Politecnico di Torino
Master of Science in Environmental and Land Engineering

LCA of Na-ion battery with bio-waste derived anode and comparison with conventional Li-ion battery in e-mobility

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A.Y. 2022/2023
December 2023

Abstract

Batteries play a crucial role in the transition towards climate neutrality and circular economy. With the aim of achieving carbon neutrality by 2050 as set forth in the European Green Deal, the shift from fossil fuels to electromobility is necessary. New regulations and the energy crisis anticipate a rapid growth in battery demand in the coming years. The European Union has committed to establish a comprehensive regulatory framework covering the entire lifecycle of batteries, emphasizing reduced use of critical raw materials, waste management, recycling, and second-life applications.

Lithium-ion batteries dominate the electric mobility landscape, and their demand is projected to surge. To address issues related to the extraction and purification of critical raw materials like cobalt, nickel, and lithium, alternative solutions are required. Sodium-ion technology emerges as a promising contender for energy storage in electric vehicles and large-scale stationary applications. The advantages include potential cost reduction and increased sustainability due to sodium abundance and the possibility of replacing copper with aluminum in the anode current collector.

Despite the chemical similarities between lithium and sodium, lithium-ion batteries demonstrate significantly higher specific capacity using graphite as the anode active material. The sustainability of graphite has propelled the commercialization of these batteries. Sodium-ion batteries typically employ hard carbon derived from petroleum coke or biomass through pyrolysis. This thesis explores the utilization of bio-waste from wine production as a precursor for hard carbon, using the software OpenLCA to conduct a life cycle assessment (LCA) to identify environmental impact differences compared to petroleum coke and another biomass precursor already developed. Additionally, a comparative LCA analysis with conventional lithium-ion batteries is performed under a common application scenario for both technologies.

The analysis focuses on specific battery materials examined at IREC, the Catalonia Institute for Energy Research, utilizing a "cradle to gate" approach due to data limitations stemming from the topic's novelty. The environmental impact of the battery is influenced significantly by cathode production materials, particularly the use of critical raw materials, like nickel and cobalt, primarily affecting the manufacturing phase. Battery performance requirements, such as energy capacity, also impact environmental indicators due to increased material usage. The non-cell materials within the battery pack can likewise influence environmental outcomes.

Utilizing waste biomass for hard carbon production reduces environmental impact and extraction costs. However, inefficient biomass transformation processes can offset these benefits. The replacement of copper with aluminum in the current collector does not substantially reduce environmental impact, but it aligns with the desirable goal of reducing copper usage.

The primary limitations of this analysis are its exclusive focus on the manufacturing phase and the need for a "cradle to grave" assessment to comprehensively evaluate the entire lifecycle of the battery, which exceeds the study current scope due to data limitations.

In conclusion, lithium-ion batteries remain cost-effective but require research into potential new materials, especially for cathode production. Using secondary raw materials could significantly reduce the environmental impact during the extraction phase. Sodium-ion batteries show promise for future batteries from an environmental standpoint, with the added benefit of waste material utilization in a circular economy context. However, the novelty of this technology and identified gaps in previous research, emphasize the need for further investigation in this field to draw more comprehensive conclusions in the future.

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1 Introduction

Batteries constitute a pivotal resource in the transition towards climate neutrality and circular economy. The shift from fossil fuel usage in vehicles to electromobility could significantly help to the goal of achieving carbon neutrality by 2050, as established in the European Green Deal. As a result of new regulations, coupled with the energy crisis, a rapid growth in battery demand is expected in the coming years. To address this, the EU has committed to establish a regulatory framework for addressing the entire lifecycle of batteries, encompassing reduced utilization of critical raw materials, waste battery management, recycling, and batteries' second life.

Lithium-ion batteries are the most widespread technology in the electric mobility landscape, and it is anticipated that the demand will experience significant growth in the upcoming years. Therefore, novel solutions must be sought, considering the issues associated with the extraction and purification of the critical raw materials utilized in lithium-ion batteries (cobalt, copper, nickel, and lithium).

Sodium-ion technology stands out among the most promising future technologies for energy storage in electric vehicles and large-scale stationary applications. The advantages of sodium-ion batteries over lithium-ion ones are manifold, with the primary benefits encompassing potentially lower costs and enhanced sustainability due to the greater abundance of sodium in the Earth's crust and possibility of replacing copper with aluminum in the current collector of anode, reaching not only a reduction in cost but, also, an environmental benefit (Moon et al., 2023).

Although lithium and sodium chemistries are quite similar, the specific capacity achievable using graphite as the active material in the anode of the battery is significantly higher in lithium-ion batteries. The sustainability of graphite is one of the factors that propelled the commercialization of this type of batteries. The low capacity of graphite to intercalate sodium ions is attributed to the competition between ionization energy and ion-substrate coupling, which leads to weak chemical binding of sodium ions to numerous substrates (Del Mar Saavedra Rios et al., 2020).

Typically, in sodium-ion batteries, hard carbon is employed as the active material in the anode, and this component typically is derived from petroleum coke or biomass through pyrolysis. In this thesis work, the utilization of bio-waste precursors generated from the wine production process has been contemplated, and a life cycle assessment (LCA) analysis has been conducted to identify the processes with the most significant environmental impact, assessing the differences that exist when utilizing petroleum coke or other types of waste as hard carbon's precursors. Furthermore, a comparison with the life cycle assessment (LCA) of a conventional lithium-ion battery, in electric mobility, has been performed by estimating a common application scenario for both technologies.

Indeed, the analysis centers on specific materials for battery analyzed at IREC, the Catalonia Institute for Energy Research, following a “cradle to gate” approach.

A “cradle to grave” assessment could not be performed due to limitations in the availability of data caused by the novelty of the topic. However, a comparison between the use phase of the batteries has been contemplated and an overall analysis related to the end of life of batteries has been performed, focusing on the recycling of valuable elements that can enter in the market as secondary materials.

The results can be employed to assist battery manufacturers in their pursuit of sustainable product development and to pinpoint critical parameters that influence the environmental performance of battery packs.

1.1 Battery raw materials: an overview

A battery constitutes an electrochemical cell designed for the storage of energy within a chemical medium. The battery possesses the capacity to transmute this chemical energy into practical electrical energy. Batteries find application across a diverse spectrum of everyday activities. By employing distinct chemical compounds for the cathodes and anodes, the discharge procedure furnishes an electric current. Ideally, in the case of rechargeable batteries, this procedure is fully reversible through recharging and reconversion of cell materials to their initial state.

Battery cells are grouped together into modules which encompass enclosures for the cells themselves, cooling mechanisms, and interconnections. In the context of electric vehicles (xEVs), these modules are then assembled into a larger unit referred to as a 'battery pack.' This battery pack comprises an external housing, a battery management system, multiple sensors, a cooling system, and associated wiring.

Nowadays, more than half of the global production of certain raw materials is dedicated to use in battery applications. For instance, over 50% of the worldwide demand for cobalt and over 60% of lithium demand are channeled into battery production and the demand of battery raw materials is expected to rise sharply (European Parliament, 2023). From this perspective, reuse and recycling can play a substantial role in mitigating the effects stemming from the future demand for materials, while also providing a valuable opportunity to enhance circularity and access to secondary raw materials.

Lithium-ion batteries represent one of the most prevalent technologies in the realm of electric mobility. Among the materials pivotal to this technology, lithium occupies a significant role, the largest lithium reserves are located in South America and the global production is dominated by Australia and Chile. Nearly 60% of global lithium mineral refining facilities are in China (http://www.visualcapitalism.com). China also holds the distinction of being the primary producer of natural graphite, a vital active material employed in the anode of lithium-ion batteries.

Concerning the cathode of these batteries, commonly employed materials encompass cobalt (mainly sourced from Congo) and nickel. Regarding the latter, although nickel production boasts a higher degree of diversification compared to cobalt and lithium, not all globally produced nickel is suitable for lithium-ion battery production and new investments in the production of high-purity nickel sulphate should be made.

Specific supply risks along the supply chain are related to the battery raw materials employed. For raw materials such as cobalt, mining in the Democratic Republic of the Congo is associated with unstable political conditions and business difficulties. Another supply risk is related to positive and negative price peaks which affect investments in mining and refining capacities. Furthermore, the refining of extracted materials constitutes a problem mainly due to the transportation over a long distance, from the mine to the refiners, followed by large investments in this sector.

1.2 Battery raw materials: EU regulations

Europe is fully dependent on Asia for the supply of processed natural and artificial graphite, anodes, separators and some kind of cathode materials. In fact, China, Japan, and South Korea supply most of the processed materials and components for Li-ion batteries at global scale. Furthermore, China is the major producer of Li-ion cells turning Europe practically entirely dependent even on import of battery cells.

Regarding battery packs, the Europe capacity of production is expected to increase noticeably in a few years.

The European Union has adopted several key policies devoted to a more sustainable supply of battery raw materials.

In 2008, the Commission endorsed “The raw materials initiative”, delineating a strategic approach to address the challenge of raw materials accessibility within the European Union. This strategy is underpinned by three core principles that seek to establish an equitable and enduring inflow of raw materials from worldwide markets, foster a sustainable domestic raw material supply, and enhance resource efficiency. Additionally, the strategy underscores the significance of procuring 'secondary raw materials' via recycling processes.

The first list of Critical Raw Materials (CRM) was published in 2011, in the “Communication on raw materials”. The list is updated and revised at least every 3 years.

Furthermore, in the “First Circular Economy Action Plan (CEAP)”, adopted in 2015, improvements in the market of secondary raw materials are covered. A detailed discussion on the recovery of CRM is reported in the “Critical Raw Materials and the Circular Economy-background report” (2018).

In 2017, in the renewed industry policy strategy, a revised list of Critical Raw Materials and several of these are found in batteries. The aim of this policy is to highlight the need for a secure, sustainable, and affordable supply for the EU manufacturing industry.

However, the only EU legislation entirely devoted to batteries is the Batteries Directive (2006/66/EC). The directive establishes regulations governing batteries introduced into the European Union market, encompassing stipulations concerning their hazardous substance composition. It outlines precise rules for the retrieval, processing, recycling, and proper disposal of discarded batteries and accumulators. The directive is aimed at advancing the environmental sustainability of batteries and accumulators, as well as refining the practices of all engaged economic entities. For further information, the European Commission report on the implementation of the Batteries Directive was released in 2019.

In 2020, in the “Communication on Critical Raw Materials”, the launch of an industrial alliance devoted to a secure and sustainable supply of raw materials was announced. The aim of this alliance is to increase EU resilience in elements that play a crucial role in key sectors, such as automotive, renewable energy and aerospace, to support the circular economy and meet the requirement of the EU Green Deal. Furthermore, “A new Circular Economy Action Plan” was adopted, announcing initiatives along the entire life cycle of products, and introducing legislative and non-legislative measures to bring real added value.

The most updated list of CRM is the fifth one that has been released on 2023, including 34 materials. Among them, it is relevant to mention the presence of cobalt, copper, lithium, manganese, natural graphite, and nickel.

2 Methodology

2.1 LCT approach

“The circular economy is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products as long as possible, leading to a reduction of waste to a minimum” (https://www.europarl.europa.eu). The switch towards circular economy is needed to reduce the dependance from primary raw materials, which supply is limited, and protect the environment, limiting the biodiversity loss and reducing the total annual greenhouse gas emissions (European Commission, 2023).

A scheme of the battery’s lifecycle in a circular economy perspective is reported in *figure 1*. It is important to highlight the “extended use phase” of the battery that allows to reuse the battery after their first life on a vehicle so, after losing 20-30% of their initial capacity. This life enlargement could avoid the manufacture of new batteries for these secondary uses and so, reduce the environmental impact. The difficulty in the exploitation of resources useful in the manufacturing stage and the significant ecological footprint derived from the extraction of raw materials made recycling a crucial step in the lifecycle of batteries that cannot be overlooked.

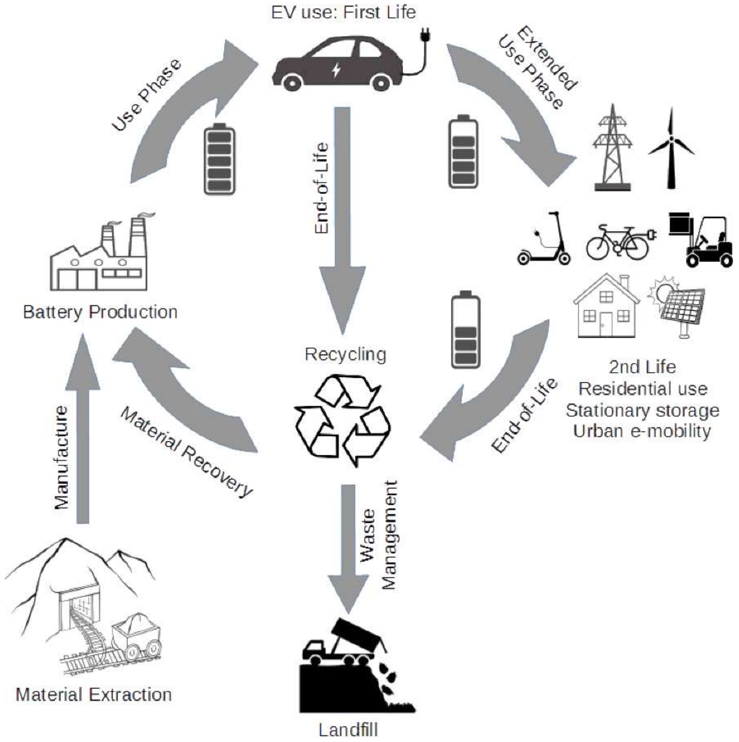

Figure 1-Lifecycle of a battery in a circular economy perspective (Kotak et al., 2021)

Considering the shift towards circular economy, the most useful concept is the Life Cycle Thinking (LCT), which enables an assessment of a product or service throughout its entire life cycle in terms of environmental, economic, and social impacts. LCT approach forms the foundation of the methodology employed in the thesis considering all the life cycle stages of the product:

- Resources extraction
- Manufacturing
- Transportation
- Retail and use
- Disposal
- Recycling, re-use and recovery

To make LCT operational, several methodologies exist, and the most relevant ones are Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social Life Cycle Assessment (sLCA).

The Life Cycle Assessment (LCA) constitutes a methodological and standardized framework regulated by the International Standard Organization (ISO 14040/14044, 2006) applied for the quantification of both direct and indirect environmental impacts linked to a given product or service.

LCA identifies and quantifies energy and materials used, as well as releases to the environment and their potential impact throughout the whole life cycle, using the so-called “from cradle to grave” approach. Moreover, LCA functions as an invaluable structure for scrutinizing the environmental compromises among diverse technologies that furnish comparable services.

The technique relies on the development of a model wherein the life cycle phases are depicted through "unit operations," inter-connected by the flow of products, energy, and materials. However, the application of LCA to batteries introduces several complexities arising from methodological selection to the insufficiency of primary data regarding battery production.

LCA methodology is divided in four steps:

1. Goal and scope definition
2. Inventory
3. Impact assessment
4. Interpretation and improvement

Figure 2 helps to illustrate how Life Cycle Assessment (LCA) is a comprehensive and iterative procedure that systematically evaluates the environmental impact of a product or service. The entire life cycle of the product can be covered, from raw material extraction, manufacturing, transportation, operation, and disposal.

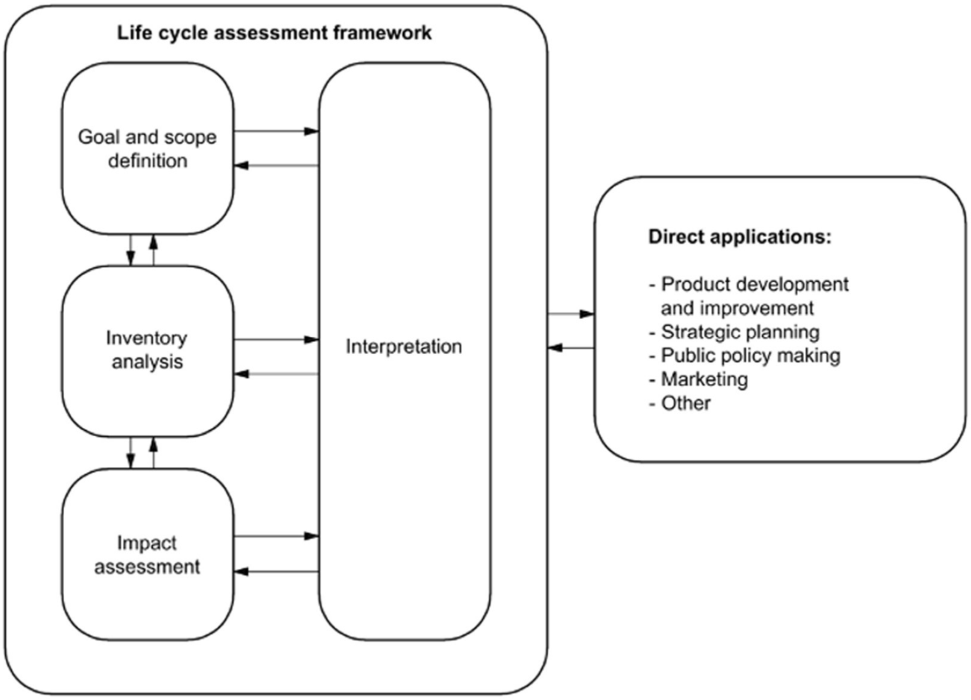

Figure 2-LCA procedure (ISO 14040:14044, 2006)

2.2 Goal and scope definition

The first step of the LCA procedure is dedicated to the definition of goal, scope function and functional unit of the study.

The goal of a LCA shall unambiguously state the intended application, including the reasons for carrying out the study and the intended audience (ISO 14040, 2006).

This encompasses the determination of the recipients for whom the study findings will be conveyed, as well as ascertaining whether the outcomes will be employed in comparative statements intended for public disclosure.

Furthermore, the scope of the LCA must be defined, encompassing details about the analyzed product and the process to achieve the set goal. For this purpose, it is necessary to establish the functional unit, system boundaries, and methodological choices.

Various aspects of the scope may require modification during the analysis, to meet the original goal of the study, because of the iterative characteristics of the LCA technique.

2.2.1 Functional Unit

The Functional Unit definition is essential to build and model a product system in Life Cycle Assessment, it corresponds to a reference parameter to which the results of the LCA are ascribed. This reference is necessary to guarantee comparability of LCA results. Despite the choice being arbitrary, it must align consistently with the study's objective and the intended function for which the product system had been designated.

A function may be based on different features of the product analyzed, such as performance, aesthetics, technical quality, additional services, and costs.

2.2.2 System Boundary

The System Boundaries delineate the Units of Process that need to be encompassed within the LCA model. Ideally, the product system should be structured in a way that inputs and outputs at its boundary consist of elementary flows. However, due to the complexity of real product systems, this is virtually impossible with reasonable resources. Moreover, in accordance with the overarching objectives of an LCA, a complete expansion of the model is frequently unnecessary. Hence the need to introduce cut-off criteria, to save time and money.

