abi = json.loads('''[
    {
       "inputs": [
          {
             "internalType": "string",
             "name": "_hash",
             "type": "string"
          },
          {
             "internalType": "string",
             "name": "_hashFunction",
             "type": "string"
          }
       ],
       "name": "addPassport",
       "outputs": [
          {
```

```
        "internalType": "bytes32",
        "name": "",
        "type": "bytes32"
      }
    ],
    "stateMutability": "nonpayable",
    "type": "function"
  },
  {
    "anonymous": false,
    "inputs": [
      {
        "indexed": true,
        "internalType": "bytes32",
        "name": "passportId",
        "type": "bytes32"
      },
      {
        "indexed": true,
        "internalType": "address",
        "name": "owner",
        "type": "address"
      },
      {
        "indexed": false,
        "internalType": "string",
        "name": "passportHash",
        "type": "string"
      },
      {
        "indexed": false,
        "internalType": "string",
        "name": "hashFunction",
        "type": "string"
      }
    ],
    "name": "AddPassport",
    "type": "event"
  },
  {
    "inputs": [
      {
        "internalType": "bytes32",
        "name": "_passportId",
        "type": "bytes32"
      },
      {
        "internalType": "string",
        "name": "_newHash",
        "type": "string"
      }
    ],
```

```
        "name": "updatePassport",
        "outputs": [],
        "stateMutability": "nonpayable",
        "type": "function"
    },
    {
        "inputs": [
            {
                "internalType": "bytes32",
                "name": "",
                "type": "bytes32"
            }
        ],
        "name": "passports",
        "outputs": [
            {
                "internalType": "address",
                "name": "owner",
                "type": "address"
            },
            {
                "internalType": "address",
                "name": "updater",
                "type": "address"
            },
            {
                "internalType": "string",
                "name": "passportHash",
                "type": "string"
            },
            {
                "internalType": "string",
                "name": "hashFunction",
                "type": "string"
            }
        ],
        "stateMutability": "view",
        "type": "function"
    }
]''')

contract_address = Web3.to_checksum_ad-
dress('0x07ab35ae4d25879704eda2972d0b0df4b9479ef3')
contract = w3.eth.contract(address=contract_address, abi=contract_abi)

class User(db.Model):
    id = db.Column(db.Integer, primary_key=True)
    eth_address = db.Column(db.String(42), unique=True, nullable=False)

class Document(db.Model):
    id = db.Column(db.Integer, primary_key=True)
    passport_id = db.Column(db.String(100), nullable=False)
```

```python
    file_path = db.Column(db.String(300), nullable=False)
    user_id = db.Column(db.Integer, db.ForeignKey('user.id'), nullable=False)

def login_required(f):
    @wraps(f)
    def decorated_function(*args, **kwargs):
        if 'user_id' not in session:
            return redirect(url_for('index'))
        return f(*args, **kwargs)
    return decorated_function

def get_account_index(address):
    accounts = w3.eth.accounts
    if address in accounts:
        return accounts.index(address)
    return None  # Se l'indirizzo non è trovato, restituisci None

def get_user_role_by_index(address):
    index = get_account_index(address)
    roles = {
        0: 'ENEA',
        1: 'BASF',
        2: 'Green Lithium',
        3: 'Freudenberg',
        4: 'KME Group',
        5: 'Slim Aluminium',
        6: 'STMicroelectronics',
        7: 'Sa.Ma GreenRecycle',
        8: 'Acciaierie Venete',
        9: 'Regulatory Entity',
    }
    return roles.get(index, 'Unknown')

@app.route('/')
def index():
    return render_template('login.html')

@app.route('/login', methods=['POST'])
def login():
    address = request.form['address']
    if w3.is_address(address) and address in w3.eth.accounts:
        user = User.query.filter_by(eth_address=address).first()
        if not user:
            user = User(eth_address=address)
            db.session.add(user)
            db.session.commit()

        user_role = get_user_role_by_index(address)
        session['user_role'] = user_role
        session['user_id'] = user.id
        return redirect(url_for('dashboard'))
    return render_template('login.html', error="Invalid account")
```

```python
@app.route('/dashboard')
@login_required
def dashboard():
    user = db.session.get(User, session['user_id'])
    if not user:
        return redirect(url_for('logout'))
    return render_template('dashboard.html', user=user)

@app.route('/download_template')
def download_template():
    template_path = r'static/template.xml'
    return send_file(template_path, as_attachment=True)

@app.route('/generate_passport')
@login_required
def generate_passport():
    return render_template('generate_passport.html')

def append_log(file_path, log_data):
    with open(file_path, 'a') as log_file:
        log_file.write(log_data + '\n')