Although the ISO standards mention only one approach, referred to as "cradle to grave," that covers all operations starting with raw materials extraction and ending with waste materials leaving the system, other two relevant methods are included in the previous one. The “cradle to gate” approach covers all operations starting with raw materials in the Earth and ending with a product leaving the system. Instead, the “gate to gate” includes all the operations starting with materials and fuels entering the production system and ending with a product leaving the system.

2.3 Inventory Analysis

The Inventory Analysis constitutes a crucial stage in the Life Cycle Assessment (LCA), encompassing the systematic compilation and quantification of inputs and outputs for a designated product system over the entire course of its life cycle. Before collection of data, all systems should be broken down into unit operations. A unit operation represents the smallest unit for which data is available.

The inventory phase involves collecting data on every process unit within the system boundaries, including consumption, emissions, product quantity and weight. The mentioned data can be primary or secondary, the difference between the two consists in the way the data are being obtained, with on-site measurement or from the literature.

Typically, each stage of the life cycle is represented by a process unit and the system boundaries are defined with the help of a flow chart in which each process unit is interconnected by product, energy, and material flows. Furthermore, a connection with the ecosystem is created. It provides resources to the unit process and receives waste released by the unit process.

The inventory results are divided in the following categories:

- Raw materials
- Energy resources
- Air emissions
- Water emissions
- Soil emissions

- Solid wastes

A scheme of the input and output flows for a general unit operation is reported in *figure 3*.

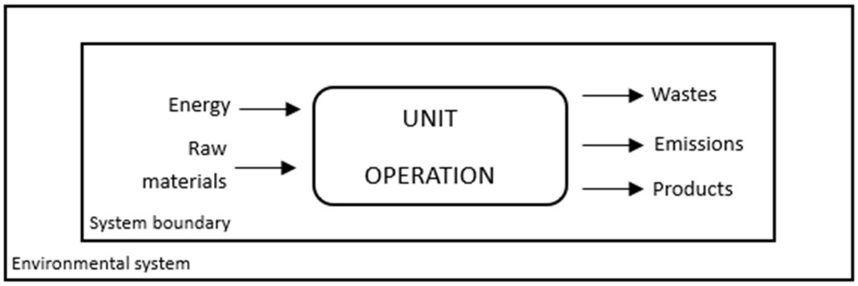

Figure 3-input and output flows for a unit operation

2.3.1 Data collection and calculation

The data is collected for each unit operation within the system's boundary, including input and output data. The fuels, energy and raw materials in input and heat and solid waste, emission to air and water, and products in output are considered.

After the data collection, calculation procedures are needed to generate the results of the inventory of the defined system for each unit process. This necessity arises from the objective of the inventory analysis, which is to determine the flow of inputs and outputs within a given system.

2.3.2 Allocation criteria

In the case of multi-function systems, which involve processes generating more than a single product, the allocation procedure must be considered to ensure that all environmental impacts are taken into account. Typically, subsystems are established, each corresponding to a singular output product.

2.3.3 End of life management

The LCA is also aimed at quantifying the environmental impacts associated with end-of-life. An important aspect of the end-of-life management is the recycling process, which can take two forms (both considered in LCAs regarding the environmental benefits): closed and open loop recycling. Closed loop recycling occurs when material flows to be recycled are re-entered in the same process that was at their origin, this implies a reduction in the need for virgin materials and in the waste produced. Instead, open loop recycling occurs when origin and destination process differ. Also in this case the need for virgin material and the waste could be reduced even if additional energy and resources for transportation and processing may be required.

2.4 Life Cycle Impact Assessment

The objective of the Life Cycle Impact Assessment (LCIA) is to evaluate the inventory outcomes of a product system to gain a deeper comprehension of their potential environmental implications. The LCIA phase employs specific environmental concerns, called impact categories, along with corresponding category indicators, to streamline and structure the Life Cycle Inventory (LCI) findings. These category indicators are designed to reflect aggregated emissions or resource utilization, subsequently portraying potential environmental impacts.

According to ISO 14044 (2006), Life Cycle Impact Assessment includes four steps:

- Classification, assignment of each environmental flow to a specific impact category
- Characterization, quantitative modelling of each impact emission according to the underlying environmental mechanism
- Normalization, correlating the various characterized impact to a common reference
- Weighting, balancing performed on the different environmental impact categories, reflecting their relative importance

The initial two steps are mandatory, while the subsequent ones are optional.

The phase of Impact Assessment is the result of the combination between impact, the physical result of an activity into the ecosystem which physical estimation is obtained after the inventory phase, and effect that can be estimated from the impact, under given hypothesis and adopting appropriate models.

2.4.1 Classification

The classification is a mandatory procedure of the LCIA step that assigned all the input and output inventoried during the compilation of the Life Cycle Inventory (LCI) to the impact categories to which they contribute using the provided classification data.

Global Warming Potential (GWP), acidification, eutrophication, ozone depletion are only some examples of the environmental impact categories.

2.4.2 Characterization

Characterization is the second mandatory step of the LCIA that assigned the characterization factors, typically expressed in number, to each impact category. The characterization factor represents the contribution per unit input or output to the category.

2.4.3 Normalization and Weighting

Normalization and Weighting are optional steps of the LCIA, as mentioned before.

These analyses represent a useful support to policies to determine the most relevant impact categories in a given region, identify the most relevant life cycle stages, processes and emissions in each region and to steer strategies towards the most effective solutions for decoupling.

2.4.4 LCIA limitation

The outcomes of LCIA are relative in nature and signify potential environmental effects, rather than forecasting definite impacts on category endpoints, surpassing thresholds, safety margins, or posing risks.

The main limitation of LCIA is related to the selection of impact categories that can vary depending on the goal and scope of the study. The same problem concerns the weighting of different impact categories.

The limitations associated with the LCIA highlight the need for sensitivity and uncertainty analysis to assess the robustness of the results.

2.5 Interpretation

The interpretation step is the result of the combination of the previous three steps, according to the stated goal and scope, with the purpose of developing conclusions and recommendations.

This step includes the identification of significant issues that should reflect the relative approach upon which LCIA results are based; evaluation that considers completeness, sensitivity and consistency checks and provide conclusions, limitations, and recommendations.

Overall, the results drawn of the life cycle interpretation must align with the evaluation component's outcomes. These conclusions and recommendations should be congruent with the predefined goal and scope of the study.

3 Literature review

In recent years, Life Cycle Assessment (LCA) has found extensive application and adoption across various fields, garnering considerable attention and coverage in the process. Regarding the LCA of lithium-ion batteries in the automotive sectors, seventeen documents were suitable according to Temporelli et al. (2020). The bibliography following 2019 has been analyzed using the Scopus database (http://www.scopus.com), yielding an additional nineteen documents that align with the research topic, the papers devoted to the review of previous works are taken for granted. The documents are summarized in *table 1*.

Table 1- Literature regards the LCA of lithium-ion batteries

AUTHORS	TITLE	YEAR
Notter, D, A; Gauch, M; Widmer, R; Wager, P; Stamp, A; Zah, R; Althaus, H, J	Contribution of Li-ion batteries to the environmental impact of electric vehicle	2010
Majeau-Bettez, G; Hawkins, T, R; Strømman, A, H	Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-In Hybrid and Battery Electric Vehicles	2011
Dunn, J, B; Gaines, L; Barnes, M; Sullivan, J	Material and Energy Flows in the Materials Production, Assembly, and End-of-Life Stages of the Automotive Lithium-Ion Battery Life Cycle	2012
U.S. Environmental Protection Agency	Application of Life-Cycle Assessment to Nanoscale Technology: Lithium-ion Batteries for Electric Vehicles	2013
Ellingsen, L, A, W; Majeau-Bettez, G; Singh, B; Srivastava, A, K; Valøen, L, O; Strømman, A, H	Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack	2014
Faria, R; Marques, P; Garcia, R; Moura, P; Freire, F; Delgado, J; de Almeida, A, T	Primary and secondary use of electric mobility batteries from a life cycle perspective	2014
Oliveira, L; Messagie, M; Rangaraju, S; Sanfelix, J; Rivas, M, H; Van Mierlo, J	Key issues of lithium-ion batteries from resource depletion to environmental performance indicators	2015
Richa, K; Babbitt, C. W; Nenadic, N, G; Gaustad, G	Environmental trade-offs across cascading lithium-ion battery life cycles	2015
Helmers, E; Weiss, M	Advances and critical aspects in the life cycle assessment of battery electric cars	2017
Romare, M; Dahllöf, L	The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries	2017
Cusenza, M, A; Bobba, S; Ardente, F; Cellura, M; Di Persio, F	Energy and environmental assessment of a traction lithium-ion battery pack for plug-in hybrid electric vehicles	2019
Dai, Q; Kelly, J, C; Gaines, L.; Wang, M	Life Cycle Analysis of Lithium-Ion Batteries for Automotive Application	2019
Ioakimidis, C, S; Murillo-Marrodàn, A; Bagheri, A; Thomas, D; Genikomaskis, K	Life Cycle Assessment of a Lithium Iron Phosphate (LFP) Electric Vehicle Battery in Second Life Application Scenarios	2019
Liu, C; Lin, J; Cao, H; Zhang, Y; Sun, Z	Recycling of spent lithium-ion batteries in view of lithium recovery: A critical review	2019
Kallitsis, E; Korre, A; Kelsall, G; Kupfersberger, M; Nie, Z	Environmental life cycle assessment of the production in China of lithium-ion batteries with nickel-cobalt-manganese cathodes utilising novel electrode chemistries	2020
Sun, X; Luo, X; Zhang, Z; Meng, F; Yang, J	Life cycle assessment of lithium nickel cobalt manganese oxide (NCM) batteries for electric passenger vehicles	2020
The Advanced Rechargeable & Lithium Batteries Association	PEFCR - Product Environmental Footprint Category Rules for High Specific Energy Rechargeable Batteries for Mobile Applications	2020
Wang, F; Deng, Y; Yuan, C	Life cycle assessment of lithium oxygen battery for electric vehicles	2020
Yang, J; Gu, F; Guo, J	Environmental feasibility of secondary use of electric vehicle lithium-ion batteries in communication base stations	2020
Zhu, L; Chen, M	Research on Spent LiFePO4 Electric Vehicle Battery Disposal and Its Life Cycle Inventory Collection in China	2020

Accardo, A; Dotelli, G; Musa, M, L; Spessa, E	Life Cycle Assessment of an NMC Battery for Application toElectric Light-Duty Commercial Vehicles and Comparison with a Sodium-Nickel-Chloride Battery	2021
Iturrondobeitia, M; Akizu-Gardoki, O; Minguez, R; Lizundia, E	Environmental Impact Analysis of Aprotic Li–O2 Batteries Based on Life Cycle Assessment	2021
Koroma, M, S; Costa, D; Cardellini, G; Messagie, M	Life Cycle Assessment of Lithium-ion Battery Pack: Implications of Second life and Changes in Charging Electricity	2021
Rajaeifar, M, A; Marco Raugei, Steubing, B; Hartwell, A; Anderson, P, A; Heidrich, O	Life cycle assessment of lithium-ion battery recycling using pyrometallurgical technologies	2021
Rinne, M; Elomaa, H; Porvali, A; Lundstrom, M	Simulation-based life cycle assessment for hydrometallurgical recycling of mixed LIB and NiMH waste	2021
Benveniste, G; Sanchez, A; Rallo, H; Corchero, C; Amante, B	Comparative life cycle assessment of Li-Sulphur and Li-ion batteries for electric vehicles	2022
Bhosale, A, P; Bodke, K; Babhulkar, A; Amale, S; Mastud, S, A; Chavan, A	Comparative environmental assessment of different battery technologies used for electric vehicles	2022
Chordia, M; Nordelöf, A; Ellingsen, A	Environmental life cycle implications of upscaling lithium-ion battery Production	2022
Quan, J; Zhao, S; Song, D; Wang, T; He, W; Li, G	Comparative life cycle assessment of LFP and NCM batteries including the secondary use and different recycling technologies	2022
Guo, W; Feng, T; Li, W; Hua, L; Meng, Z; Li, K	Comparative life cycle assessment of sodium-ion and lithium iron phosphate batteries in the context of carbon neutrality	2023
Kim, H, C; Lee, S; Wallington, T, J	Cradle-to-Gate and Use-Phase Carbon Footprint of a Commercial Plug-in Hybrid Electric Vehicle Lithium-Ion Battery	2023
Philippot, M, L; Costa, D; Cardellini, G; Sutter, L; Smekens, J; Mierlo, J; Messagie, M	Life cycle assessment of a lithium-ion battery with a silicon anode for electric vehicles	2023

Notter et al. (2010) performed a “cradle to grave” life cycle analysis comparing the environmental impacts of an electric vehicle with those of an internal combustion engine car. The results revealed that the environmental burdens are dominated by the operation phase in both cases and the major contributions for the electric vehicle are caused by the extraction of critical raw materials used in the battery. This document remains one of the main references for the LCA of lithium-ion batteries cited in several reports.

Majeau-Bettez et al. (2011) presented the life cycle assessment of three lithium-ion battery technologies for plug-in hybrid electric vehicles with a “cradle to gate” approach, also including the use phase.

Dunn et al. (2012) conducted a “cradle to gate” life cycle analysis for a lithium-ion battery with an active cathode material of lithium manganese oxide. Furthermore, an overview of the different possible recycling mechanisms is reported.

U.S. EPA (2013) provided a life cycle assessment using data directly provided by lithium-ion suppliers, manufacturers, and recyclers. The aim was to identify the processes and materials that most contribute to impacts on public health and environment.

Ellingsen et al. (2014) reported a “cradle to gate” analysis for a nickel cobalt manganese traction battery based on primary data with the aim of providing a transparent inventory for this lithium-ion battery technology.

Faria et al. (2014) assessed the life cycle environmental impacts associated with the use of a battery in an electric vehicle and the benefits derived from the use of a battery, no longer suitable for electric mobility, for energy storage in a household.

Oliveira et al. (2015) carried out a “cradle to grave” analysis for lithium manganese oxide (LMO) and lithium iron phosphate (LFP) technologies using secondary data taken from previous paper works.

Richa et al. (2015) performed a study to analyze the environmental trade-offs of cascading reuse of lithium-ion batteries in stationary energy storage at automotive end-of-life with the purpose of extending the life cycle of batteries.

Helmers et al. (2017) presented an overview of the environmental and health-related impacts of the batteries of electric vehicles trying to identify areas of improvements for LCA methodology and battery technology, both.

Romare et al. (2017) reported the findings of the Swedish Energy Agency and the Swedish Transport Administration regarding the energy consumptions and greenhouse gas emissions from lithium-ion batteries. The manufacturing and end of life stages are analyzed based on the literature review highlighting the criticisms related to the recycling of lithium-ion batteries.

Cusenza et al. (2019) conducted a “cradle to grave” life cycle analysis on LMO-NMC traction battery cell considering the application of the battery pack to a plug-in hybrid electric vehicle and modelling the end-of-life stage in accordance with the Waste Batteries Directive (Directive, 2006/66/EC). Furthermore, several assumptions have been made in the study due to lack of primary data so, a sensitivity analysis was conducted.

Dai et al. (2019) performed a “cradle to gate” life cycle analysis for a NCM111 battery pack composed of prismatic cells.

Ioakimidis et al. (2019) provided a life cycle analysis of a LFP battery to examine the environmental impact from the reuse of EV batteries considering four possible scenarios. In all the scenarios, the secondary use of the battery in smart buildings and/or solar panels is contemplated. After the use phase, the battery is directly intended for the second use and subsequent disposed (scenario 1 and 3) or it is firstly disposed and then a new smaller battery is manufactured (scenario 2 and 4).

Liu et al. (2019) analyzed the current situation in the recycling of lithium-ion batteries focusing on the description of the different processes applicable for the extraction of lithium from batteries at the end-of-life stage.

Kallitsis et al. (2020) investigated the environmental burdens associated to the production of a lithium-ion battery with silicon-graphite anode and nickel-cobalt-manganese as cathode active material through a “cradle to gate” analysis.

Sun et al. (2020) evaluated the life cycle environmental impacts of lithium-ion power batteries for passenger electric vehicles to identify key stages that contribute to the overall environmental burden. A “cradle to grave” analysis is performed using primary data even if assumptions were made for the recycling process.

The Advanced Rechargeable & Lithium Batteries Association (2020) provided technical guidance on how to conduct a Product Environmental Footprint (PEF) study. The document contributes to set some rules for developing PEF for high specific energy rechargeable batteries used in the e-mobility.

Wang et al. (2020) performed an analysis regarding lithium oxygen battery use in electric vehicle. A conventional lithium-ion battery (NCM-graphite) is taken as a reference to benchmark the life cycle environmental impact results of the Li-O_2 battery system and a “cradle to gate” analysis is conducted.

Yang et al. (2020) proposed a LCA comparison between repurposed EV lithium-ion batteries and lead-acid batteries used in conventional energy storage systems to identify the environmental impacts. A “cradle to grave” approach is used, and a sensitivity analysis is conducted to assess the reliability of the results.

Zhu et al. (2020) analyzed the dismantling and disposal processes of a spent LFP lithium-ion battery.

Accardo et al. (2021) evaluated a “cradle to grave” life cycle analysis of a NCM111 lithium-ion battery for application to electric light-duty commercial vehicles and compared the results with a sodium-nickel-chloride battery. The results show that the NCM111 battery has the highest impact from production in most of the impact categories, the situation is completely reversed in the use phase.

Iturrondobeitia et al. (2021) compared the life cycle analysis results of aprotic lithium oxygen batteries used in an electric vehicle with the environmental burdens of a reference lithium-ion battery, reference sodium-ion battery and the average value of lithium sulfur batteries considering the same capacity for all the batteries. The aim was to create a road map to enable the practical design of sustainable lithium oxygen batteries within a circular economy prospective.

Koroma et al. (2021) conducted a "cradle to grave" LCA of a lithium-ion battery pack focusing on the global warming potential reduction achievable with the recycling of the battery cells.

Rajaeifar et al. (2021) performed a comparison between two different pyrometallurgical technologies for the recovery of valuable metals from lithium-ion batteries (NCM111). Finding the analogies with results reported in literature was not an easy procedure because of factors that can differ across the studies, such as battery chemistry considered, modelling approach of the recycling process and recycling assumptions.

Rinne et al. (2021) investigated the environmental impact of hydrometallurgical battery recycling process using nickel metal hydride as a reductant for lithium-ion battery waste.

Benveniste et al. (2022) conducted a LCA of a lithium sulfur battery cell to compare it with a conventional lithium-ion battery (NCM) under the same driving distance. The environmental impact assessment results show that the lithium sulfur batteries present a most favorable environmental profile compared to NCM batteries.

Bhosale et al. (2022) compared the environmental impact of lithium-ion battery with lead acid battery with a "cradle to grave" life cycle approach and considering the same automotive application for both batteries.

Chordia et al. (2022) examined the effects of upscaling lithium-ion battery production, from small scale facility to large scale one, remodeling the work done by Ellingsen et al. (2014) for a NCM111 pouch cell into a NCM811 cylindrical cell. The aim was to demonstrate the emissions reduction achievable with the upscaling production.

Quan et al. (2022) quantified the environmental impacts of LFP and NCM batteries using the LCA approach evaluating, also, different recycling methods. The findings indicate that the NCM battery exhibits superior environmental performance compared to the LFP battery, although it possesses a shorter service life throughout the entire life cycle.