@app.route('/upload_passport', methods=['POST'])
@login_required
def upload_passport():
    passport_id = request.form.get('passport_id')
    file = request.files.get('file')

    user = User.query.filter_by(id=session['user_id']).first()
    user_eth_address = user.eth_address if user else None

    print("Passport ID:", passport_id)

    if not passport_id or not file:
        flash("Passport ID or file missing", "error")
        return redirect(url_for('generate_passport'))

    filename = secure_filename(f"{passport_id}.xml")
    filepath = os.path.join(app.config['UPLOAD_FOLDER'], filename)
    file.save(filepath)

    print("File saved at:", filepath)

    if not os.path.isfile(filepath):
        flash("XML file not found.", "error")
        return redirect(url_for('generate_passport'))

    with open(filepath, 'rb') as f:
        xml_content = f.read()

    hash_function = contract.functions.passports(passport_id).call()[3]
```

```
    xml_hash = calculate_hash(xml_content, hash_function)

    try:
        passport_data = contract.functions.passports(passport_id).call()
        contract_hash = passport_data[2] if passport_data else None

        print("XML Hash:", xml_hash)
        print("Contract Hash:", contract_hash)
        print("HASH FUNCTION:", hash_function)

        if xml_hash != contract_hash:
            flash("Hash mismatch. Verification failed.", "error")
            print(f"xml_hash:{xml_hash}, contract_hash: {contract_hash}")
            return redirect(url_for('generate_passport'))


        with open(filepath, 'wb') as f:
            f.write(xml_content)
        flash("File uploaded successfully", "success")

    except Exception as e:
        flash(f"Error: {str(e)}", "error")
        print("An error occurred:", str(e))

    log_data = f"Account: {user_eth_address}, Passport ID: {passport_id}, Hash:
{xml_hash}, Hash Function: {hash_function}, Date: {datetime.datetime.now()}"
    log_file_path = os.path.join(app.config['UPLOAD_FOLDER'], f"{pass-
port_id}_log.txt")
    append_log(log_file_path, log_data)

    return redirect(url_for('dashboard'))

def calculate_hash(content, hash_function):

    if hash_function == "sha256":
        return hashlib.sha256(content).hexdigest()

    elif hash_function == "sha3_256":
        return hashlib.sha3_256(content).hexdigest()

    elif hash_function == "blake2s":
        return hashlib.blake2s(content).hexdigest()

    else:
        raise ValueError(f"Unsupported hash function: {hash_function}")

@app.route('/update_passport', methods=['GET', 'POST'])
@login_required
def update_passport():
    if request.method == 'GET':
        return render_template('update_passport.html')
```

```
    user = User.query.filter_by(id=session['user_id']).first()
    user_eth_address = user.eth_address if user else None

    passport_id = request.form['passport_id']
    file = request.files.get('file')

    if not passport_id and not file:
        flash("Passport ID or file missing", "error")
        return redirect(url_for('update_passport'))

    session['passport_id'] = passport_id

    if passport_id and not file:

        try:
            passport_data = contract.functions.passports(passport_id).call()
            if not passport_data[0]:
                flash("Passport ID not found in the smart contract", "error")
                return redirect(url_for('update_passport'))
        except Exception as e:
            flash(f"Error: {str(e)}", "error")
            return redirect(url_for('update_passport'))

        file_path = os.path.join(app.config['UPLOAD_FOLDER'], f"{pass-
port_id}.xml")
        if not os.path.isfile(file_path):
            flash("XML file not found.", "error")
            return redirect(url_for('update_passport'))

        return render_template('update_passport.html', passport_id=passport_id,
download_url=url_for('download_file', passport_id=passport_id))

    filename = secure_filename(f"{passport_id}.xml")
    filepath = os.path.join(app.config['UPLOAD_FOLDER'], filename)
    file.save(filepath)

    print("File saved at:", filepath)

    if not os.path.isfile(filepath):
        flash("XML file not found.", "error")
        return redirect(url_for('generate_passport'))

    try:
        with open(filepath, 'rb') as f:
            xml_content = f.read()

        hash_function = contract.functions.passports(passport_id).call()[3]
        xml_hash = calculate_hash(xml_content, hash_function)
        print("XML Content:", xml_content)
        passport_data = contract.functions.passports(passport_id).call()
        contract_hash = passport_data[2] if passport_data else None
```

```
        print("XML Hash:", xml_hash)
        print("Contract Hash:", contract_hash)
        print("HASH FUNCTION:", hash_function)

        if xml_hash != contract_hash:
            flash("Hash mismatch. Verification failed.", "error")
            print(f"xml_hash:{xml_hash}, contract_hash: {contract_hash}")
            return redirect(url_for('update_passport'))

        flash("Passport successfully updated!", "success")
        print(f"xml_hash:{xml_hash}, contract_hash: {contract_hash}")

    except Exception as e:
        print("An error occurred:", str(e))
        flash(f"Error: {str(e)}", "error")

    log_data = f"Account: {user_eth_address}, Passport ID: {passport_id}, Hash:
{xml_hash}, Hash Function: {hash_function}, Date: {datetime.datetime.now()}"
    log_file_path = os.path.join(app.config['UPLOAD_FOLDER'], f"{pass-
port_id}_log.txt")
    append_log(log_file_path, log_data)

    return redirect(url_for('dashboard'))

@app.route('/download_file/<passport_id>')
@login_required
def download_file(passport_id):
    file_path = os.path.join(app.config['UPLOAD_FOLDER'], f"{passport_id}.xml")
    if os.path.isfile(file_path):
        return send_file(file_path, as_attachment=True)
    flash("XML file not found.", "error")
    return redirect(url_for('update_passport'))