Guo et al. (2023) performed a comparison between the environmental impact of a sodium-ion battery with a LFP lithium-ion technology through LCA. The results show that LFP battery has higher environmental performance in the production stage, but NIB seems better in the long-term perspective.

Kim et al. (2023) reported the "cradle to gate" and use phase greenhouse gas emissions for a plug-in hybrid electric vehicle NCM622 battery showing that emissions during the manufacturing and use phase are comparable.

Philippot et al. (2023) evaluated the impact of the entire life cycle of a lithium nickel manganese cobalt oxide battery with a silicon-rich anode comparing it with the state-of-art graphite-based battery using primary data. The results show that considering the same cycle life, silicon-based battery has lower environmental impacts than a graphite-based one.

In summary, the majority of works regarding the LCA of lithium-ion batteries is related to a "cradle to grave" approach. Some reports consider a "cradle to gate" LCA only and few studies added the use phase. Furthermore, some papers that embrace the end-of-life stage in their analysis, consider only the possible recycling processes for the batteries without including quantitative data. *Table 2* provides a quantitative estimation of the documents including a specific stage of the life cycle assessment in their analysis.

It is important to highlight that most of the research are based on secondary data and previous literature information and, sometimes, data is not reported clearly, especially concerning the end-of-life phase which is often discussed primarily in a theoretical manner. A very small number of documents rely on primary data in their analysis.

Table 2-Quantification of the number of documents analyzing a specific LCA stage

LCA PHASE	**NUMBER OF DOCUMENTS**
Cradle to gate	8
Cradle to gate + use phase	2
Cradle to grave	17
EoL only	3

The wide range of LCA approaches used to study the environmental performance of Li-ion batteries for electric vehicles, the different functional unit and system boundaries selected, and battery lifetime assumptions make it challenging to compare the various studies.

Regarding the LCA of sodium-ion batteries applied to the automotive sector, a few numbers of papers are published due to the relative novelty of the technology.

In addition to the aforementioned work by Guo et al. (2023), it is advisable to give relevance to the study of Peters et al. (2016) which provide a life cycle assessment (“cradle to gate”) to produce a sodium-ion battery with a layered transition metal oxide as a positive electrode material and hard carbon as a negative electrode. The analysis results have been compared with existing studies regarding the environmental impacts of state-of-the-art LIBs.

4 LCA comparison of Na-ion and Li-ion batteries

The Catalonia Institute for Energy Research (IREC) is a research center dedicated to the analysis of the materials employed in various battery technologies and devising innovative solutions aimed at diminishing the utilization of critical raw materials.

The thesis is grounded in an ongoing project at IREC funded by the European Union, which revolves around the analysis and juxtaposition of Na-ion batteries and Li-ion batteries, with the prospective application of the former in sectors where Li-ion batteries currently exert influence in the market, such as electric mobility. The aim is finding a more sustainable battery technology with the use of waste to produce hard carbon. Indeed, the hard carbon, used as the active material in the sodium-ion battery anode, is derived from waste generated during wine production through a pyrolysis process. Further details will be provided in the dedicated chapter later on.

To achieve the objective, a life cycle assessment (LCA) has been conducted, evaluating the life cycle of the product using a “cradle to gate” approach, and opposing not only Na-ion battery against Li-ion one, but also various precursors of hard carbon. Specifically, the manufacturing phase has been analyzed with the aim of obtaining consistent results regarding the impact of different materials and various resources required to build the battery and how these factors influence the environmental impact of the battery pack in which they are utilized.

5 Na-ion vs Li-ion batteries: LCA methodology

Life Cycle Assessment (LCA) serves as a methodology for assessing the potential environmental impacts of a product, encompassing various phases of its life cycle, ranging from raw material acquisition and processing to manufacturing and eventual disposal. By pinpointing the pivotal phase within the product's life cycle that gives rise to the most significant impacts, companies can devise strategies to mitigate these effects.

In this thesis, the LCA case study adheres to international standards and is executed utilizing OpenLCA, an open-source and complimentary software dedicated to sustainability and Life Cycle Assessment. This software enables swift calculations employing an extensive repository of data.

5.1 Goal definition

The thesis case study focuses on two different battery technologies and evaluates each process "from cradle to gate" using the mentioned software. The aim is to identify the most critical technology from an environmental point of view and, for each battery, the components responsible for the main impacts with further suggestions to reduce them.

5.2 Functional unit

The term "functional unit" is used to describe the specific quantity of a product that is being evaluated in an LCA. The definition of the functional unit is a crucial process, utilizing an identical functional unit enables the establishment of pertinent juxtapositions among diverse products, facilitating the assessment of their relative environmental performance.

For energy-providing batteries such as electric vehicle batteries, the European Commission suggests using one kWh (kilowatt-hour) of the total energy provided over the service life by the battery system, which serves as a reference to compare the environmental impacts of the batteries analyzed.
The total energy (measured in kWh), commensurate with the defined functional unit, represents the entirety of electricity (in kWh) supplied by the battery throughout its operational lifespan. For the electric vehicles, this quantity of energy shall be calculated by multiplying the average amount of delivered energy over each cycle with the service life in cycles.

Nevertheless, for the purpose of the comparative analysis between two types of batteries, it has proven more advantageous to employ a unit of battery pack as the functional unit. Therefore, the results of the analysis will be referenced to one item.

5.3 System boundaries

The system boundaries define the extent of the chain being studied, depending on the way they are set; indirect consequences may not be included in the analysis.

The LCA conducted covers the steps involved in the production of the battery pack. The analysis starts with the manufactory step through the examination of each component of the battery pack, from the extraction of raw materials to the assembly of the battery cells and subsequent of the battery pack. The other steps usually included in a LCA regard the distribution to the final user, the collection, and the disposal of the battery pack and have been partially analyzed due to limitations in the data available. However, all the steps normally included in a LCA are explained in the following sections even if not all of them have been developed in the thesis.

5.3.1 Raw material acquisition and pre-processing

The phase of raw material acquisition and pre-processing encompasses the retrieval of natural resources and their initial processing until they are integrated into components utilized within the battery's manufacturing facility. This life-cycle stage should include the transportation of raw materials and intermediary goods between extraction and pre-processing sites up to the battery manufacturing plant and packaging production.

In the thesis, the information regarding this life cycle stage is assumed from the Environmental Footprint dataset for most of the materials.

5.3.2 Manufacturing

The manufacturing phase incorporates several components, involving the production of anode, cathode, electrolyte and separator, the assembly of cells, and the construction of battery pack which includes cells and electric/electronic elements. This phase accounts for energy consumption and emissions.

Starting from the data regarding the precursors and using OpenLCA, the different steps needed to arrive at the assembly of the battery pack were modelled.

5.3.3 Distribution

The distribution phase considers the transport of the battery from the manufacturing site to the final use site including the transport impacts associated to this stage.

5.3.4 Use phase

The use phase of a battery refers to the period during which the battery is actively employed to provide electrical power to the system. The discharge and charge of the battery are the two key processes occurring in this phase. The first one refers to the electrical energy released from the battery to power the connected device or system. Instead, the latter one regards the process of recharging the battery and requires external energy. The energy consumed during the use phase of the battery is defined by the energy losses due to the battery and charger efficiency during the whole life of the application (PEFCR, 2020).

To analyze the use phase, it is important to consider the number of charge and discharge cycles that occur over the battery's lifespan. The battery is considered no longer usable when it reaches 80% of its initial capacity.

5.3.5 End-of-life

The end-of-life (EoL) phase commences upon the disposal of the product within the defined scope and its associated packaging by the user. It concludes when the product within the specified scope is either returned to the environment as waste or becomes part of another product's life cycle.

This stage includes various activities, the main ones regard the disassembly of the battery pack in battery cells and not battery cells components, the transportation to dedicated recycling facilities, the disassembly of components, the processes of crushing and shredding, and the subsequent separation and conversion into recycled material. The input materials, energy requirements, emissions and products of the recycling procedure should be taken into account.

The items acquired through the recycling process are classified as secondary materials. Therefore, the advantages stemming from the reduction in the utilization of primary raw materials in further processes should be considered.

The main recycling processes for batteries are four: hydrometallurgical, pyrometallurgical, and intermediate and direct physical processes. The term “intermediate” indicates that the cathodic active material can be obtained from upgrading of process outputs. Instead, in a direct method the outputs can be incorporated into batteries with little or no additional processing (Dunn et al., 2012). The main recovered material is cobalt due to its high value.

The pyrometallurgical process can recover cobalt and nickel both, from batteries with a cobalt and nickel containing active material. The lithium enters in the slag, but it is not economical or energy efficient to recover it.

On the other hand, the other recycling processes can also recover lithium containing materials that must undergo further processing to regenerate useable active material.

5.4 Impact categories

During the Life Cycle Impact Assessment (LCIA) step of the LCA, the necessity of converting different emissions, each causing a similar impact, into a singular unit is manifested in the creation of a unified impact category.

Following European guidelines, various impact assessment methodologies can be applied. The Environmental Footprint (EF 3.0) method was used in this thesis.

According to the Product Environmental Footprint Category Rules (PEFCR, 2020) for high specific energy rechargeable batteries, and considering the Environmental Footprint impact assessment method, the LCA analysis shall include the impact categories reported in *table 3*. The level of robustness defined by the Joint research Center (2019) for each impact category is also included. The level I is recommended and satisfactory, the level II is recommended but it needs some improvements, and the level III is recommended but should be applied with caution.

Table 3-LCIA impact categories, unit measure and level of robustness

IMPACT CATEGORY	**UNIT**	**ROBUSTNESS**
Acidification	mol $H+_{eq}$	II
Climate change	kg $CO_{2\ eq}$	I
Ecotoxicity	CTUe	III
Eutrophication marine	kg N_{eq}	II
Eutrophication, freshwater	kg P_{eq}	II
Eutrophication, terrestrial	mol N_{eq}	II
Human toxicity	CTUh	III
Ionizing radiation	kBq U-235 $_{eq}$	II
Land use	Pt	III
Ozone depletion	kg CFC11 $_{eq}$	I
Particulate Matter	disease incidence	I
Photochemical ozone formation	kg NMVOC $_{eq}$	II
Resource use, fossils	MJ	III
Resource use, minerals and metals	kg Sb $_{eq}$	III
Water use	m^3 world $_{eq}$	III

According to PEFCR (2020), the most relevant impact category in the field of electric mobility is climate change followed by resource use. The life cycle stage that contributes the most to these impact categories is the raw material extraction. Furthermore, the production of the battery pack has a relevant impact regarding climate change and fossils resource use.

Therefore, more relevance will be given to these indicators in the results' analysis.

5.5 Assumptions and limitations

The thesis primarily relies on primary data collected from IREC, which is mainly associated with the manufacturing phase of the battery components. Certain assumptions have been made due to lack of data, typically concerning the production of precursor materials used in batteries. Moreover, for the battery cell scaling up (process explained in chapter 6), secondary data sourced from literature, particularly from prior life cycle analyses, have been employed.

In the manufacturing stage, assumptions have been made regarding the location of production of the different components of battery cells. The productive countries with the highest percentage of manufacturing of a certain material were considered. Considering sodium-ion and lithium-ion batteries, the latter one has the highest percentage of components produced outside Europe.

Instead, the assembly and distribution of battery pack was assumed to take place in Europe for both technologies.

Regarding energy consumption, for electricity it is assumed the grid mix at consumer (EU-28) as defined in the PEFCR (2020). For thermal heat consumption, the natural gas mix at the consumer level (EU-28) is assumed due to lack of precise information in the Environmental Footprint database.

The information related to transport is taken from literature and is based on the Ecoinvent database.

Therefore, it is crucial to acknowledge the limitations of the conducted study and the potential sources of uncertainty that could impact the outcomes. Taking these factors into account, all the assumptions made are clearly justified, rendering the study valuable for enhancing the product’s environmental performance.

6 Li-ion battery: Life cycle inventory

In the life cycle inventory, the raw materials and energy required and the emissions, wastes, and product generated are determined for each life cycle stage.

6.1 Manufacturing phase

The final product generated in the manufacturing phase is the battery pack.

6.1.1 Lithium-ion coin cell: Battery analysis in IREC

Within the Functional Nanomaterials division at IREC, scrutiny of battery materials occurs on a laboratory scale. Consequently, the data accessible pertains to what is commonly known as a coin cell.

An exemplification of the main components of a typical coin cell is depicted in *figure 4*, the assembly of half-cell is reported.

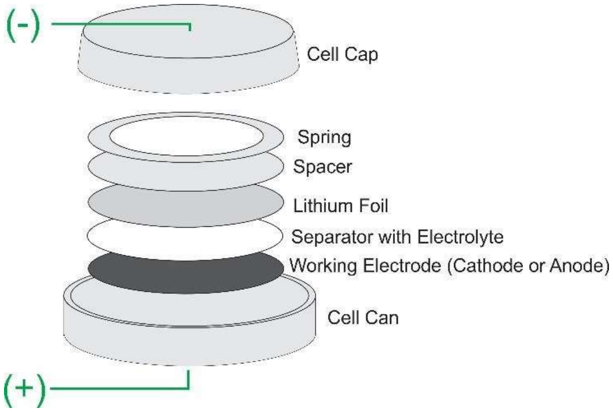

Figure 4- Main components of a coin cell (Luthfi et al., 2018)

Figure 5-Lithium-ion coin cell in IREC

The data related to the assembly of a lithium-ion coin cell obtained from IREC is reported in *table 4*.

Table 4-Quantity of components in Li-ion coin cell (IREC)

COMPONENT	MASS [mg]	WEIGHT PERCENTAGE [%]
Anode without collector	6.56	0.18
Anode collector	8.20	0.23
Cathode without collector	12.78	0.35
Cathode collector	6.39	0.18
Electrolyte	39	1.07
Separator	4.52	0.12
Steel casing	1700	46.79
PP gasket	99	2.73
Spacer	1590	43.77
Spring	167	4.60

The active material of the anode is graphite with a specific capacity of 340 mAh/g. Instead, NCM811 with a specific capacity of 188 mAh/g is used for the cathode.

The specific capacity of a battery cell is reasonably estimated to be equal to the specific capacity of the cathode.

The mass quantities of anode and cathode without collector are calculated knowing the loading (density of active material in the electrode) and the diameter of each electrode. The diameter of the cathode and anode may vary and is determined by ensuring that the capacities of the two electrodes are as similar as possible.

Starting from the density of each component it is also possible to determine the mass of collectors, electrolyte, and separator.

Regarding the casing, gasket, spacer and spring, the mass values are standard values valid for all the coin cells assembled in IREC.

This battery type is not employed on an industrial scale due to its limited performance. Thus, a scaling up process results essential to gather data for a battery that can be employed in the realm of electric mobility. Furthermore, the predominant contribution to the weight of coin cells originates from components like steel casing, gasket, spacer, and spring. These elements are exclusive to coin cells and therefore will not be taken into account during the scaling up of the battery cell.

Another distinctive aspect of coin cells is the surplus of electrolyte used in laboratory analyses, which does not mirror the actual quantities employed in electric vehicle applications.

Despite this, the same raw materials that constitute the coin cell components will be considered in the size-up process that is described in detail in chapter 6 section 1.2.

6.1.2 Size up procedure: from coin to pouch cell

The battery coin cell has been sized up to battery system that could be used in electric vehicles. In particular, a pouch cell has been chosen.

A pouch cell is constituted by a cathode, an anode, electrolyte, separator, and current collectors. Although the shape is quite similar to that of prismatic cells, the mass of the pouch cells is reduced due to the absence of any kind of metal enclosure. The pouch consists solely of a layer of plastic film coated with aluminum.

The process of transitioning from manufacturing coin cells to pouch cells involves several key steps regarding the changing in the shape of the cell and adjustments to electrode design, assembly methods and safety considerations.

The electrode size, shape and layout need to be adapted from a circular configuration to a rectangular one. Although it has been assumed that the majority percentage of materials used in the coin cell will not change during the size-up, it is necessary to consider a standard value of electrolyte commonly used in pouch cells for electric vehicles. Furthermore, considerations regarding size and packaging of the battery pack need to be made.

The data necessary to proceed with the size up are taken from the literature.

As the first step, an analysis related to a commercial pouch cell was considered. The pouch cell is used in a Volkswagen ID.3 electric vehicle and information is taken regarding the number of cells in a battery pack, the capacity and mass of the battery cells, and the percentage of the different components contained in a cell.

In *table 5*, some useful characteristics of Volkswagen's electric vehicle are summarized.

Table 5-Characteristics of the Volkswagen ID.3 battery (http://ev-database.org)

Nominal capacity [kWh]	55
Useable capacity [kWh]	45
Number of cells	192
Nominal voltage [V]	350
Total power [kW]	107
Energy consumption [Wh/km]	164
Distance [km]	275
Cell capacity [Ah]	78
Total mass of battery pack [kg]	350

The battery pack is constituted by 8 modules with configuration 12s2p in series (http://bauaelectric.com). From the parallel/series configuration it is possible to conclude that the capacity of each battery module is double of the one of a single battery cell and the capacity of the battery pack is equal to the capacity of each module.

Furthermore, an analysis conducted by Günter & Wassiliadis (2022) on a pouch cell employed in the aforementioned vehicle reveals the average cell mass and the weight percentage of the different components constituting the battery cell. The percentages are reported in *table 6* and it is assumed that the same ones can be used in the size up because of similarity in the materials employed in both cases.

Table 6-Mass percentage of the different components in a Li-ion pouch cell (Günter & Wassiliadis, 2022)

COMPONENT	**WEIGHT PERCENTAGE [%]**
Anode	37.8
Cathode	46.5
Separator	3.8
Electrolyte	7.1
Packaging	4.6
Tapes	0.2
Cell	100

Comparing the weight percentage of the components of coin cell (*table 4*) and pouch cell (*table 6*), it is possible to notice that, in proportion, a higher quantity of material for anode and cathode is used in the pouch cell and a corresponding lower percentage of electrolyte is found.

During the investigation, the pouch cell mass value is fixed, equal to 1101.4 g, according to the work of Günter & Wassiliadis (2022). Assuming that the specific capacity of the coin cell does not change during the size up, the capacity of the battery cell (expressed in Ah) obtained from the size up can be determined following the equation reported below:

$$cell\ capacity = specific\ capacity * mass$$

Using the specific capacity of the coin cell studied at IREC, a cell capacity of 207 Ah is obtained. This value is compared with the one provided in *table 5*. The significant difference between the two values can be explained by the fact that two distinct cathode active materials have been used in the two cases, resulting in different specific capacities: NCM811 in IREC (specific capacity 188 mAh/g), and NCM712 in the Volkswagen electric vehicle (specific capacity 71 mAh/g).

Furthermore, to conduct the analysis, it is asserted that the new battery pack is constituted by battery cells in series only, with the assumption that eight modules will be present, each of them formed by twelve battery cells.

The lower number of battery cells implies lower weight of the battery pack and subsequent, a lower quantity of materials needed for the assembly.

The weight of the battery pack is obtained from assumptions taken from bibliography, considering the following mass percentage in a battery pack: 80% battery cells, 14.5% casing and 5.5% BMS (Peters et al., 2016).