@app.route('/verify_passport_id', methods=['POST'])
@login_required
def verify_passport_id():
    data = request.get_json()
    passport_id = data.get('passport_id')

    if not re.match(r'^[0-9a-fA-F]+$', passport_id):
        return jsonify({'error': 'Invalid passport ID format'}), 400

    try:
        passport_data = contract.functions.passports(passport_id).call()
        if passport_data[0] == w3.to_checksum_ad-
dress('0x0000000000000000000000000000000000000000'):
            return jsonify({'error': 'Passport ID not found'}), 404
    except Exception as e:
        return jsonify({'error': str(e)}), 500

    file_path = os.path.join(app.config['UPLOAD_FOLDER'], f"{passport_id}.xml")
    if not os.path.isfile(file_path):
```

```
        return jsonify({'error': 'XML file not found'}), 404

    return jsonify({'message': 'File ready for download', 'download_url':
url_for('verify_passport_id', passport_id=passport_id)})

@app.route('/view_passport', methods=['GET', 'POST'])
@login_required
def view_passport():
    if request.method == 'POST':
        passport_id = request.form['passport_id']
        try:
            passport_data = contract.functions.passports(passport_id).call()
            if passport_data[0] == w3.to_checksum_ad-
dress('0x0000000000000000000000000000000000000000'):
                flash('Passport not found in the contract.', 'error')
                return redirect(url_for('view_passport'))

            file_path = os.path.join(app.config['UPLOAD_FOLDER'], f"{pass-
port_id}.xml")
            if not os.path.isfile(file_path):
                flash('XML file not found.', 'error')
                return redirect(url_for('view_passport'))

            xml_data = read_xml_data(file_path)
            return jsonify(xml_data)
        except Exception as e:
            flash(str(e), 'error')
            return redirect(url_for('view_passport'))
    return render_template('view_passport.html')


def read_xml_data(file_path):
    try:
        tree = ET.parse(file_path)
        root = tree.getroot()
        xml_data = element_to_dict(root)
        return xml_data
    except Exception as e:
        print("Errore durante la lettura del file XML:", e)
        return None

def element_to_dict(element):

    node = {}

    tag_name = element.tag.split('}')[-1]
    text_content = (element.text or '').strip()
    node_text = f"{tag_name}: {text_content if text_content else '-'}"

    if element.attrib:
        clean_attributes = {k.split('}')[-1]: v for k, v in element.at-
trib.items()}
```

```
        attr_text = ', '.join([f'{k}: {v}' for k, v in clean_attributes.items()])
        node_text += f" ({attr_text})"

    node['text'] = node_text

    child_nodes = [element_to_dict(child) for child in element]
    if child_nodes:
        node['children'] = child_nodes

    return node

@app.route('/logout')
def logout():
    session.pop('user_id', None)
    return redirect(url_for('index'))

if __name__ == '__main__':
    with app.app_context():
        db.create_all()
    app.run(debug=True)
```

Annex VII.
Front-End Files Code

style.css

```
body {
    font-family: 'Roboto', sans-serif;
    background-color: #f5f5f5;
}

.container {
    margin-top: 2em;
}

h1 {
    color: #333;
}

.btn {
    border-radius: 5px;
    transition: background-color 0.3s;
}

.btn:hover {
    background-color: #007bff;
}

.form-control, .btn {
    margin-bottom: 1em;
}

.form-container {
    background-color: #fff;
    padding: 2em;
    border: 1px solid #ccc;
    border-radius: 8px;
    box-shadow: 0 2px 4px rgba(0, 0, 0, 0.1);
}

.error {
    color: red;
}

.alert {
    border-radius: 5px;
    padding: 1em;
}
```

login.html

```
<!DOCTYPE html>
<html lang="en">
<head>
    <meta charset="UTF-8">
    <meta name="viewport" content="width=device_width, initial_scale=1.0">
    <link rel="stylesheet" href="https://cdn.jsdelivr.net/npm/boot-
strap@5.3.0/dist/css/bootstrap.min.css">
    <link rel="stylesheet" href="{{ url_for('static', filename='css/style.css')
}}">
    <title>Login</title>
</head>
<body>
    <div class="container">
        <div class="form-container">
            <h1>Login with Your Ethereum Address</h1>

            <form action="{{ url_for('login') }}" method="post">
                <input type="text" class="form-control" name="address" place-
holder="Enter Ethereum Address" required>
                <button type="submit" class="btn btn-primary">Login</button>
            </form>

            {% if error %}
            <p style="color: red;">{{ error }}</p>
            {% endif %}
        </div>
    </div>
</body>
</html>
```

dashboard.html

```
<!DOCTYPE html>
<html lang="en">
<head>
    <meta charset="UTF-8">
    <meta name="viewport" content="width=device_width, initial_scale=1.0">
    <link rel="stylesheet" href="https://cdn.jsdelivr.net/npm/boot-
strap@5.3.0/dist/css/bootstrap.min.css">
    <link rel="stylesheet" href="{{ url_for('static', filename='css/style.css')
}}">
    <style>
        .btn-full-width {
            width: 100%;
        }
    </style>
    <title>Dashboard</title>
</head>
```

```
<body>
    <div class="container">

        {% with messages = get_flashed_messages(with_categories=True) %}
            {% if messages %}
                {% for category, message in messages %}
                    <div class="alert alert-{{ category }}">{{ message }}</div>
                {% endfor %}
            {% endif %}
        {% endwith %}

        <div class="form-container">
            <h1>Welcome to Your Dashboard, {{ session['user_role'] }}</h1>

            {% if session['user_role'] in ['ENEA', 'Regulatory Entity'] %}
                <div><a href="{{ url_for('generate_passport') }}" class="btn btn-
primary mb-2 btn-full-width">Generate a Passport</a></div>
            {% endif %}

            {% if session['user_role'] in ['ENEA', 'BASF', 'Green Lithium',
'Freudenberg', 'KMEGroup', 'SlimAluminium', 'STMicroelectronics', 'SaMaGreenRecy-
cle', 'AcciaierieVenete', 'RegulatoryEntity'] %}
                <div><a href="{{ url_for('update_passport') }}" class="btn btn-
primary mb-2 btn-full-width">Update a Passport</a></div>
            {% endif %}

            <div><a href="{{ url_for('view_passport') }}" class="btn btn-primary
mb-2 btn-full-width">Visualize a Passport</a></div>
            <div><a href="{{ url_for('logout') }}" class="btn btn-danger btn-
full-width">Logout</a></div>
        </div>
    </div>

    <script src="https://cdn.jsdelivr.net/npm/bootstrap@5.3.0/dist/js/boot-
strap.bundle.min.js"></script>
</body>
</html>
```

generate_passport.html

```
<!DOCTYPE html>
<html lang="en">
<head>
    <meta charset="UTF-8">
    <meta name="viewport" content="width=device_width, initial_scale=1.0">
    <link rel="stylesheet" href="https://cdn.jsdelivr.net/npm/boot-
strap@5.3.0/dist/css/bootstrap.min.css">
    <link rel="stylesheet" href="{{ url_for('static', filename='css/style.css')
}}">
    <title>Generate a Passport</title>
</head>
```

```
<body>
    <div class="container">
        <div class="form-container">
            <h1>Generate a Passport</h1>
            <p><a href="{{ url_for('download_template') }}">Download Passport
Generation Toolkit</a></p>

            <form id="upload-form" action="{{ url_for('upload_passport') }}"
method="post" enctype="multipart/form-data">
                <input type="text" id="passport_id" name="passport_id"
class="form-control" placeholder="Passport ID" required>
                <input type="file" id="file" name="file" required class="form-
control">
                <button type="submit" class="btn btn-primary">Upload</button>
            </form>

            {% with messages = get_flashed_messages(with_categories=True) %}
                {% if messages %}
                    {% for category, message in messages %}
                        <p style="color: {% if category == 'error' %}red{% else
%}green{% endif %};">{{ message }}</p>
                    {% endfor %}
                {% endif %}
            {% endwith %}
        </div>
    </div>

    <script src="https://cdn.jsdelivr.net/npm/bootstrap@5.3.0/dist/js/boot-
strap.bundle.min.js"></script>
</body>
</html>
```

update_passport.html

```
<!DOCTYPE html>
<html lang="en">
<head>
    <meta charset="UTF-8">
    <meta name="viewport" content="width=device-width, initial-scale=1.0">
    <title>Update a Passport</title>
    <link rel="stylesheet" href="https://cdn.jsdelivr.net/npm/boot-
strap@5.3.0/dist/css/bootstrap.min.css">
    <link rel="stylesheet" href="{{ url_for('static', filename='css/style.css')
}}">
</head>
<body>
    <div class="container">
        <div class="form-container">
            <h1>Update a Passport</h1>

            <form id="update_form" action="/update_passport" method="post"
```

```
enctype="multipart/form-data">
                <div class="d-flex align-items-center">
                    <label for="passport_id">Enter ID:</label>
                    <input type="text" id="passport_id" name="passport_id"
class="form-control" value="{{ passport_id }}" required>
                    <button type="submit" class="btn btn-primary ml-2">Ver-
ify</button>
                </div>

                {% if download_url %}
                    <a id="download_link" href="{{ download_url }}">Download
Passport Updating Toolkit</a>
                    <label for="file">Upload XML File:</label>
                    <input type="file" id="file" name="file" class="form-control"
required>
                    <button type="submit" class="btn btn-primary">Update</button>
                {% endif %}
            </form>

            {% with messages = get_flashed_messages(with_categories=True) %}
                {% if messages %}
                    {% for category, message in messages %}
                        <p style="color: {% if category == 'error' %}red{% else
%}green{% endif %};">{{ message }}</p>
                    {% endfor %}
                {% endif %}
            {% endwith %}
        </div>
    </div>

    <script src="https://cdn.jsdelivr.net/npm/bootstrap@5.3.0/dist/js/boot-
strap.bundle.min.js"></script>
</body>
</html>
```

upload_passport.html

```
<!DOCTYPE html>
<html lang="en">
<head>
    <meta charset="UTF-8">
    <meta name="viewport" content="width=device-width, initial-scale=1.0">
    <title>Upload Passport</title>
    <script src="https://cdnjs.cloudflare.com/ajax/libs/crypto-js/4.1.1/crypto-
js.min.js"></script>
    <script>
        function showUploadForm() {
            var uploadForm = document.getElementById("upload-form-container");
            uploadForm.style.display = "block";
        }
```