The results of the size up procedure are summarized in *table 7*.

Table 7-Size up's results for the Li-ion battery

Mass of a battery cell [kg]	1.11
Capacity of the cell [Ah]	207
Number of battery cells [-]	96
Mass of 96 battery cells [kg]	107
Mass of battery pack [kg]	133
Mass of casing [kg]	19
Mass of BMS [kg]	7

The analysis for each battery cell component is reported in detail in the upcoming sections of chapter 6. The data related to energy consumed, transport, and emissions and wastes produced are taken from the literature due to lack of data (Notter et al., 2010).

Except for the battery pack assembly, material transport is assumed to take place using a freight train (without fuel) with a payload capacity of 726 tons and articulated lorries with a payload capacity of 22 tons. For the transport of the battery pack materials, a transoceanic ship with a 27500-dwt payload capacity and the above-mentioned articulated lorries are considered.

6.1.3 Anode manufacturing

The anode of a battery is the electrode where oxidation reactions occur during the discharge of the battery.

In the lithium-ion battery cell considered, the anode is obtained from a mixture of styrene butadiene rubber (SBR), the binder, with a water-based solvent, black carbon, and graphite (the active material) in a ball mill to a slurry followed by coating of the collector with the slurry. No organic solvent is needed, and copper is used as current collector. Thermal heat energy is required to heat up the slurry to dry the coated anode through water evaporation.

The analysis results referred to 1 kg of anode are reported in *table 8*. The same constituents' weight percentage valid for the anode of the coin cell are assumed. The data related to the transport are supposed according to ecoinvent standards transport distance for inorganic chemicals and metals (Europe).

Furthermore, due to the limitation of data of the Environmental Footprint database, the graphite is substituted by the carbon black default dataset according to PEFCR (2020).

Table 8-Dataset for the production of 1 kg of anode (Li-ion battery)

	AMOUNT	**UNIT**
INPUT FLOW		
Carbon black	0.44	kg
SBR	$5*10^{-3}$	kg
Copper sheet	0.56	kg
De-ionized water	0.42	kg
Electricity (grid mix)	$2*10^{-3}$	kWh
Heat (natural gas)	1.22	MJ
Transport (articulated lorry)	113	kgkm
Transport (freight train)	470	kgkm
OUTPUT FLOW		
Anode	1	kg
Waste heat	$7*10^{-3}$	MJ
Wastewater	$1.1*10^{-4}$	m^3
Water evaporated	0.42	kg

6.1.4 Cathode manufacturing

The cathode of a battery is the electrode where reduction reactions take place. The flow of electrons, generated by the chemical reactions occurring at both electrodes, creates an electric circuit that can be used to power devices connected to the battery.

The battery considered is an NCM811 lithium-ion battery. Lithium Nickel Manganese Cobalt oxide batteries are characterized by the highest energy density after Lithium Nickel Cobalt Aluminum oxide ones. Therefore, the focus of research and innovation activities has shifted towards this technology after the launching of mass-market electric vehicles (Accardo et al., 2021). In NCM811 Li-ion batteries, the ratio between nickel, cobalt and manganese is 8:1:1. Nowadays, this technology is preferred to other NCM, such as NCM111, because of the lower amount of cobalt contained. Cobalt is a critical raw material because of limited supply and elevated cost compromising also the sustainability of the batteries containing it. Therefore, the cobalt content in batteries is being reduced in favor of nickel content.

The increment of nickel content increases the energy density and extends the life cycle of the battery cells. On the other hand, the battery cell has a slightly lower voltage than cobalt-based cells.

The NCM811 precursors include lithium carbonate, nickel sulphate, cobalt sulphate, and manganese sulphate.

The quantity of precursors necessary to obtain 1 kg of NCM811 is taken from the research work of Zang et al. (2020) regarding NCM333, considering the carbonate co-precipitation process and elaborating the data to make them suitable for the active material analyzed. In particular, a different proportion between the quantities of nickel sulphate, cobalt sulphate and manganese sulphate has been considered to make it realistic for NCM811, keeping invariant the lithium carbonate amount. Furthermore, all the data including the quantities of water and electricity consumed and carbon dioxide emitted are transformed to be suited for 1 kg of final product, considering that in the paper, taken as reference, the information are related to a mass daily flow rate. The results are shown in *table 9*.

Table 9-Dataset for the production of 1 kg of NCM811

	AMOUNT	**UNIT**
INPUT FLOW		
Lithium carbonate	0.4	kg
Nickel sulphate	1.47	kg
Manganese sulphate	0.16	kg
Cobalt sulphate	0.2	kg
Sodium hydroxide	1.27	kg
Electricity (grid mix)	3.76	kWh
Transport (freight train)	3223	kgkm
Transport (articulated lorry)	564	kgkm
OUTPUT FLOW		
NCM811	1	kg
Carbon dioxide (fossil)	3.64	kg
Waste heat	0.02	MJ

The process to generate the cathode is the same described above for the anode. The current collector is aluminum and the solvent used is 1-methyl-2-pyrrolidone (NMP).

The same hypothesis made for anode is assumed valid also for cathode and the results of the analysis to produce 1 kg of cathode are summarized in *table 10*.

Table 10-Dataset for the production of 1 kg of cathode (Li-ion battery)

	AMOUNT	UNIT
INPUT FLOW		
NCM811	0.63	kg
Carbon black	0.01	kg
SBR	$1.3*10^{-2}$	kg
Methyl pyrrolidone	$1.3*10^{-2}$	kg
Aluminum foil	0.33	kg
Electricity (grid mix)	$2*10^{-3}$	kWh
Heat (natural gas)	0.65	MJ
Transport (freight train)	758	kgkm
Transport (articulated lorry)	126	kgkm
OUTPUT FLOW		
Cathode	1	kg
Waste heat	$7*10^{-3}$	MJ

6.1.5 Current collectors manufacturing

The current collectors serve as conductive pathways that connect the electrodes of a battery to the external circuit, they are positioned on the surfaces of the electrodes providing a means for electrons to move between the electrodes and the external circuit.

The typical current collector material for the anode of a lithium-ion battery is copper foil. Instead, for the cathode is aluminum foil. Copper and aluminum current collectors are regarded as inactive materials because they do not contribute to the battery cell capacity (Wang et al., 2020).

The main concern regarding the current collectors revolves around the utilization of copper. Indeed, this substance qualifies as a critical raw material, necessitating considerable energy and water resources for its extraction, and entailing energy-intensive manufacturing procedures. Considering these factors, it is necessary to seek alternative solutions to mitigate the associated environmental impact.

6.1.6 Electrolyte manufacturing

The electrolyte of a battery is a substance that facilitates the movement of ions between the electrodes during the charging and discharging processes. Different types of electrolytes are available: aqueous, non-aqueous and solid-state. The choice of the electrolyte type impacts the characteristics, performance, and safety of a battery.

In the battery studied, the electrolyte chosen is based on $LiPF_6$, the most common salt used in lithium-ion batteries with non-aqueous electrolyte solution. $LiPF_6$ is dissolved in a solvent facilitating the movement of ions.

The synthesis of $LiPF_6$ involves reaction between lithium fluoride (LiF), phosphorus pentachloride (PCl_5) and hydrogen fluoride (HF). The data related to the production processes of the first two precursors, missed in the Environmental Footprint database, are taken from the work of Notter et al. (2010) and inserted in OpenLCA software.

The analysis to produce 1 kg of $LiPF_6$ is reported in *table 11*. The electric energy input is calculated for a heat pump with an assumed coefficient of performance of 1.5 and the transport is determined from the ecoinvent standards transport distance for inorganic chemicals and metals (Europe).

Table 11-Dataset for the production of 1 kg of LiPF6

	AMOUNT	**UNIT**
INPUT FLOW		
Lithium fluoride	0.2	kg
Phosphorus pentachloride	1.98	kg
Hydrogen fluoride	4.04	kg
Calcium hydroxide	7.44	kg
Nitrogen (liquid)	$1*10^{-3}$	kg
Electricity (grid mix)	0.54	kWh
Transport (freight train)	8190	kgkm
Transport (articulated lorry)	1370	kgkm
OUTPUT FLOW		
$LiPF_6$	1	kg
Waste heat	1.95	MJ
Landfill of inert material	8.61	kg

The electrolyte solution is immersed in a mixture of ethylene carbonate (EC) and dimethyl carbonate (DMC) of 30% and 70% in weight. These solvents are both organic and their combination creates a balanced electrolyte formulation.

The EC production needs ethylene oxide and carbon dioxide as input materials, as shown in *table 12* (Notter et al., 2010).

Table 12-Dataset for the production of 1 kg of ethylene carbonate

	AMOUNT	UNIT
INPUT FLOW		
Ethylene oxide	0.5	kg
Carbon dioxide (liquid)	0.51	kg
Electricity (grid mix)	$2*10^{-3}$	kWh
Heat (natural gas)	0.14	MJ
Transport (freight train)	351	kgkm
Transport (articulated lorry)	101	kgkm
OUTPUT FLOW		
EC	1	kg
Waste heat	$7*10^{-3}$	MJ
Carbon dioxide (fossil)	$5*10^{-3}$	kg
Ethylene oxide	$2.5*10^{-4}$	kg

On the other hand, to produce DMC, ethylene carbonate and methanol are required, and the dataset referred to 1 kg of final product, taken from the work of Peters et al. (2016), is reported in *table 13*.

Table 13-Dataset for the production of 1 kg of dimethyl carbonate

	AMOUNT	UNIT
INPUT FLOW		
Ethylene carbonate	0.98	kg
Methanol	0.71	kg
Electricity (grid mix)	$3*10^{-3}$	kWh
Heat (natural gas)	0.1	MJ
OUTPUT FLOW		
DMC	1	kg
Ethylene glycol	0.69	kg

6.1.7 Separator manufacturing

The separator primary function is to prevent the direct contact between the electrodes of the battery while allowing the flow of ions between them. Typically, separators are made from materials that are chemically stable, electrically non-conductive and with good ion permeability. The choice of the separator material is crucial for the performance, safety, and lifespan of the battery.

The separator material used in the battery analyzed at IREC is polypropylene (PP). Its main characteristics include chemical stability that prevents unwanted reactions in the battery, porous structure that allows the flow of ions, thermal resistance that contributes to the safety of the battery, affordability, and manufacturability.

The information needed to produce 1 kg of polypropylene is taken from literature (Notter et al., 2010) and reported in *table 14*. The assumptions made regard the similarity between polypropylene and polyethylene and between plastic foil and fiber.

Table 14-Dataset for the production of 1 kg of polypropylene

	AMOUNT	**UNIT**
INPUT FLOW		
Polypropylene fiber	0.35	kg
Electricity (grid mix)	$2*10^{-3}$	kWh
Heat (natural gas)	0.19	MJ
Transport (freight train)	525	kgkm
Transport (articulated lorry)	98.4	kgkm
OUTPUT FLOW		
Polypropylene	1	kg
Waste heat	$7*10^{-3}$	MJ

6.1.8 Battery cell manufacturing

A general scheme of a lithium-ion pouch cell assembly is reported in *figure 6*.

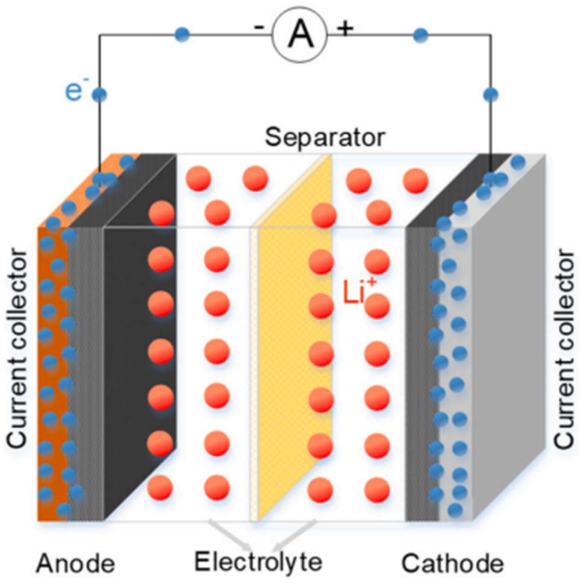

Figure 6-Scheme of a Li-ion pouch cell (Zhu et al., 2020)

In the software OpenLCA, the battery cell analysis refers to 1 kg of pouch cell. The quantity of the different components needed is taken from the study conducted by Günter & Wassiliadis (2022), considering the mass percentage reported in *table 6*.

A comprehensive procedure for creating a pouch cell generally encompasses the following stages: electrode cutting/trimming, electrode stacking, tab welding, pouch sealing, electrolyte injection, formation, and ultimate degassing and resealing (Dai & Cai, 2022).

The dataset regarding the production of 1 kg of battery cell is reported in *table 15*. Regarding the electrolyte, a typical composition consists of approximately 20% salt and 80% solvent. This ratio has been utilized in the case study and the work done by Notter et al. (2010) is used to obtain the data related to energy and transport.

Table 15-Dataset for the production of 1 kg of Li-ion battery cell

	AMOUNT	**UNIT**
INPUT FLOW		
Anode	0.38	kg
Cathode	0.47	kg
$LiPF_6$	0.01	kg
EC	0.02	kg
DMC	0.04	kg
Separator	0.04	kg
Polypropylene film	0.05	kg
Nitrogen (liquid)	0.01	kg
Electricity (grid mix)	0.14	kWh
Heat (natural gas)	0.07	MJ
Transport (freight train)	167	kgkm
Transport (articulated lorry)	27.8	kgkm
OUTPUT FLOW		
Battery cell	1	kg
Waste heat	0.38	MJ

6.1.9 Battery pack manufacturing

The battery pack of an electric vehicle is the component that stores and provides energy for the car. The modelling of a battery pack is the final aim of the manufacturing step.

The battery pack's structure employed for the Volkswagen ID.3 electric vehicle is schematized in *figure 7*.

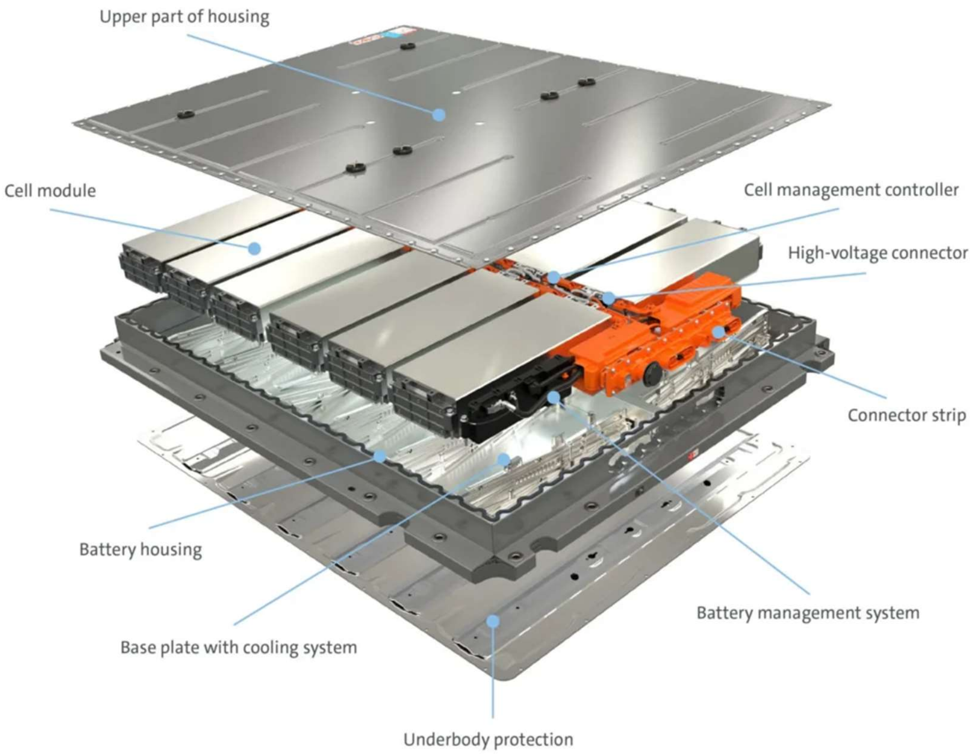

Figure 7- Volkswagen ID.3 battery pack (http://bauaelectric.com)

The main components considered in the analysis include the battery cells, the battery management system (BMS) and cables, and the housing. The BMS is a crucial component because it monitors and manages the battery cells, preventing overcharging and undercharging. The materials considered for the casing are plastic and steel with a mass composition of 20% and 80%, respectively.

Considering the analysis to obtain the number of cells composing the battery pack and the mass percentage of the different components in a battery pack, described in the section 6.1.2, it is possible to determine the total weight of the battery pack and subsequent, the mass of each component constituting it.

In the software OpenLCA, the dataset is created for one unit of battery pack. Unlike the various components, the assembly of the battery pack is anticipated to occur in Europe and the quantity of electricity required for the final assembly of the battery is calculated multiplying the total mass of the battery pack for the specific energy use reported in the study of Yuan et al. (2017).

The battery management system (BMS) used in the lithium-ion battery can be reasonably considered equal to the one analyzed by Peters et al. (2016) for a sodium-ion battery and the same dataset is assumed valid. Furthermore, since the printed wiring board (PWB) quantity is given in mass unit but in the Environmental Footprint database this data is expressed in squared meters, the average density, and dimensions of PWB are considered. The area of PWB is assumed to be equal to 0.5m x 0.6m (Nassajfar, 2021).

The analysis referred to 1 kg of BMS is reported in *table 16*.

Table 16-Dataset for the production of 1 kg of battery managment system

	AMOUNT	UNIT
INPUT FLOW		
Printed wiring board (SMD Pb-free)	0.3	m^2
Cable 3-core	7.11	m
Transport (freight train)	563.74	kgkm
Transport (articulated lorry)	93.98	kgkm
OUTPUT FLOW		
BMS	1	kg

Notter et al. (2010) provide information related to the transport of a lithium-ion battery pack, these data are assumed valid also in this analysis. The inputs and outputs data needed for the assembly of a battery pack are summarized in *table 17*.

Table 17-Dataset for the production of 1 item of Li-ion battery pack

	AMOUNT	UNIT
INPUT FLOW		
Battery cell	107	kg
PP film	3.8	kg
BMS	7	kg
Steel	15.2	kg
Transport (transoceanic ship)	7810	kgkm
Transport (articulated lorry)	1020	kgkm
Electricity (grid mix)	3.99	kWh
OUTPUT FLOW		
Battery pack	1	item
Waste heat	14.36	MJ

6.2 Use phase

The intended application of the battery pack pertains to an electric vehicle. However, the data necessary to model this phase are not completely available, and making assumptions would be a compelled process particularly because of the relative novelty of the field of study. There is a dearth of prior research examining the use phase of NCM811 battery pack. In an upcoming chapter, this LCA step will be compared with the sodium-ion battery one, with a focus on a theoretical assessment of the differences in their respective lifespans.

6.3 End of life

The end-of-life phase for batteries is still in its early stage, the European Parliament has recently published the "Regulation of the European Parliament and of the council concerning batteries and waste batteries" (2023). This new regulation is aimed at ensuring that batteries have a low carbon footprint, contain fewer harmful substances, need fewer raw materials from non-EU countries, and are collected, reused, and recycled to a high degree within Europe.

Under this regulation, there will be declaration requirements, the establishment of performance classes and implementation of maximum limits on the carbon footprint of electric vehicles by 2025. Additionally, in the same year, gradual targets will be introduced for recycling efficiency, material recovery and recycled content; particularly related to critical raw materials, such as cobalt, lithium and nickel, abundant materials in the lithium-ion batteries.

Given the novelty of this topic, modelling the end-of-life stage in the OpenLCA software would require numerous assumptions. Therefore, it has been decided to limit the analysis reporting only the recycling percentage, concerning electric vehicles, imposed by the European Commission in the Battery Regulation aforementioned.

Regarding the lithium-based batteries, 65% of the average weight of the battery should be recycled by 2025 and, no later than December 2030, this percentage should reach 70%. Before recycling, the treatment shall include removal of all fluids and acids, the waste batteries shall be stored in treatment facilities in such a way that they are not mixed with waste from conductive or combustible materials and special precautions and safety measures shall be included (European Parliament & Council of the European Union, 2023).

The materials recovery targets from the recycling processes at the end of 2027 and at the end of 2031 are mentioned in *table 18* and *table 19*, respectively.

Table 18-Materials recovery targets in 2027

MATERIAL	**RECOVERY [%]**
Cobalt	90
Copper	90
Lead	90
Lithium	50
Nickel	90

Table 19-Materials recovery targets in 2031

MATERIAL	RECOVERY [%]
Cobalt	95
Copper	95
Lead	95
Lithium	80
Nickel	95

The minimum percentage of secondary materials present in electric vehicle batteries that have been recovered from waste in 2031 and in 2036 are reported in *table 20* and *table 21*, respectively.

Table 20-Secondary materials' content in batteries in 2031

SECONDARY MATERIAL	CONTENT [%]
Cobalt	16
Lead	85
Lithium	6
Nickel	6

Table 21-Secondary materials' content in batteries in 2036

SECONDARY MATERIAL	CONTENT [%]
Cobalt	26
Lead	85
Lithium	12
Nickel	15

From the information provided by the European Commission, it is evident how significant recycling and reutilization of cobalt are, among the raw materials used in lithium-ion batteries, while the percentages associated with lithium are considerably lower, despite not being negligible.

6.4 Life Cycle Impact Assessment method

The product system related to the lithium-ion battery pack analyzed has been generated in the OpenLCA software using the Environmental Footprint database. The Environmental Footprint Mid-point indicator has been used as the impact assessment method. The LCIA results represent potential impacts and can be used to identify areas for improvements in the life cycle of the battery, even if they cannot be used to predict actual impacts, safety margins, or risks.

The results related to the impact categories are reported in *table 22*, including the normalization and weighting steps, using the product environmental footprint standard, and considering a person as single score unit.

Table 22-Impact category results for lithium-ion battery pack

IMPACT CATEGORY	REFERENCE UNIT	RESULT	NORMALIZED	WEIGHTED
Acidification	mol $H+_{eq}$	66.37	1.2	0.08
Climate change	kg $CO_{2\ eq}$	880	0.11	0.03
Climate change-Biogenic	kg $CO_{2\ eq}$	1.34		
Climate change-Fossil	kg $CO_{2\ eq}$	879		
Climate change-Land use and land use change	kg $CO_{2\ eq}$	0.26		
Ecotoxicity, freshwater	CTUe	2457	0.21	0
Eutrophication marine	kg N_{eq}	1.1	0.04	$1*10^{-3}$
Eutrophication, freshwater	kg P_{eq}	0.63	0.25	$7*10^{-3}$
Eutrophication, terrestrial	mol N_{eq}	12.13	0.07	$3*10^{-3}$
Human toxicity, cancer	CTUh	$3.02*10^{-5}$	0.78	0
Human toxicity, non-cancer	CTUh	$1.63*10^{-4}$	0.34	0
Ionising radiation, human health	kBq U-235 $_{eq}$	71.220	0.02	$1*10^{-3}$
Land use	Pt	4090	$3*10^{-3}$	$2.59*10^{-4}$
Ozone depletion	kg CFC11 $_{eq}$	$3.15*10^{-5}$	$1*10^{-3}$	$9.1*10^{-5}$
Particulate Matter	disease incidence	$1.43*10^{-4}$	0.22	0.02
Photochemical ozone formation - human health	kg NMVOC $_{eq}$	6.63	0.16	$8*10^{-3}$
Resource use, fossils	MJ	11779	0.18	0.02
Resource use, minerals and metals	kg Sb $_{eq}$	0.03	0.53	0.04
Water use	m^3 world $_{eq}$	395	0.03	$3*10^{-3}$

The most impacting processes regard the production of nickel sulphate and cobalt. Analyzing the top five contributions to impact category results, it is possible to notice that the nickel sulphate production has the highest impact in the acidification, ecotoxicity, eutrophication, human toxicity (non-cancer), land use, particulate matter emission, photochemical ozone formation and in minerals and metals use. Instead, cobalt production is the process that mainly contributes to human toxicity (cancer), ozone depletion, and water and fossils resources use. The two materials have a similar contribution in the climate change category. Regarding the ionizing radiation, the cobalt production and electricity grid mix have the main impact values.

Other relevant processes in terms of environmental impact concern the use of graphite in the anode and the production of the materials used for the assembly of the battery pack and the electricity. These components mainly affect the use of resources.

However, the main impacts contribution in the production of the battery pack is given by the battery cells. Analyzing the battery cell in detail, the most impacting element is the cathode, and the highest contributions regard the production of the cathode active material. Instead, the most impacting processes regarding the anode are the copper current collector and active material production. The other battery cell component with a relevant contribution is the electrolyte, which main impact is linked to the precursors production.

Furthermore, the production of the battery management system has a not negligible impact regarding the use of resources. In particular, the three-phase system of cables is the main contributor to the impact of this battery pack component.

The transport seems to have negligible impacts, only the transoceanic ship has a limited contribution in the categories of particulate matter, resource use and photochemical ozone formation.

In summary, the impacts of the different battery components for the production of 1 kg of battery cell are reported in *figure 8*. For each indicator, the result related to the battery cell is set to 100% and the results of the other variants are displayed in relation to this result. The category "other parts" include the energy, nitrogen liquid and transport necessary for the battery cell creation. For simplicity, only the most relevant impact categories are reported, in reference to chapter 5 section 4.

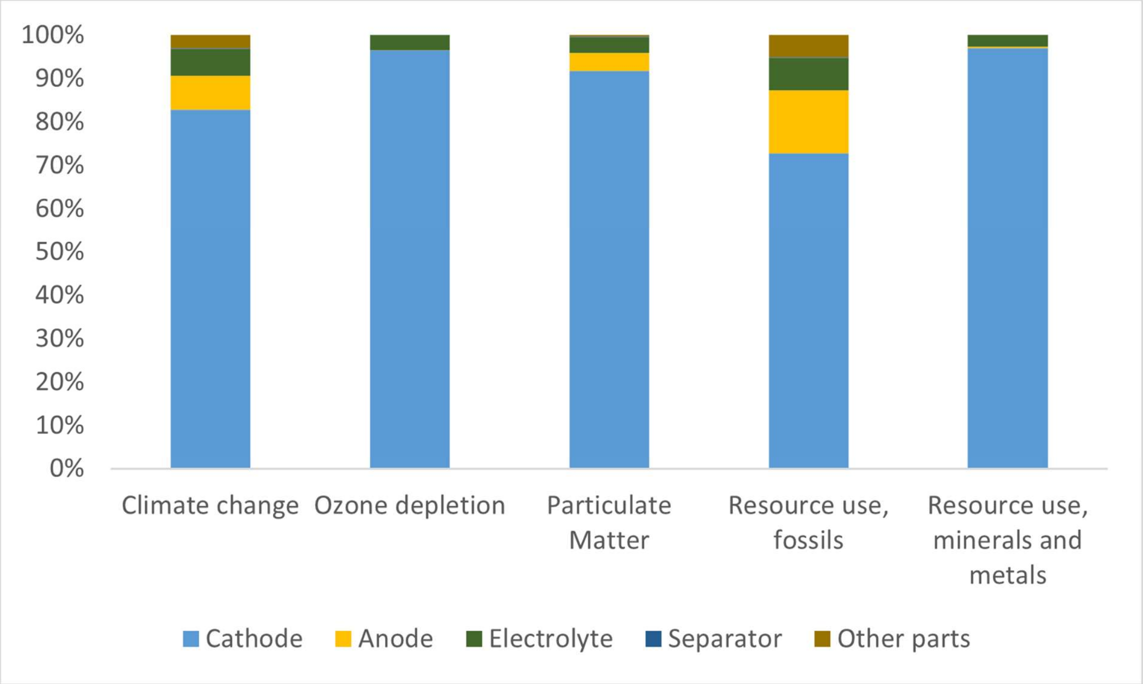

Figure 8-Impact contribution of the different components constituting a Li-ion battery cell

One potential solution to reduce the impact of this type of cells would involve reducing the use of cobalt and nickel in the battery cathode or their complete replacement, as it has been observed that they are the elements with the highest environmental impact. In Chapter 8, this cathode will be compared to the one used in sodium-ion batteries, which is free of cobalt and nickel, in order to determine how the environmental impact may change.

The relative contribution of battery cells, BMS and other parts (including packaging, electricity and transport) to the impact of the battery pack is reported in *figure 9*. In chapter 8, these results will be compared with the ones of the sodium-ion battery pack to analyze the differences in the impact of non-cell components.

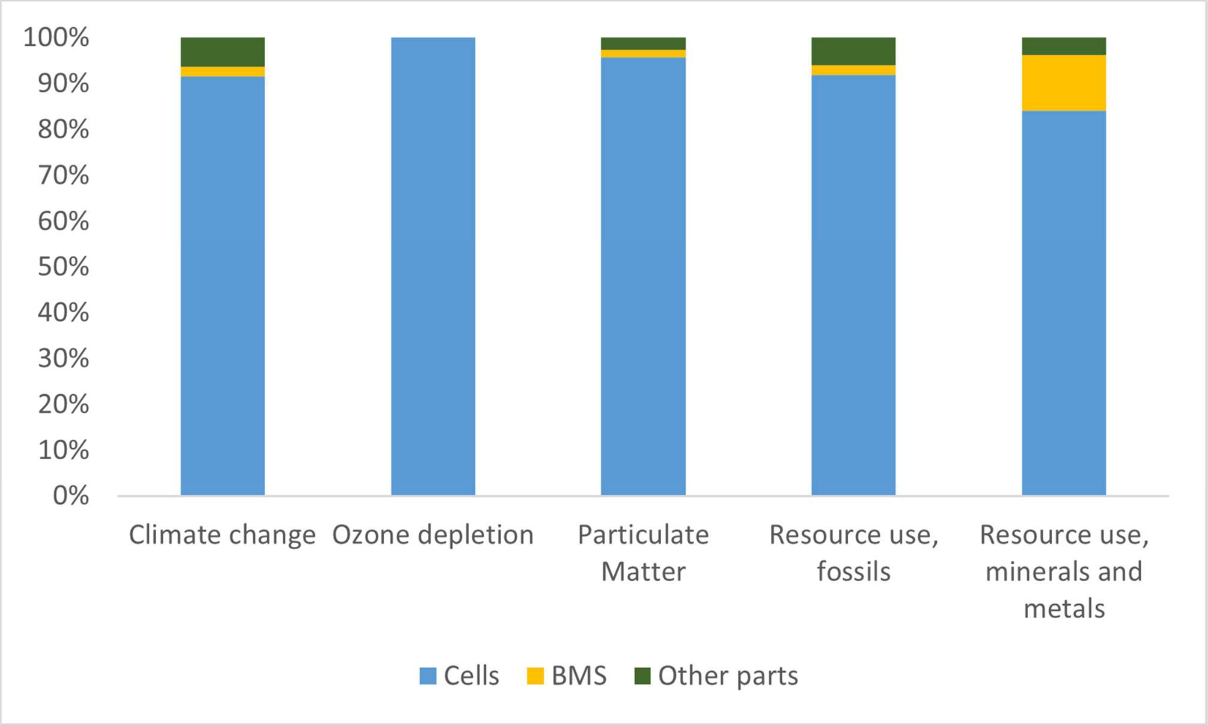

Figure 9-Relative contribution of battery cells and BMS to the impact of Li-ion battery pack

6.5 Cost analysis

A cost analysis is conducted to determine the overall cost of the battery pack and the components most relevant in the cost calculation process.

Managing a cost analysis for a battery is not a straightforward task. Indeed, among other factors, it is necessary to take into consideration price fluctuations and the geographical location where raw materials are extracted, components are manufactured, and the battery is assembled. For this reason, a qualitative analysis has been carried out in this thesis with the primary aim of comparing the cost of lithium-ion batteries with that of sodium-ion batteries in relation to the cost of materials used in these technologies. Therefore, the costs related to the energy used and transportation have not been taken into account.

The specific prices of the different materials involved in the creation of a battery cell are taken from literature (Nelson et al., 2018) and reported in *table 23*. The average worldwide price in 2022 is used for polypropylene (http://www.statista.com) and N-methyl-2-Pyrrolidone (http://www.researchandmarkets.com), the price index is utilized for black carbon (http://www.businessanalytiq.com) and also the nitrogen liquid price is assumed from a website (http://www.procurement.uark.edu).

Table 23-Specific prices of the components constituting a Li-ion battery cell

COMPONENT	PRICE [$/kg]
ANODE	
Graphite	15
Binder	10
Black carbon	1.7
Copper sheet	25
CATHODE	
NCM811	26
Binder	10
Black carbon	1.7
Methyl pyrrolidone	2
Aluminum foil	15
ELECTROLYTE	
$LiPF_6$ + solvent	18
SEPARATOR	
Polypropylene	1.13
CELL MANUFACTURING	
Polypropylene	1.13
Nitrogen liquid	2.5

Considering the amount of each component present in 1 kg of cell, it is possible to determine a specific price of 19 $/kg for each battery cell.

The specific prices of the non-cell materials constituting the battery pack are summarized in *table 24*. The specific price of BMS (http://www.element-energy.co.uk) and steel cold rolled (http://www.mepsinternational.com) are considered.

Table 24-Specific prices of the non-cell components constituting a battery pack

COMPONENT	PRICE [$/kg]
BMS	185
Steel cold rolled	1.12
Polypropylene	1.13

In conclusion, considering the quantity of each component necessary to produce an item of battery pack and contemplating the qualitative nature of the cost analysis reported, it is possible to determine that the price of the lithium-ion battery pack, based only on the materials employed, is equal to 3360 $.

7 Na-ion battery: Life cycle inventory

A battery pack with the same capacity of the lithium-ion one is assumed for the sodium-ion technology.

7.1 Manufacturing phase

As in the previous case, the final product generated in the manufacturing phase is the battery pack.

7.1.1 Sodium-ion coin cell: Battery analysis in IREC

In the Catalonia Institute for Energy Research, the same components that constitute the lithium-ion coin cell are used to create the sodium-ion coin cell but with different mass percentage of the different elements as reported in *table 25*.

Table 25-Quantity of components in Na-ion coin cell (IREC)

COMPONENT	MASS [mg]	WEIGHT PERCENTAGE [%]
Anode without collector	5.78	0.16
Anode collector	4.69	0.13
Cathode without collector	24	0.65
Cathode collector	6.39	0.17
Electrolyte	73.20	1.99
Separator	4.52	0.12
Steel casing	1700	46.27
PP gasket	99	2.69
Spacer	1590	43.27
Spring	167	4.55

The active material of the anode is hard carbon with a specific capacity of 386 mAh/g. Instead, $Na_{0.7}MnO_2$ is the active material of the cathode and the specific capacity is 100 mAh/g.

In general, taking the same assumptions of the case of lithium-ion, the specific capacity of the sodium-ion coin cell is slightly lower than the one of lithium-ion cell. Consequently, assuming the same capacity of both battery cells, the sodium-ion cell will have a higher mass value than the lithium-ion one.

Also in this case, the scale up to pouch cell is necessary and the same procedure of the lithium-ion battery has been applied.

The size up procedure of the sodium-ion battery is based on the assumption that the capacity of the cell is the same as the lithium-ion one in order to simplify the further comparison process.

The results of the size up procedure are summarized in *table 26* taking weight percentage information from the work of Peters et al. (2016). It is possible to notice that the battery pack mass is greater than the lithium-ion one so, a higher mass of BMS and casing is needed.

Table 26-Size up's results for the Na-ion battery

Capacity of the cell [Ah]	207
Mass of a battery cell [kg]	2.07
Number of battery cells [-]	96
Mass of 96 battery cells [kg]	198
Mass of battery pack [kg]	248
Mass of casing [kg]	36
Mass of BMS [kg]	14

The analysis of each battery component is reported in detail in the upcoming sections. Due to lack of data, most of the information required is taken from literature as in the case of lithium-ion battery.

7.1.2 Hard carbon production

The hard carbon is a suitable active material for the anode of sodium-ion batteries. The precursors of this component are mainly derived by a variety of organics or biomass that is thermally treated through a pyrolysis process. The hard carbon structure will vary depending on the main components of the biomass precursor material (cellulose, lignin, hemicellulose). The presence of inorganic impurities is another factor that significantly affects the performance of the resulting hard carbon.

The biomass precursors can be of three types:

- Raw biomass used directly in the production of hard carbon after harvesting. These materials require a huge number of pre-treatment steps to become suitable hard carbon precursor materials.
- Biomass by-product derived from food or material processing. An abundant source of biomass waste materials comes from the agricultural field.
- Biochar that has the advantage of high carbon efficiency.

Overall, biomass by-products originating from agroforestry and biochar coming from bio-refineries are proven to make high quality hard carbon materials (Jin et al., 2023).

In the sodium-ion battery analyzed in IREC, the hard carbon is obtained from grapes waste coming from the wine production and further information will be provided in the dedicated section.

Furthermore, the LCA is conducted for other two possible hard carbon precursors to analyze the differences in environmental impacts correlated to the yield of the hard carbon's source. The two alternatives considered regard the use of wastes coming from the production of beer and the petroleum coke that is the most common fossil precursor to produce hard carbon.

7.1.2.1 Hard carbon from winery waste

The hard carbon used in the anode of sodium-ion batteries analyzed in IREC derived from grape wastes obtained at the end of the wine production process.

The wastes are taken from a winery located in a central region of Spain at an average distance of 50 km from Barcelona, where the research center is situated. The company produces white, rose, red, sweet, and sparkling wine. The harvesting period starts at the beginning of August and lasts until the middle of September. Last year, the earliest harvest was registered due to dry weather and high temperatures (http://www.llopart.com).

Spain has more than 1.2 million hectares planted in wine grapes, making it the most widely planted wine-production nation (http://en.wikipedia.org/Spanish_wine). The climatic condition of the Country is favorable to the production of good quality wine because of the altitude of mountain vineyards, surrounded by Mediterranean forest that provides a good contrast between day and night temperature, optimal for the grapes.