```
        function validateForm() {
            var passport_id = document.getElementById("passport_id").value;
            var fileInput = document.getElementById("file");
            var file = fileInput.files[0];

            if (!validateFile(file)) {
                document.getElementById("verification-result").innerHTML = '<p
style="color: red;">Invalid file type. Please upload an XML file.</p>';
                return false;
            }

            var reader = new FileReader();
            reader.onload = function(event) {
                var xml_content = event.target.result;
                var xml_hash = generateHash(xml_content);
                document.getElementById("hash").innerHTML = "Hash calcolato: " +
xml_hash;
                document.getElementById('upload-form').submit();
            };
            reader.readAsText(file);
            return false;
        }

        function validateFile(file) {
            const allowedExtensions = /(\.xml)$/i;
            if (!allowedExtensions.exec(file.name)) {
                return false;
            }
            return true;
        }

        function generateHash(content) {
            return CryptoJS.SHA256(content).toString();
        }
    </script>
</head>
<body>
    <div class="upload-container">
        <h1>Upload Passport</h1>
        <p><a href="{{ url_for('download_template') }}">Download Template</a></p>
        <a href="#" onclick="showUploadForm()">UPLOAD PASSPORT</a>
        <div id="upload-form-container" style="display: none;">
            <form id="upload-form" action="/upload_passport" method="post"
enctype="multipart/form-data" onsubmit="return validateForm()">
                <input type="text" id="passport_id" name="passport_id" place-
holder="Passport ID" required><br><br>
                <input type="file" id="file" name="file" required><br><br>
                <button type="submit">Verify and Upload</button>
            </form>
            <div id="hash"></div>
            <div id="verification-result"></div>
            <div id="document-upload-result"></div>
```

```
        </div>

        <button id="logout-button" style="display: none;" onclick="window.loca-
tion.href='/logout'">Logout</button>
    </div>
</body>
</html>
```

view_passport.html

```
<!DOCTYPE html>
<html lang="en">
<head>
    <meta charset="UTF-8">
    <meta name="viewport" content="width=device_width, initial_scale=1.0">
    <link rel="stylesheet" href="https://cdn.jsdelivr.net/npm/boot-
strap@5.3.0/dist/css/bootstrap.min.css">
    <link rel="stylesheet" href="{{ url_for('static', filename='css/style.css')
}}">
    <title>View Passport</title>
</head>
<body>
    <div class="container">
        <div class="form-container">
            <h1>View your passport</h1>
            <form action="{{ url_for('view_passport') }}" method="post">
                <input type="text" class="form-control" name="passport_id" place-
holder="Enter ID" required>
                <button type="submit" class="btn btn-primary">View Passport</but-
ton>
            </form>

            {% with messages = get_flashed_messages(with_categories=true) %}
                {% if messages %}
                    {% for category, message in messages %}
                        <p class="{% if category == 'error' %}error{% endif
%}">{{ message }}</p>
                    {% endfor %}
                {% endif %}
            {% endwith %}
        </div>
    </div>

    <script src="https://cdn.jsdelivr.net/npm/bootstrap@5.3.0/dist/js/boot-
strap.bundle.min.js"></script>
</body>
</html>
```

Annex VIII.
SCS Code

```
// SPDX-License-Identifier: UNLICENSED
pragma solidity >=0.4.16 <0.9.0;

contract DigitalProductPassport {
    struct PassportData {
        address owner;
        address updater;
        string passportHash;
        string hashFunction;
    }

    event AddPassport(
        bytes32 indexed passportId,
        address indexed owner,
        string passportHash,
        string hashFunction
    );

    mapping(bytes32 => PassportData) public passports;

    function addPassport(string memory _hash, string memory _hashFunction) public
returns (bytes32) {
        require(bytes(_hashFunction).length>0, "Hash function is required");
        bytes32 passportId = keccak256(abi.encodePacked(block.timestamp, _hash,
block.number));
        require(passports[passportId].owner == address(0), "Passport ID already
exists");
        passports[passportId] = PassportData({
            owner: msg.sender,
            updater: msg.sender,
            passportHash: _hash,
            hashFunction: _hashFunction
        });
```

```
        emit AddPassport(passportId, msg.sender, _hash, _hashFunction);
        return passportId;
    }
    function updatePassport(bytes32 _passportId, string memory _newHash) public {
        require(passports[_passportId].owner != address(0), "Passport ID does not
exist");
        passports[_passportId].updater = msg.sender;
        passports[_passportId].passportHash = _newHash;
    }