Using "Water to Food" open-source software, it is possible to visualize the great relevance of Spain in the wine production and export. In fact, referring to the last year for which data are available (2016), the country is a kindly worldwide exporter, as shown in *figure 10*. The net importer countries from Spain are reported in green and the net exporter countries from Spain are in orange instead, Spain is highlighted in a dark color because is the country selected for the analysis.

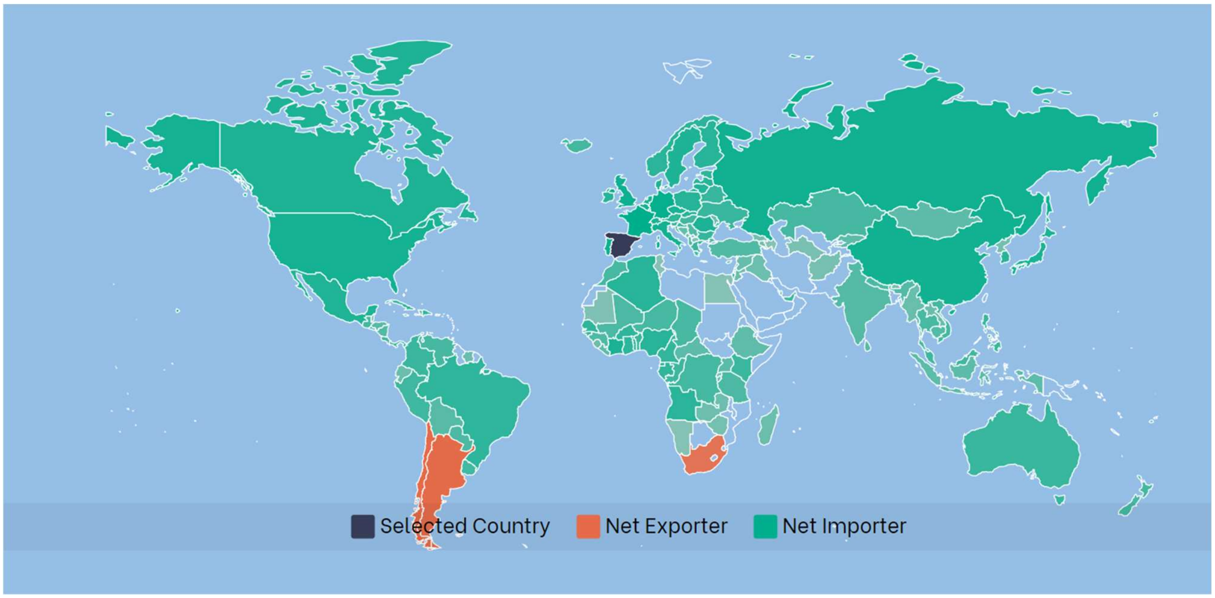

Figure 10-Net export/import of wine from Spain (http://www.watertofood.org)

The relevance of Spain in the wine production sector has brought forth the need to manage the substantial quantity of waste generated during the grapes transformation process.

The wastes of the wine making process primarily include pomace, stems and yeast. A very little amount of these materials is used for fertilization, animal feed, or generation of other products after proper treatments.

The pomace derives from the pressing of grapes during the production of must and includes grape skin, seeds, and stalks as shown in *figure 11*. Generally, the skin represents 45% of the mass of the pomace, stalks are 25% and the remaining quantity is depicted by seeds (Spinei and Oroian, 2021). Another important waste that is generated from the process of fermentation until the bottling is the wastewater that should be properly treated.

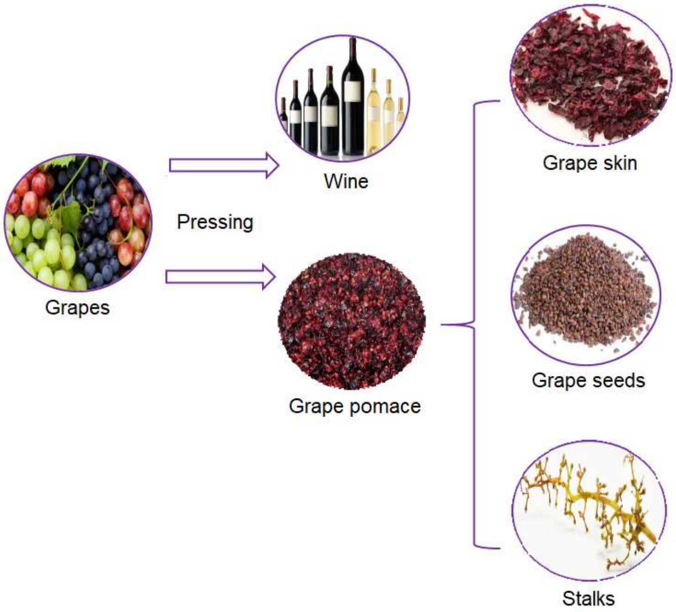

Figure 11-Pomace composition (Spinei and Oroian, 2021)

The main aim for these wastes is their use as raw materials in remarkable processes. Some studies have been done related to the use of these wastes for soil fertility but the application in batteries is a totally new field of study.

The winery wastes are rich in lignin, cellulose and hemicellulose making them suitable to produce hard carbon. In particular, the composition of the wastes analyzed at IREC is reported in *table 27*.

Table 27-Composition of grape waste analyzed at IREC

COMPONENT	**AMOUNT [%]**
Cellulose	20
Hemicellulose	35
Lignin	35
Others*	10

*Protein, oils

For the analysis, the quantity of fixed carbon is important. The fixed carbon is the amount of non-volatile carbon that remains in the sample after the pyrolysis process and its quantity is determined with a proximate analysis, a method of analyzing the physical properties of a material in terms of ash, moisture, volatile matter, and fixed carbon.

The quantity of fixed carbon is around 25% in weight for the grape wastes analyzed in IREC. For simplicity, it is assumed that 100% of the fixed carbon can be transformed into hard carbon and the inputs data required to produce 1 kg of hard carbon are taken from the study conducted by Peters et al. (2019). In particular, considering the amount of fixed carbon contained in sugar (10%) and coconut shells (20%), a proportion has been done to obtain the quantity of electricity, heat, nitrogen and water necessary for the production of hard carbon from grape waste.

The dataset for the production of 1 kg of hard carbon derived from grape waste is reported in *table 28*. The transport is considered negligible considering the location of the waste source.

Table 28-Dataset for the production of 1 kg of hard carbon from winery waste

	AMOUNT	**UNIT**
INPUT FLOW		
Grape waste	4	kg
De-ionized water	$9*10^{-5}$	m^3
Electricity (grid mix)	0.02	kWh
Heat (natural gas)	2.35	MJ
Nitrogen liquid	1.70	kg
OUTPUT FLOW		
Hard carbon	1	kg
Waste heat	2.42	MJ

7.1.2.2 Hard carbon from petroleum coke

The dataset for the production of 1 kg of hard carbon from petroleum coke is reported in *table 29*. The information stems from the work carried out by Peters et al. (2016). The yields and energy demand are estimated for a green petroleum coke with an overall 89% of carbon content assuming that 100% of the fixed carbon content is converted into hard carbon. The de-ionized water amount is taken from the study of Peters et al. (2019).

Table 29-Dataset for the production of 1 kg of hard carbon from petroleum coke

	AMOUNT	**UNIT**
INPUT FLOW		
Petroleum coke	1.140	kg
De-ionized water	$1*10^{-5}$	m^3
Electricity (grid mix)	0.018	kWh
Heat (natural gas)	1.89	MJ
Transport (freight train)	777	kgkm
Transport (articulated lorry)	159	kgkm
Nitrogen liquid	0.9	kg
OUTPUT FLOW		
Hard carbon	1	kg
Carbon dioxide (fossil)	0.083	kg
Waste heat	1.95	MJ

7.1.2.3 Hard carbon from brewery waste

One of the aims of the thesis is to compare grape waste with another bio-waste already studied for battery applications and the study conducted by Magar et al. (2023) has been considered remarkable for this purpose. The decision to analyze the waste generated from the beer manufacturing process has been driven by both the desire to compare waste from similar processes, the production of an alcoholic beverage, and the significance of Spain in the beer fabrication process.

The importance of Spain in the production of beer of Barley is understandable from *figure 12* that is exemplificative of the situation in 2016.

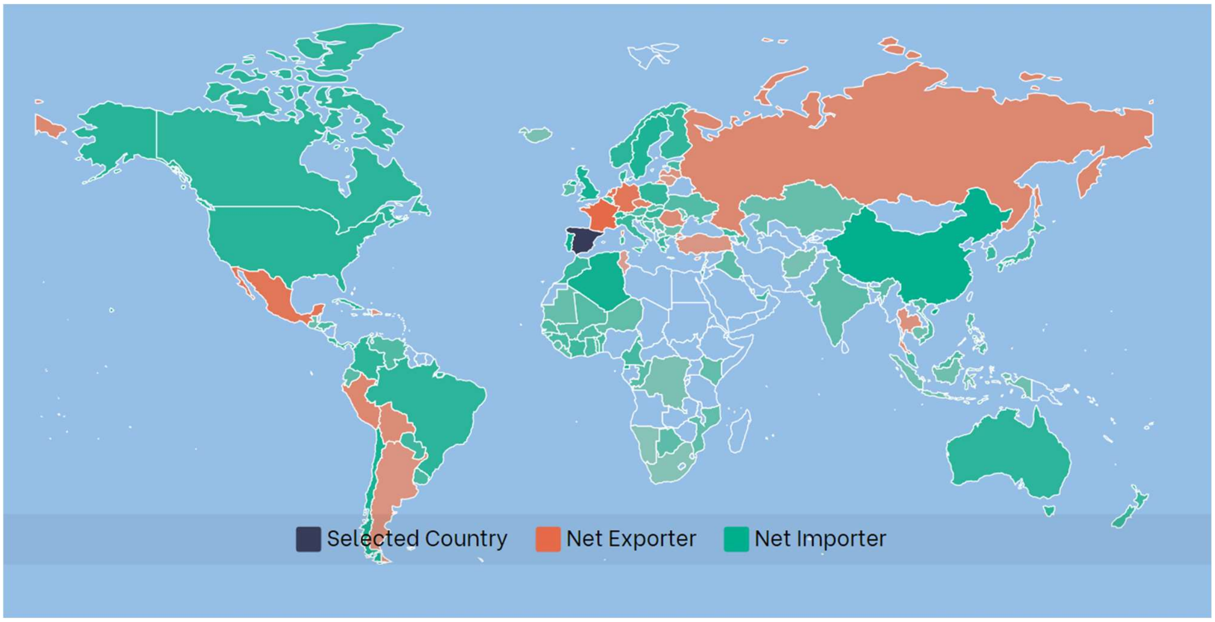

Figure 12-Net export/import of beer from Spain (http://watertofood.org)

The brewer's spent grain (BSG) is the major by-product generated from the brewery industry, accounting for 85% of the total waste generated (Borel et al., 2018). The reuse of these residues should be carefully planned considering the huge quantity of beer produced worldwide, estimated to increase in the future.

BSG is a lignocellulosic fibrous material, which composition depends on the species of barley and the process conducted to obtain the final product.

The composition of the waste considered is taken from the work carried out by Borel et al. (2018), obtaining a percentage in mass of fixed carbon of 10%.

The dataset for the production of 1 kg of hard carbon from brewer's spent grains is referred to the research conducted by Peters et al. (2019), considering the same procedure applied for the hard carbon obtained from winery waste described in chapter 7 section 1.2.1. The results are reported in *table 30*.

Table 30-Dataset for the production of 1 kg of hard carbon from brewery waste

	AMOUNT	UNIT
INPUT FLOW		
BSG	11	kg
De-ionized water	$1*10^{-4}$	m^3
Electricity (grid mix)	0.06	kWh
Heat (natural gas)	5.23	MJ
Nitrogen liquid	3.84	kg
OUTPUT FLOW		
Hard carbon	1	kg
Waste heat	5.61	MJ

7.1.3 Anode manufacturing

The anode of the sodium-ion battery considered is obtained from a mixture of styrene butadiene rubber with a water-based solvent, black carbon, and hard carbon.

In addition to the anode active material, another relevant difference compared to lithium-ion batteries is the possibility of using aluminum as the current collector for the anode, which results in a reduction in the manufacturing costs of this battery type.

The mass percentage of the components constituting the anode is assumed to be the same of the sodium-ion coin cell. Due to lack of data, the information related to the transport, and electricity and heat use are taken from the work of Peters et al. (2016) considering the similarity between the study and the analysis conducted in this thesis. The results for 1 kg of anode obtained after the scale up procedure are reported in *table 31*. The analysis is conducted three times changing the hard carbon precursor.

Table 31-Dataset for the production of 1 kg of anode (Na-ion battery)

	AMOUNT	UNIT
INPUT FLOW		
Hard carbon	0.53	kg
Carbon black	0.02	kg
De-ionized water	0.35	kg
SBR	$6*10^{-3}$	kg
Aluminium foil	0.45	kg
Electricity (grid mix)	$2.06*10^{-6}$	kWh
Heat (natural gas)	1.11	MJ
Transport (freight train)	57.7	kgkm
Transport (articulated lorry)	18.8	kgkm
OUTPUT FLOW		
Anode	1	kg
Waste heat	1.12	MJ
Water vapour	0.35	kg

7.1.4 Cathode manufacturing

The cathode of the sodium-ion battery considered is based on $Na_{0.7}MnO_2$, a Mn-based layered oxide cathode material studied for the abundance and the cheapness of manganese.

The $Na_{0.7}MnO_2$ is obtained by chemical reaction between sodium carbonate and manganese oxide with emission of carbonate dioxide.

The precursors quantities of the active material are obtained from the chemical reaction, doing the proper chemical balance, and using the molar weight of the different components in the calculation. A summary of the data necessary to produce 1 kg of active material is reported in *table 32*.

In the production of $Na_{0.7}MnO_2$, it is necessary to include the boric oxide that is not present as flow in the Environmental Footprint dataset. The boric oxide can be obtained by dehydration of the boric acid with a molar proportion of 2:1, the boric acid mass quantity is determined with a proportion starting from the molar ratio and the molar weight of the components and it is inserted in the software analysis. This reaction produces 3 moles of water that are included in the output.

The sodium carbonate is modelled as soda (Peters et al., 2016).

Furthermore, the manganese oxide production should also be modelled, and the data are taken from the work conducted by Notter et al. (2010).

The information related to transport, electricity and heat reported by Peters et al. (2016) is considered valid for this analysis, with the hypothesis that layered oxide cathode production can be assumed slightly similar in terms of consumptions.

Table 32-Dataset for the production of 1 kg of Na0.7MnO2

	AMOUNT	UNIT
INPUT FLOW		
Boric acid	0.12	kg
Mn_2O_3	0.75	kg
Soda	0.35	kg
Electricity (grid mix)	0.03	kWh
Heat (natural gas)	10.6	MJ
Transport (freight train)	817	kgkm
Transport (articulated lorry)	136	kgkm
OUTPUT FLOW		
$Na_{0.7}MnO_2$	1	kg
Waste heat	10.71	MJ
Water vapour	0.05	kg

The process to generate the cathode is the same described for the anode above. The current collector is aluminum and the solvent used is 1-methyl-2-pyrrolidone (NMP).

The same assumption made for anode is assumed valid also for cathode and the results of the analysis for the production of cathode are summarized in *table 33*.

Table 33-Dataset for the production of 1 kg of cathode (Na-ion battery)

	AMOUNT	UNIT
INPUT FLOW		
$Na_{0.7}MnO_2$	0.75	kg
Black carbon	0.01	kg
SBR	0.35	kg
Methyl pyrrolidone	0.02	kg
Aluminum foil	0.21	kg
Electricity (grid mix)	$2*10^{-3}$	kWh
Heat (natural gas)	0.27	MJ
Transport (freight train)	52.8	kgkm
Transport (articulated lorry)	14.9	kgkm
OUTPUT FLOW		
Cathode	1	kg
Waste heat	0.27	MJ

7.1.5 Electrolyte manufacturing

In the sodium-ion battery analyzed, the electrolyte chosen is based on $NaPF_6$. This salt is preferred to $NaClO_4$ that can easily cause explosion (Chen et al., 2019). The choice of electrolyte is essential to improve the life cycle of sodium-ion batteries.

The synthesis of $NaPF_6$ involves reaction between sodium fluoride (NaF) and phosphorus pentachloride (PCl_5) and hydrogen fluoride (HF). Furthermore, lime is used as neutralizer during the production that takes place in an inert atmosphere. The dataset to produce 1 kg of $NaPF_6$ is reported in *table 34* (Peters et al., 2016).

Table 34-Dataset for the production of 1 kg of NaPF6

	AMOUNT	**UNIT**
INPUT FLOW		
Hydrogen fluoride	4.04	kg
Lime	7.44	kg
Sodium fluoride	0.32	kg
Nitrogen (liquid)	$1*10^{-3}$	kg
Pentachloro fluoride	1.98	kg
Electricity (grid mix)	0.54	kWh
Transport (freight train)	8270	kgkm
Transport (articulated lorry)	1380	kgkm
OUTPUT FLOW		
$NaPF_6$	1	kg
Waste heat	1.95	MJ
Wastewater	$3.61*10^{-3}$	m^3
Phosphorus trichloride	0.26	kg
Landfill of inert material	8.69	kg

The solvent mixture used is composed by 70% and 30% in weight of dimethyl carbonate and ethylene carbonate as for the lithium-ion battery.

7.1.6 Separator manufacturing

The polypropylene is the material constituting the separator, the analysis conducted for the lithium-ion battery remains valid for this battery as well.

7.1.7 Battery cell manufacturing

The configuration of a sodium-ion battery is similar to the lithium-ion one shown in *figure 6*. The only remarkable difference regards the ions transmitted, that will be sodium ions in this case.

Due to lack of data, the weight percentages of the different components constituting the battery cell are assumed the same as the lithium-ion one. Instead, the electricity and transport data are hypothesized to be equal to the ones reported in the study of Peters et al. (2016) considering the similarity with this analysis.

The same assumptions made for the lithium-ion battery cell are considered valid also in this case and the dataset related to the production of 1 kg of sodium ion battery cell is reported in *table 35*.

Table 35-Dataset for the production of 1 kg of Na-ion battery cell

	AMOUNT	UNIT
INPUT FLOW		
Anode	0.38	kg
Cathode	0.47	kg
$NaPF_6$	$1.4*10^{-2}$	kg
EC	$1.7*10^{-2}$	kg
DMC	0.04	kg
Separator	0.04	kg
Polypropylene film	0.05	kg
Nitrogen (liquid)	0.01	kg
Electricity (grid mix)	0.11	kWh
Heat (natural gas)	0.07	MJ
Transport (freight train)	250	kgkm
Transport (articulated lorry)	42	kgkm
OUTPUT FLOW		
Battery cell	1	kg
Waste heat	0.38	MJ

7.1.8 Battery pack manufacturing

The data necessary for the manufacturing of the battery pack are partially assumed from the study of Peters et al. (2016) and partially considered similar to those reported in chapter 6.

The input and output data referred to the assembly of a battery pack are reported in *table 36*.

Table 36-Dataset for the production of 1 item of Na-ion battery pack

	AMOUNT	UNIT
INPUT FLOW		
Battery cell	198	kg
PP film	7.2	kg
BMS	14	kg
Steel	28.8	kg
Transport (freight train)	542	kgkm
Transport (articulated lorry)	100	kgkm
Electricity (grid mix)	7.44	kWh
OUTPUT FLOW		
Battery pack	1	item
Waste heat	14.36	MJ

As an additional analysis, it is possible to calculate the quantity of grape waste required to produce a sodium-ion battery pack. The data concerning the amount of waste generated by the processing necessary to obtain 1 litre of wine are sourced from the study carried out by Maicas and Mateo (2020) and summarized in *table 37*.

Table 37-Inputs to produce 1 litre of wine

WASTE	QUANTITY [kg]
Total	1.4
Wastewater	1.05
Grape by-product	0.35

With the knowledge of the amount of biomass necessary to produce 1 kg of hard carbon and the quantity of hard carbon needed in a battery pack, it can be determined that approximately 158 kg of winery waste are required for the analyzed battery pack. This calculation refers to 452 liters of wine and considering bottles with a capacity of 0.75 liters each, it can be deduced that the production of 602 bottles of wine creates an amount of waste necessary to the manufacturing of a battery pack. The selected winery company has an annual production of 40.000 bottles of wine (http://www.llopart.com). Therefore, theoretically, the annual production of grape by-products could meet the hard carbon requirements for 66 sodium-ion batteries.

Instead, considering that the brewer’s spent grains represent the 85% of the wastes derived from the beer production (Borel et al., 2018) and proceeding with the same analysis, it is possible to determine that 435 kg of waste are necessary for the production of a battery pack. This indicates that the production of 511 liters of beers generate an amount of waste necessary for the manufacturing of a sodium-ion battery pack.

7.2 Use phase

The application intended for the sodium-ion battery pack is the same as the lithium-ion one.

Battery lifetime is a key factor for the environmental impact of batteries, the main difference between the two technologies consists in the different number of cycles achievable during their lifetime.

Regarding the use phase, the aim of this thesis is to give just a general idea of the difference in lifecycle of the two batteries due to the unavailability of precise data linked to the novelty of the topic.

Overall, comparing the study carried out by Han et al. (2014) regarding lithium-ion batteries and the work on sodium-ion batteries done by Che et al. (2018), it is possible to conclude that sodium-ion batteries have a lower lifecycle than the lithium-ion counterpart. The ratio between the two values, as the capacity retained, strongly depends on the materials constituting anode, cathode and electrolyte and can increase with the use of additive in the electrolyte solution.

Considering this, the sodium-ion battery will need to be replaced more frequently, and consequently, a greater usage of materials will be required. Additionally, the battery will need to be disposed of more quickly compared to the lithium-ion battery.

In order to make sodium-ion batteries competitive with lithium-ion ones, it is necessary to increase their cycle life. One example involves the use of additives in the electrolyte that can enhance the capacity retained after a certain number of cycles (Che et al., 2018).

7.3 End of life

The main valuable materials for which the European commission gives guidance, regarding the recycling process, are not present in the sodium-ion battery. On one side, this means that a negligible quantity of critical raw materials is used in this type of battery, making it more sustainable than lithium-ion one. On the other side, new methods should be implemented in the next future to manage the end of life of this type of battery considering that, up to now, there are no remarkable studies in this direction due to the novelty of the technology.

One option to consider is the reuse of the battery at the end of its life in applications feasible for a battery with a capacity lower than 80%, thereby extending its operational phase and postponing the necessity for battery recycling. Some ongoing research focuses on repurposing second-life electric vehicles batteries to fulfill the stationary energy requirements of photovoltaic systems (Kastanaki et al., 2022). Nevertheless, additional studies related to the life cycle of sodium-ion batteries should be conducted prior to proposing strategies for the end-of-life management of this battery type.

7.4 Life Cycle Impact Assessment method

Regarding the analysis conducted for the winery waste, the results related to the impact categories are reported in *table 38*, obtained following the same procedure used for the lithium-ion battery.

Table 38-Impact category results for Na-ion battery pack (winery waste)

IMPACT CATEGORY	REFERENCE UNIT	RESULT	NORMALIZED	WEIGHTED
Acidification	mol H+ $_{eq}$	2	0.04	$2*10^{-3}$
Climate change	kg CO_2 $_{eq}$	523	0.07	0.02
Climate change-Biogenic	kg CO_2 $_{eq}$	0.79		
Climate change-Fossil	kg CO_2 $_{eq}$	522		
Climate change-Land use and land use change	kg CO_2 $_{eq}$	0.26		
Ecotoxicity, freshwater	CTUe	132	0.01	0
Eutrophication marine	kg N $_{eq}$	1.02	0.04	$1*10^{-3}$
Eutrophication, freshwater	kg P $_{eq}$	0.06	0.02	$7.07*10^{-4}$
Eutrophication, terrestrial	mol N $_{eq}$	3.82	0.02	$1*10^{-3}$
Human toxicity, cancer	CTUh	$4.36*10^{-6}$	0.11	0
Human toxicity, non-cancer	CTUh	$5.02*10^{-5}$	0.11	0
Ionising radiation, human health	kBq U-235 $_{eq}$	45.59	0.01	$1*10^{-3}$
Land use	Pt	1368	$1*10^{-3}$	$8.66*10^{-5}$
Ozone depletion	kg CFC11 $_{eq}$	$2.4*10^{-4}$	$1.03*10^{-4}$	$6.92*10^{-6}$
Particulate Matter	disease incidence	$2.91*10^{-6}$	0.05	$4*10^{-3}$
Photochemical ozone formation - human health	kg NMVOC $_{eq}$	1.06	0.03	$1*10^{-3}$
Resource use, fossils	MJ	8009	0.12	0.01
Resource use, minerals and metals	kg Sb $_{eq}$	0.01	0.21	0.02
Water use	m^3 world $_{eq}$	266	0.02	$2*10^{-3}$

Taking a brief glance, it is possible to notice that the impact values in all the categories are lower than the ones obtained for the lithium-ion battery. However, determining the components that have the greatest impact is complex in this case. In fact, upon analyzing the results, it is possible to observe how the impact of the elements varies significantly depending on the indicator considered.

Overall, the materials used in the cells have the greatest impact in most of the impact categories, except in the use of minerals and metals resources in which the BMS production is the most relevant process. The BMS production process and the steel used in the casing of the battery pack have a greater impact than in the lithium-ion case study and this is mainly due to the higher quantity of material necessary to produce the sodium-ion battery pack. A deeper comparison between the two batteries will be given in chapter 8.

Analyzing the battery cell in detail, the components that have the greatest impact are the cathode and the electrolyte. The electrolyte has the highest value in acidification, climate change (biogenic), ecotoxicity, eutrophication (marine and freshwater), human toxicity, ozone depletion, particular matter, and resource use (minerals and metals) categories. On the other hand, the foremost contribution to climate change, climate change (fossil), climate change (land use and land use change), eutrophication (terrestrial), ionizing radiation, land use, photochemical ozone formation, resource use (fossils) and water use regards the cathode production, in particular the manufacturing of the active material and of the aluminum current collector. The impact values associated with the active material are mainly caused by the production of the manganese oxide and the use of nitrogen liquid for its fabrication.

The impact values associated to the anode production are very low. Anyway, it is important to highlight that the aluminum of the current collector, the carbon black, and the hard carbon are the components that mainly have an effect. Regarding the hard carbon, relevant contributions, however minimal, regard acidification, climate change, ionizing radiation, land use, and particular matter indicators and are linked to the use of nitrogen liquid in the production process.

In summary, the impacts of the different battery components for the production of 1 kg of battery cell are reported in *figure 13*. For each indicator, the result related to the battery cell is set to 100% and the results of the other variants are displayed in relation to this result. The category "other parts" include the energy, nitrogen liquid and transport necessary for the battery cell creation. For clarity purposes, only the impact categories with robustness of I and the resources use are considered, in reference to chapter 5 section 4.

Furthermore, the relative contribution of the battery cells and of the BMS to the battery pack's impact is shown in *figure 14*. It is possible to highlight the higher influence of the BMS than in the lithium-ion case study.

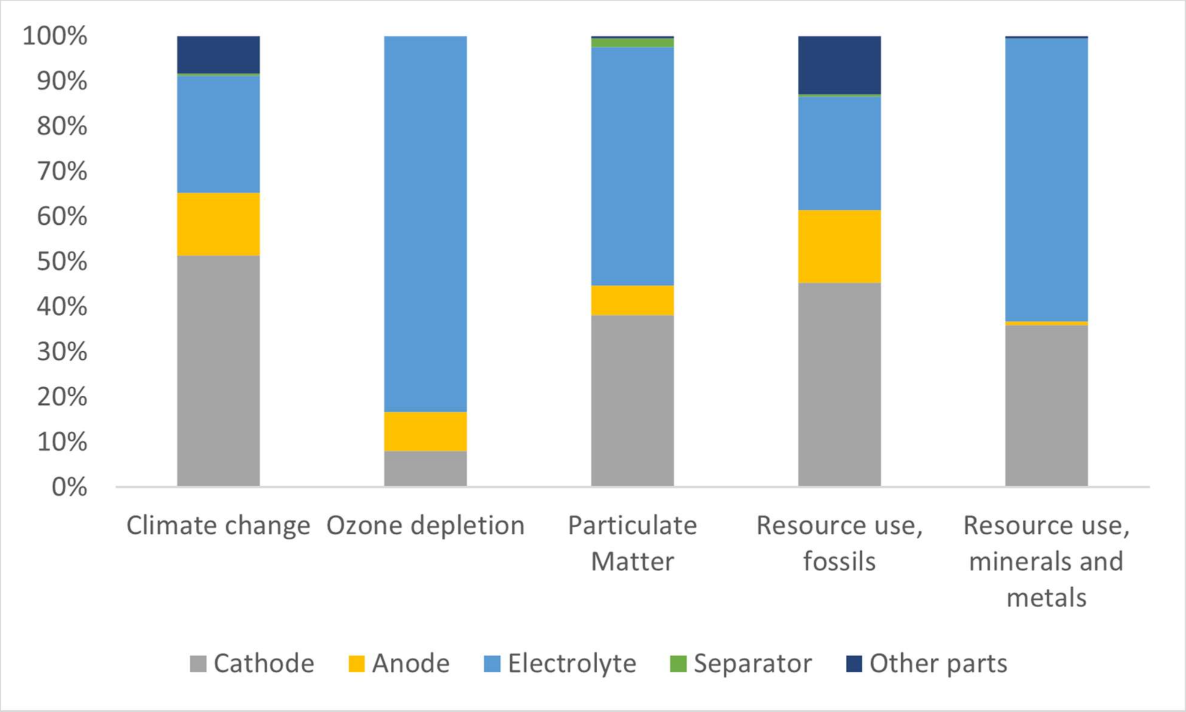

Figure 13-Impact contribution of the different components constituting a Na-ion battery cell (winery waste)

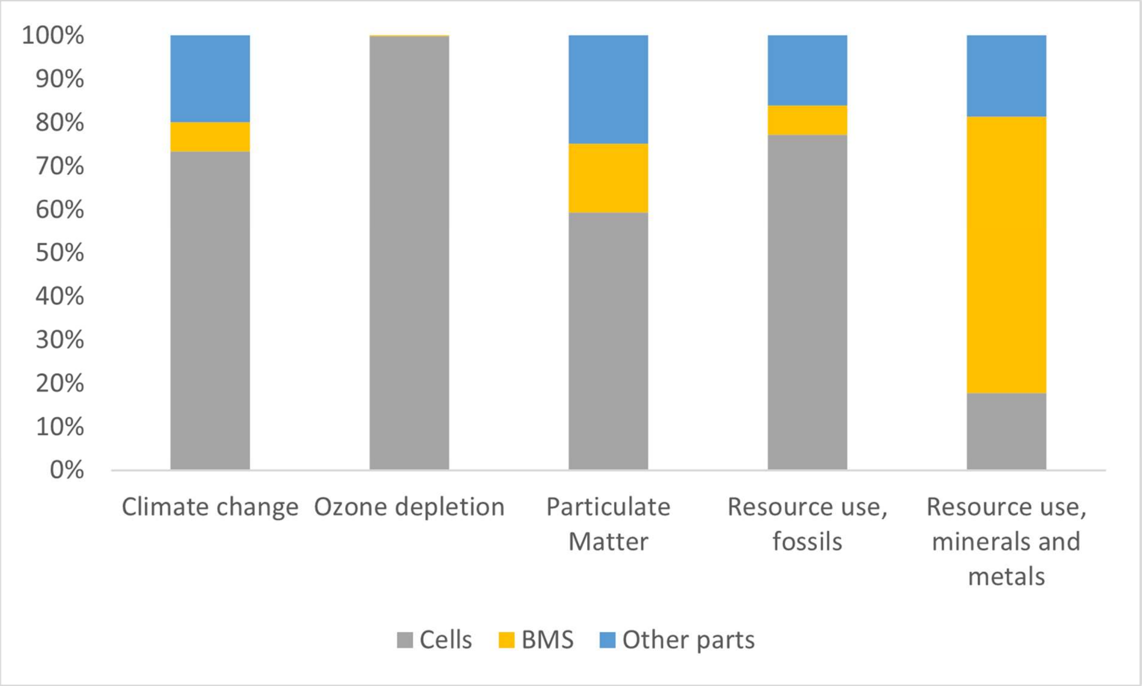

Figure 14-Relative contribution of battery cells and BMS to the impact of Na-ion battery pack (winery waste)

At this juncture, it is intriguing to compare the results just exposed with those obtained using different sources to generate hard carbon. For both cases, the contribution of the different components of the battery pack to the impact categories follows the same trend described above.

The impact categories results derived from the battery pack construction using hard carbon obtained from petroleum coke, are reported in *table 39*.

Table 39-Impact category results for Na-ion battery pack (petroleum coke)

IMPACT CATEGORY	REFERENCE UNIT	RESULT	NORMALIZED	WEIGHTED
Acidification	mol H+ $_{eq}$	2.16	0.04	$3*10^{-3}$
Climate change	kg $CO_{2\ eq}$	549	0.07	0.02
Climate change-Biogenic	kg $CO_{2\ eq}$	0.77		
Climate change-Fossil	kg $CO_{2\ eq}$	548		
Climate change-Land use and land use change	kg $CO_{2\ eq}$	0.27		
Ecotoxicity, freshwater	CTUe	133	0.01	0
Eutrophication marine	kg N $_{eq}$	1.08	0.04	$1*10^{-3}$
Eutrophication, freshwater	kg P $_{eq}$	0.06	0.02	$7.07*10^{-4}$
Eutrophication, terrestrial	mol N $_{eq}$	4.3	0.02	$1*10^{-3}$
Human toxicity, cancer	CTUh	$4.41*10^{-6}$	0.12	0
Human toxicity, non-cancer	CTUh	$5.04*10^{-5}$	0.11	0
Ionising radiation, human health	kBq U-235 $_{eq}$	42.48	0.01	$1*10^{-3}$
Land use	Pt	1372	$1*10^{-3}$	$8.69*10^{-5}$
Ozone depletion	kg CFC11 $_{eq}$	$2.4*10^{-6}$	$1.03*10^{-4}$	$6.91*10^{-6}$
Particulate Matter	disease incidence	$3.04*10^{-5}$	0.05	$5*10^{-3}$
Photochemical ozone formation - human health	kg NMVOC $_{eq}$	1.18	0.03	$1*10^{-3}$
Resource use, fossils	MJ	7976	0.12	0.01
Resource use, minerals and metals	kg Sb $_{eq}$	0.01	0.21	0.02
Water use	m^3 world $_{eq}$	261	0.02	$2*10^{-3}$

Overall, the production of the battery pack under study has higher impact than the battery pack obtained from grape waste. However, it is important to highlight that the production of hard carbon from grapes waste has higher values, for some indicators, than the petroleum coke ones: climate change (biogenic), ionizing radiation, fossils resource and water use. The main reason is that a higher quantity of input, particularly nitrogen liquid, is required to produce hard carbon from waste.

The battery pack built with the hard carbon derived from brewer's spent grains produces the impact values summarized in *table 40*.

Table 40-Impact category results for Na-ion battery pack (brewery waste)

IMPACT CATEGORY	REFERENCE UNIT	RESULT	NORMALIZED	WEIGHTED
Acidification	mol H+ $_{eq}$	2.08	0.04	$2*10^{-3}$
Climate change	kg $CO_{2\ eq}$	554	0.07	0.02
Climate change-Biogenic	kg $CO_{2\ eq}$	0.87		
Climate change-Fossil	kg $CO_{2\ eq}$	553		
Climate change-Land use and land use change	kg $CO_{2\ eq}$	0.28		
Ecotoxicity, freshwater	CTUe	133	0.01	0
Eutrophication marine	kg N $_{eq}$	1.04	0.04	$1*10^{-3}$
Eutrophication, freshwater	kg P $_{eq}$	0.06	0.02	$7.07*10^{-4}$
Eutrophication, terrestrial	mol N $_{eq}$	3.97	0.02	$1*10^{-3}$
Human toxicity, cancer	CTUh	$4.38*10^{-6}$	0.11	0
Human toxicity, non-cancer	CTUh	$5.06*10^{-5}$	0.11	0
Ionising radiation, human health	kBq U-235 $_{eq}$	54.84	0.01	$1*10^{-3}$
Land use	Pt	1474	$1*10^{-3}$	$9.33*10^{-5}$
Ozone depletion	kg CFC11 $_{eq}$	$2.41*10^{-6}$	$1.03*10^{-4}$	$6.95*10^{-6}$
Particulate Matter	disease incidence	$2.98*10^{-5}$	0.05	$4*10^{-3}$
Photochemical ozone formation - human health	kg NMVOC $_{eq}$	1.1	0.03	$1*10^{-3}$
Resource use, fossils	MJ	8531	0.13	0.01
Resource use, minerals and metals	kg Sb $_{eq}$	0.01	0.21	0.02
Water use	m^3 world $_{eq}$	281	0.02	$2*10^{-3}$

The battery pack under analysis has greater values than the battery pack with the use of grape wastes in all the impact categories. Instead, comparing it with the battery pack obtained from petroleum coke, the higher values regard the climate change, human toxicity (non-cancer), ionizing radiation, land use, ozone depletion, fossils resource use and water use. It can be inferred that as the yield of hard carbon from waste decreases, the number of impact indicators for which battery packs derived from waste have higher values than those derived from petroleum coke increases.

The relative contribution of the different hard carbon sources to the impact categories for which hard carbon has a relevant role, is reported in *figure 15*. For each impact category, the sum of the impact values of all the precursors is set to 100% and the relative contribution of each precursor is calibrated as percentage value.