}
```

Annex IX.
LCI's integration from DPP

Table 38 - Other manufacturing components LCI

Component	Units	DPP Value	LCI Value	Reference Dataset	DPP Position
Input					
Lithium ore	kg	1,52E+01	5,60E+00	Lithium, natural resource, in ground	BATTERY / CATHODE / MATERIAL / SEMI-FIN-ISHED (I) /
Sodium carbonate	kg	1,95E-02	7,20E-03	soda ash, light	
NaOH	kg	1,46E-02	5,40E-03	sodium hydroxide, without water, in 50% solution state	
Oxidized paraffin soap	kg	3,57E-02	1,32E-02	paraffin	
Electricity	kWh	1,12E-01	4,12E-02	electricity, medium voltage	
Diesel	kg	8,12E-04	3,00E-04	diesel	
Output					
Lithium concentrates (n°96)	kg	2,71E+00	1,00E+00		
Input					
Lithium concentrates	kg	2,71E+00	8,08E+00		BATTERY / CATHODE / MATERIAL / SEMI-FIN-ISHED (II) /
H2SO4	kg	6,97E-01	2,08E+00	sulfuric acid	
CaCO3	kg	1,81E-01	5,40E-01	calcium carbonate, precipitated	
CaO	kg	1,81E-01	5,40E-01	quicklime, milled, loose	
NaOH	kg	1,68E-02	5,00E-02	sodium hydroxide, without water, in 50% solution state	
Sodium carbonate	kg	5,26E-01	1,57E+00	soda ash, light	
Electricity	kWh	1,11E+00	3,30E+00	electricity, medium voltage	

Hard coal	kg	2,26E-01	6,75E-01	hard coal	
Steam	kg	5,13E+00	1,53E+01	steam, in chemical industry	
Output					
SO2	kg	5,26E-04	1,57E-03	Sulfur dioxide, air, unspecified	
Dust	kg	2,65E-03	7,90E-03	Particulates, air, unspecified // (>2.5, <10)	
COD	kg	1,41E-04	4,20E-04	COD, Chemical Oxygen Demand, water, unspecified	
Ammonia nitrogen	kg	1,42E-05	4,25E-05	Ammonia, water, unspecified	
Suspended solids	kg	8,04E-05	2,40E-04	Suspended solids, unspecified, water, unspecified	
Li2CO3 (n°:96)	kg	3,35E-01	1,00E+00		
Input					
FeSO4	kg	1,10E+00	8,08E-01	iron sulfate	BATTERY / CATHODE / MATERIAL / SEMI-FIN-ISHED (III) /
H3O4P (>35%)	kg	2,46E+00	1,80E+00	phosphoric acid	
H2O2 (≥27.5%)	kg	4,52E-01	3,31E-01	hydrogen peroxide, without water, in 50% solution state	
NaOH (≥30%)	kg	2,53E+00	1,85E+00	sodium hydroxide, without water, in 50% solution state	
Water	kg	6,83E+01	5,00E+01	tap water	
Electricity	kWh	1,33E+00	9,72E-01	electricity, medium voltage	
Natural gas	Nm3	2,81E-01	2,06E-01	heat, district or industrial, natural gas	
Output					
Chemical oxygen demand (COD)	kg	1,56E-03	1,14E-03	COD, Chemical Oxygen Demand, water, unspecified	
Ammonia nitrogen	kg	8,19E-06	6,00E-06	Ammonia, water, unspecified	

SO2	kg	2,81E-05	2,06E-05	Sulfur dioxide, air, unspecified	
NO2	kg	1,72E-04	1,26E-04	Nitrogen dioxide, air, unspecified	
Soot	kg	6,55E-09	4,80E-09	Particulates, < 2.5 um, air, unspecified	
Dust	kg	8,19E-04	6,00E-04	Particulates, air, unspecified // (>2.5, <10)	
Iron phosphate (n°: 96)	kg	1,37E+00	1,00E+00		
Input					
Anhydrous iron phosphate	kg	1,37E+00	9,70E-01	New	BATTERY / CATHODE /
Li2CO3（99%）	kg	3,35E-01	2,38E-01	New	
Glucose（99%）	kg	1,36E-01	9,68E-02	glucose	
N2（99.9%）	kg	3,06E-01	2,17E-01	Inorganic Nitrogen	
Deionized water	kg	4,29E+00	3,05E+00	water, deionised	
Electricity	kWh	6,98E-01	4,96E-01	electricity, medium voltage	
Natural gas	m3	7,32E-01	5,20E-01	heat, district or industrial, natural gas	
Output					
Dust	kg	4,11E-04	2,92E-04	Particulates, air, unspecified // (>2.5, <10)	
Water vapour	kg	4,48E+00	3,18E+00	Water, air, unspecified	
N2	kg	3,06E-01	2,17E-01	Nitrogen , water, unspecified	
CO2	kg	2,39E-01	1,70E-01	Carbon dioxide, fossil, air, unspecified	
LFP cathode material (n°: 96)	kg	1,41E+00	1,00E+00		
Input					

Electricity	kWh	6,47E-01	8,91E-01	electricity, medium voltage	BATTERY / ANODE /
Natural gas	m3	1,38E-02	1,90E-02	heat, district or industrial, natural gas	
Graphite	kg	6,87E-01	9,47E-01	graphite	
Water	kg	5,31E-01	7,31E-01	tap water	
Coke	kg	7,67E-02	1,06E-01	coke	
Output					
Non-methane hydro-carbons	kg	5,16E-04	7,10E-04	hydrocarbons, unspecified, air, un-specified	
Dust	kg	3,03E-04	4,18E-04	particulates, air, unspecified // (>2.5, <10)	
Benzoapyrene	kg	1,02E-09	1,41E-09	PAH, polycyclic aromatic hydrocar-bons, air, unspecified	
Soot	kg	1,22E-04	1,68E-04	particulates, < 2.5 um, air, unspeci-fied	
Anode material (n°: 96)	kg	7,26E-01	1,00E+00		
Input					
Polypropylene	kg	6,27E-02	1,09E+00	polypropylene, granulate	BATTERY / SEPARA-TOR /
Electricity	kWh	2,25E-01	3,91E+00	electricity, medium voltage	
Diesel	kg	2,30E-04	3,99E-03	diesel	
Natural gas	Nm3	1,85E-02	3,22E-01	heat, district or industrial, natural gas	
Output					
NMVOC	kg	2,19E-05	3,80E-04	NMVOC, non-methane volatile or-ganic compounds air, unspecified	
SO2	kg	8,28E-06	1,44E-04	Sulfur dioxide, air, unspecified	

NOx	kg	3,66E-05	6,36E-04	Nitrogen oxides, air, unspecified	
PM10	kg	4,53E-06	7,87E-05	Particulate Matter, > 10 um, air, unspecified	
Separator in PP (n°: 96)	Kg	5,75E-02	1,00E+00		
Input					
Methanol	kg	3,04E-01	7,50E-01	methanol	BATTERY / DIM-CARB /
Coke	kg	9,73E-02	2,40E-01	coke	
Oxygen	kg	2,15E-01	5,29E-01	oxygen, liquid	
Electricity	kWh	9,69E-02	2,39E-01	electricity, medium voltage	
Steam	kg	2,23E-03	5,50E-03	steam, in chemical industry	
Output					
NMVOC	kg	6,61E-06	1,63E-05	NMVOC, non-methane volatile organic compounds air, unspecified	
CO	kg	4,18E-07	1,03E-06	Carbon monoxide, fossil, air, unspecified	
COD	Kg	3,75E-06	9,25E-06	COD, Chemical Oxygen Demand, water, unspecified	
BOD	Kg	7,42E-07	1,83E-06	BOD5, Biological Oxygen Demand, water, unspecified	
Suspended solids	kg	2,62E-06	6,46E-06	Suspended solids, unspecified, water, unspecified	
Dimethyl carbonate (n°: 96)	kg	4,06E-01	1,00E+00		
Input					
Ethylene oxide	kg	2,07E-01	5,10E-01	ethylene oxide	

CO2	kg	2,28E-01	5,62E-01	carbon dioxide, in chemical industry	BATTERY / ETH-CARB /
Electricity	kWh	8,88E-03	2,19E-02	electricity, medium voltage	
Steam	kg	1,09E+00	2,69E+00	steam, in chemical industry	
Output					
NMVOC	kg	1,19E-06	2,93E-06	NMVOC, non-methane volatile organic compounds air, unspecified	
Ethylene carbonate (n°: 96)	kg	4,06E-01	1,00E+00		
Input					
Electricity	kWh	8,85E+00	1,24E+01	electricity, medium voltage	BATTERY / COPPER FOIL /
Natural gas	m3	2,46E-04	3,44E-04	heat, district or industrial, natural gas	
Copper	kg	7,14E-01	1,00E+00	copper, cathode	
Concentrated sulfuric acid	kg	1,15E-02	1,62E-02	sulfuric acid	
Hydrochloric acid	kg	9,56E-05	1,34E-04	hydrochloric acid, without water, in 30% solution state	
Tartaric Acid	kg	8,06E-05	1,13E-04	carboxylic acids	
Active carbon	kg	2,39E-04	3,34E-04	activated carbon, granular	
Cobalt Sulphate Hexahydrate	kg	4,77E-04	6,68E-04	cobalt sulfate	
Zinc Sulphate Heptahydrate	kg	4,77E-04	6,68E-04	zinc monosulfate	
Carboxyethyl cellulose	kg	9,56E-05	1,34E-04	carboxymethyl cellulose, powder	
3-Carboxy-1-propane-sulfonate	kg	4,77E-05	6,68E-05	naphthalene sulfonic acid	

Water	kg	7,98E+00	1,12E+01	tap water	
Output					
Sulfuric acid mist	g	5,04E-01	7,06E-01	Sulfuric acid, air, unspecified	
Copper	g	2,67E-04	3,74E-04	Copper ion, water, unspecified	
Cobalt	g	3,53E-05	4,94E-05	Cobalt II, water, unspecified	
Copper foil (n°: 96)	kg	7,14E-01	1,00E+00		
Input					
Electrolytic aluminum	kg	1,02E+00	1,32E+00	Aluminium, primary, liquid, prebake	BATTERY / ALUMINIUM FOIL /
Water	kg	2,19E+00	2,86E+00	tap water	
Diatomite	kg	3,16E+00	4,12E+00	silica sand	
Rolling Oil	kg	1,00E+01	1,30E+01	lubricating oil	
Output					
Non-methane hydrocarbons	kg	2,28E+00	2,97E+00	hydrocarbons, unspecified, air, unspecified	
Chemical oxygen demand (COD)	kg	3,80E-02	4,95E-02	COD, Chemical Oxygen Demand, water, unspecified	
Suspended solids	kg	7,57E-04	9,85E-04	suspended solids, unspecified, water, unspecified	
Ammonia nitrogen	kg	7,48E-04	9,73E-04	ammonia, water, unspecified	
Aluminum foil (n°: 96)	kg	7,68E-01	1,00E+00		
Input					
Electricity	kWh	8,22E+00	3,76E-01	electricity, medium voltage	BATTERY / ALUMINIUM SHELL /
Stretching oil	kg	6,57E-01	3,01E-02	lubricating oil	
Water	kg	3,60E-02	1,65E-03	tap water	

Aluminum	kg	1,65E+00	7,54E-02	aluminium, primary, ingot	
Output					
Shell: Aluminium (n°: 1)	kg	2,19E+01	1,00E+00		
Input					
Printed wiring board	kg	6,87E-01	1,42E-01	printed wiring board, through-hole mounted, unspecified, Pb free	BATTERY / BMS /
Integrated circuit	kg	3,96E-05	8,16E-06	integrated circuit, logic type	
ABS Resins	Kg	4,65E-04	9,60E-05	acrylonitrile-butadiene-styrene co-polymer	
Electronic component	kg	6,11E-01	1,26E-01	electronic component, active	
Steel	kg	1,99E+00	4,11E-01	steel, low-alloyed	
Aluminium	kg	1,75E-01	3,60E-02	Aluminium ingot, primary	
Synthetic rubber	kg	5,24E-03	1,08E-03	synthetic rubber	
Polyethylene terephthalate	kg	9,87E-02	2,04E-02	polyethylene terephthalate, granulate, amorphous	
Nylon 66	kg	8,67E-02	1,79E-02	nylon 6-6	
Connector	kg	4,89E-02	1,01E-02	electric connector, peripheral component interconnect buss	
Cable	Kg	6,54E-01	1,35E-01	cable, three-conductor cable	
Brass	Kg	1,33E-02	2,74E-03	brass	
Copper, primary	Kg	3,94E-01	8,13E-02	copper, cathode	
Polyphenylene sulfide	kg	4,65E-02	9,60E-03	polyphenylene sulfide	
Tin	kg	2,33E-02	4,80E-03	tin production	
Output					
BMS (n°: 1)	kg	4,85E+00	1,00E+00		

Table 39 - Other recycling components LCI

Component	Units	DPP Value	LCI Value	Reference Dataset	DPP Position
Input					
Waste BMS	kg	1,80E+01	1,00E+00	electronics scrap, Recycled Content cut-off	BATTERY / BMS / END OF LIFE
Output					
Aluminium	kg	2,72E-01	1,51E-02	aluminium, primary, liquid, prebake	
Copper	kg	7,02E-01	3,90E-02	copper, cathode	
Steel	kg	6,72E+00	3,73E-01	Steel, electric, low-alloyed	
Plastic	kg	1,51E+00	8,39E-02	plastic, mixed, recycled	
Waste circuit boards	kg	8,79E+00	4,88E-01	electronics scrap, Recycled Content cut-off	
Input					
Aluminum scrap	kg	1,49E+01	1,00E+00	aluminium scrap, post-consumer	BATTERY / ALUMINIUM FOIL / END OF LIFE
Water	kg	1,11E+01	7,46E-01	tap water	
Inorganic	kg	7,59E-02	5,08E-03	chemical, inorganic	
Electricity	kWh	4,03E+00	2,70E-01	electricity, medium voltage	
Natural gas	m3	1,27E+00	8,47E-02	heat, district or industrial, natural gas	
Output					
Secondary aluminum	kg	1,27E+01	8,47E-01	Aluminium, primary, liquid	
Particulates	kg	8,10E-03	5,42E-04	Particulate Matter, > 2.5 um and < 10um	

Chlorides	kg	2,41E-03	1,61E-04	Chlorides, unspecified, air, unspecified	
Fluorides	kg	5,38E-04	3,60E-05	Fluoride, air, unspecified	
Petroleum	kg	2,94E-06	1,97E-07	Hydrocarbons, unspecified, water, unspecified	
SS	kg	3,20E-05	2,14E-06	Suspended solids, unspecified, water, unspecified	
Municipal solid waste	kg	2,66E+00	1,78E-01	DummyWasteTreatment	
Input					
Copper scrap	kg	6,00E+01	1,00E+00	copper scrap, sorted, pressed, Recycled Content	BATTERY / COPPER FOIL / END OF LIFE
Electricity	kWh	4,09E+01	6,82E-01	electricity, medium voltage	
Output					
Secondary copper	kg	5,40E+01	9,00E-01	copper, cathode	
Input					
Waste plastics	kg	1,50E+02	1,00E+00	waste plastic, WEEE, unsorted, Recycled Content	BATTERY / END OF LIFE
Electricity	kWh	1,26E+01	7,00E-01	electricity, medium voltage	
Output					
Recycled plastic	kg	1,90E+01	9,00E-01	plastic, mixed, recycled	
Input					
Steel Scrap	kg	2,11E+01	1,00E+00	ferrous metal, in mixed metal scrap	BATTERY / END OF LIFE
Electricity	kWh	1,03E+02	4,87E+00	electricity, medium voltage	
Output					
Recycled steel	kg	2,00E+01	9,50E-01	Steel, electric, low-alloyed	