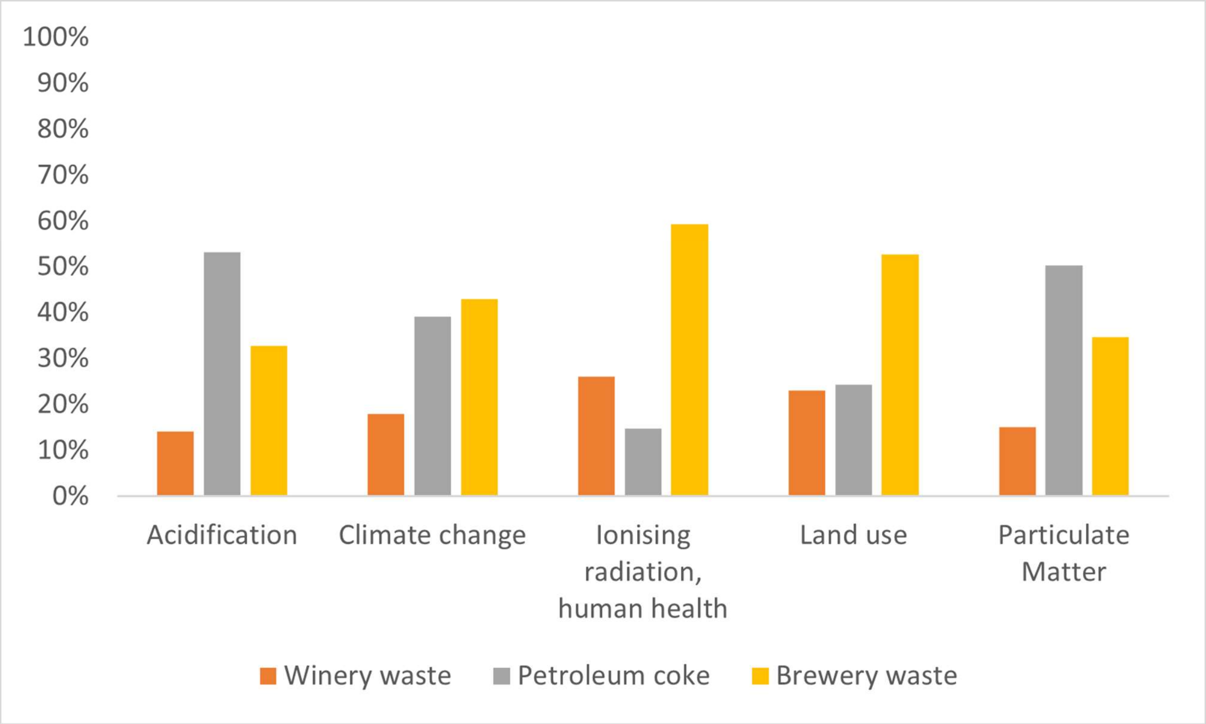

Figure 15-Relative contribution of the different hard carbon's sources

The only impact categories in which the hard carbon production has a relevant contribution and the one derived from petroleum coke has the greatest value, is represented by the acidification and particulate matter indicator. In fact, coke production is the main factor affecting the contribution of the anode to these categories.

In conclusion, evaluating different sodium-ion battery packs, where the only distinction lies in the source of hard carbon, it becomes apparent that the choice of hard carbon precursors does not uniformly influence the impact on the different indicators. Certain impact categories are predominantly affected by the quantity of the materials required for hard carbon production. A lower yield of hard carbon from the selected precursors could result in a greater impact across various categories. The use of waste reduces the costs related to the availability of the materials and enhances the sustainability of the process within the framework of the circular economy. Conversely, it is important to carefully assess the yield of the chosen hard carbon precursor.

7.5 Cost analysis

The sodium-ion battery cost depends on the source of hard carbon. The specific price of hard carbon, based on the precursor implied, is reported in *table 41* (Peters et al., 2019). A proportion has been made to obtain the final price for the winery waste. Furthermore, the actual conversion factor between the euro and the dollar is used.

Table 41-Specific cost of different hard carbon precursors

HARD CARBON SOURCE	COST [$/kg]
Winery waste	6.4
Petroleum coke	4
Brewery waste	18.9

For the cost of the cathode active material, the price for a general sodium-metal-oxide material is used. The specific cost of the materials, not yet analyzed for the cost analysis of the lithium-ion battery, are summarized in *table 42* (Schneider et al., 2019).

Table 42-Specific cost of Na-ion cathode components

COMPONENT	COST [$/kg]
Cathode active material	12.8
Electrolyte	17.6

Considering the mass quantity of each component constituting the battery cell, it is possible to determine the cost per kilogram of battery cell. The costs are stated in *table 43* and it is possible to notice that the specific cost of sodium-ion battery cell is lower than the lithium ion one, independently from the hard carbon source.

Table 43-Specific cost of Na-ion battery cell for different hard carbon precursors

HARD CARBON SOURCE	BATTERY CELL COST [$/kg]
Winery waste	13
Petroleum coke	12
Brewery waste	15

The situation changes moving from cell to battery pack. In fact, the weight of the total number of cells and of the non-cell components has a relevant influence on the final price of the battery pack, as shown in *table 44.* The higher is the hard carbon yield of the precursor, the lower will be the final price of the battery pack.

Table 44-Final cost of Na-ion battery pack for different hard carbon precursors

HARD CARBON SOURCE	BATTERY PACK COST [$]
Winery waste	5170
Petroleum coke	5075
Brewery waste	5663

8 Na-ion vs Li-ion battery: results comparison

The lithium-ion battery emerges as the most impacting technology among the ones analyzed in this thesis. This battery exhibits the highest impact values across all indicators.

Notably, the primary contributor to the impact categories within the lithium-ion battery is the cathode. When comparing it to the sodium-ion cathode, based on the same unit mass, a striking disparity in the environmental impacts of these two components becomes evident, as shown in the graph reported in *figure 16*, where the results related to the main impact categories indicators are compared based on the relative contribution to the total given by the sum of the cathodes impact. This discrepancy primary stems from the different active materials employed in the two cathodes and the absence of nickel and cobalt in the sodium-ion battery.

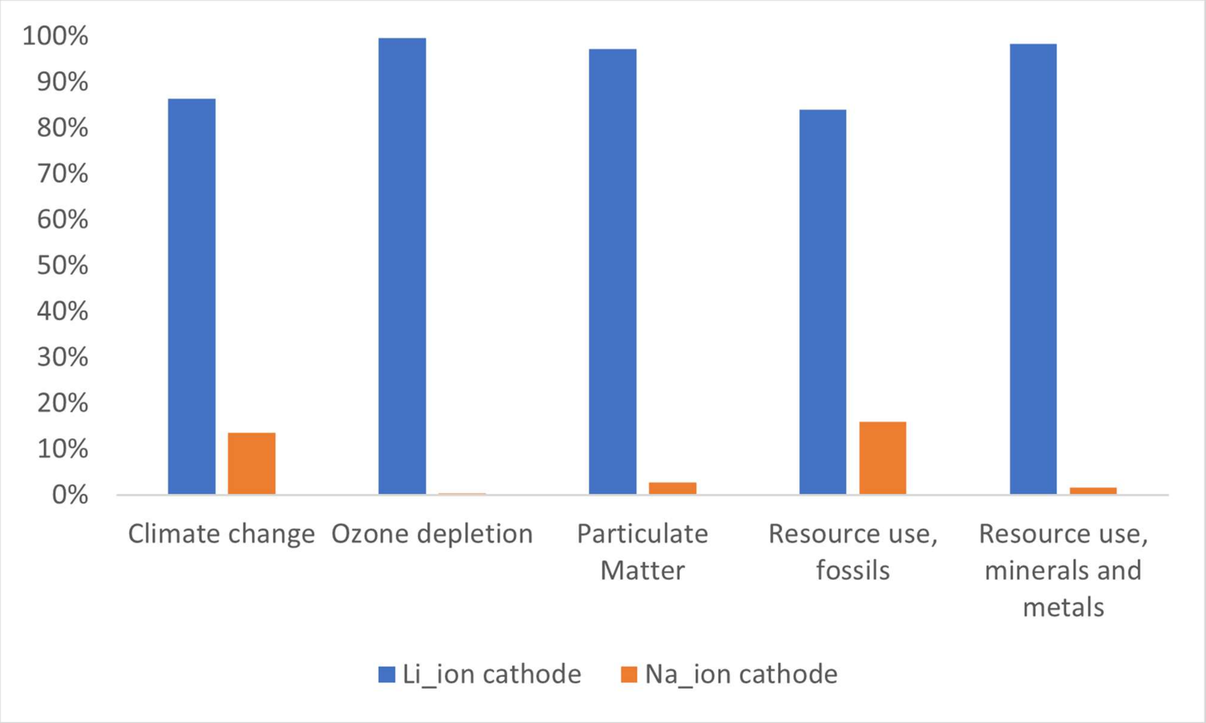

Figure 16-Relative impact contribution of Li-ion and Na-ion cathodes

In summary, the flows employed in the cathodes, which have the most significant influence on each of the indicators, are listed in *table 45*. It is possible to notice the heterogeneity of the Na-ion cathode's impacts that significantly depend on the indicator considered.

Table 45-Comparison of the cathodes' flows that contribute the most to each indicator

IMPACT CATEGORIES	Li-ion CATHODE	Na-ion CATHODE
Acidification	Nickel sulphate	Boric acid
Climate change	Cobalt	Thermal energy
Climate change-Biogenic	Cobalt	Nitrogen liquid
Climate change-Fossil	Cobalt	Thermal energy
Climate change-Land use and land use change	Nickel sulphate	Nitrogen liquid
Ecotoxicity, freshwater	Nickel sulphate	Soda
Eutrophication marine	Nickel sulphate	Boric acid
Eutrophication, freshwater	Nickel sulphate	Soda
Eutrophication, terrestrial	Nickel sulphate	Soda
Human toxicity, cancer	Cobalt	Methylpyrolidone
Human toxicity, non-cancer	Nickel sulphate	Boric acid
Ionising radiation, human health	Cobalt	Nitrogen liquid
Land use	Nickel sulphate	Nitrogen liquid
Ozone depletion	Cobalt	Aluminum foil
Particulate Matter	Nickel sulphate	Boric acid
Photochemical ozone formation - human health	Nickel sulphate	Boric acid
Resource use, fossils	Cobalt	Thermal energy
Resource use, minerals and metals	Nickel sulphate	Boric acid
Water use	Cobalt	Nitrogen liquid

When comparing the impacts associated to the electrolytes, the outcomes vary depending on the specific impact category under consideration. The salt employed in sodium-ion batteries exhibits the highest impact in categories such as climate change, climate change (fossil), and resources use. This is mainly attributed to the use of lime in the salt production process. Instead, when examining indicators for which $LiPF_6$ demonstrates the highest impact, it is evident that these are associated to the production of calcium hydroxide. Nevertheless, there are no substantial differences in the impact of the two salts across the impact categories.

However, the primary environmental impacts associated with both electrolyte components are closely tied to the manufacturing processes of phosphorus pentachloride and hydrogen fluoride. For illustrative purposes, the results obtained from acidification and ozone depletion indicators are reported in *figure 17* and *figure 18*, respectively, as indicative examples of the limited participation of lime or calcium hydroxide production, and of the substantial contribution of phosphorus pentachloride precursors and hydrogen fluoride to the overall impact of the electrolytes. The two graphs are extrapolated from the software OpenLCA.

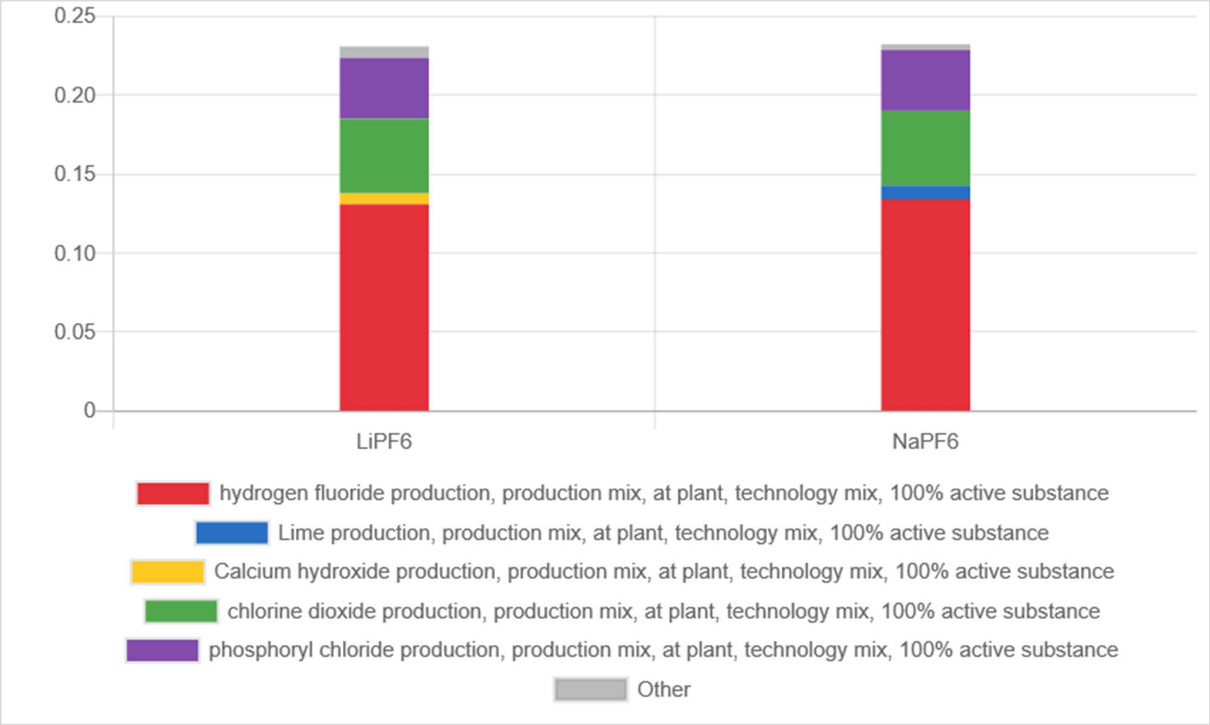

Figure 17-Contribution of the electrolytes' components to the acidification indicator (mol H+ $_{eq}$)

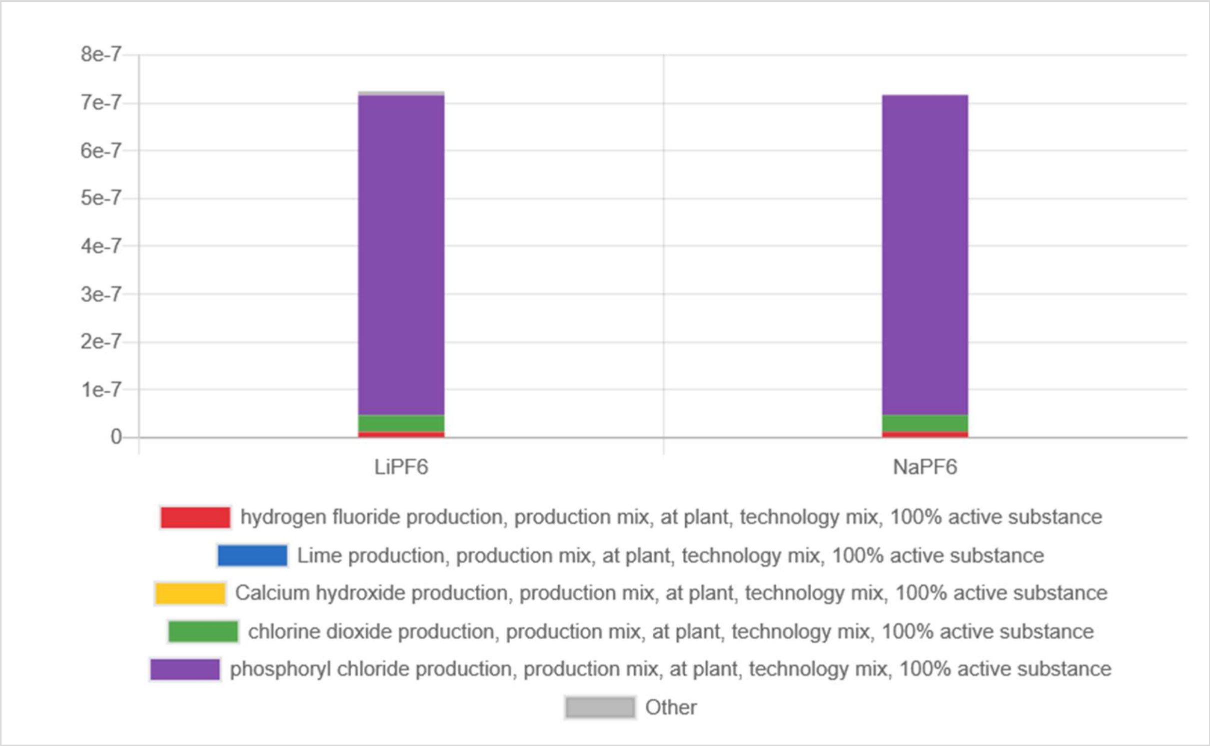

Figure 18-Contribution of the electrolytes' components to the ozone depletion indicator (kg CFC11 $_{eq}$)

In summary, the elementary flows, employed in the electrolytes, that mainly influence each of the indicators, are reported in *table 46*.

Table 46-Comparison of the electrolytes' flows that contribute the most to each indicator

IMPACT CATEGORIES	**Li-ion ELECTROLYTE**	**Na-ion ELECTROLYTE**
Acidification	Hydrogen fluoride	Hydrogen fluoride
Climate change	Chlorine dioxide	Lime
Climate change-Biogenic	Chlorine dioxide	Chlorine dioxide
Climate change-Fossil	Calcium hydroxide	Lime
Climate change-Land use and land use change	Phosphoryl chloride	Phosphoryl chloride
Ecotoxicity, freshwater	Hydrogen fluoride	Hydrogen fluoride
Eutrophication marine	Hydrogen fluoride	Hydrogen fluoride
Eutrophication, freshwater	Phosphoryl chloride	Phosphoryl chloride
Eutrophication, terrestrial	Hydrogen fluoride	Hydrogen fluoride
Human toxicity, cancer	Chlorine dioxide	Chlorine dioxide
Human toxicity, non-cancer	Hydrogen fluoride	Hydrogen fluoride
Ionising radiation, human health	Phosphoryl chloride	Phosphoryl chloride
Land use	Hydrogen fluoride	Hydrogen fluoride
Ozone depletion	Phosphoryl chloride	Phosphoryl chloride
Particulate Matter	Hydrogen fluoride	Hydrogen fluoride
Photochemical ozone formation - human health	Hydrogen fluoride	Hydrogen fluoride
Resource use, fossils	Hydrogen fluoride	Hydrogen fluoride
Resource use, minerals and metals	Hydrogen fluoride	Hydrogen fluoride
Water use	Hydrogen fluoride	Hydrogen fluoride

Regarding the anode comparison, based on the same unit of mass, the lithium-ion anode exhibits the highest environmental impact in ten out of nineteen categories. The most significant contributors to these impacts are graphite and copper current collector. In fact, these components are particularly influential in these categories.

Conversely, the sodium-ion anode derived from petroleum coke registers the highest values for certain indicators, primarily associated with the production of coke. Furthermore, the anode derived from brewery waste demonstrates the highest impact in six categories, mainly due to the environmental consequences of the quantity of liquid nitrogen employed.

For clarity, only the results pertaining to the primary impact categories, as defined in chapter 6, are presented in *figure 19*. As previously described, these represent the results relative to the maximum value obtained for each indicator that is equal to the sum of the impacts of the anodes and is set equal to 100%.

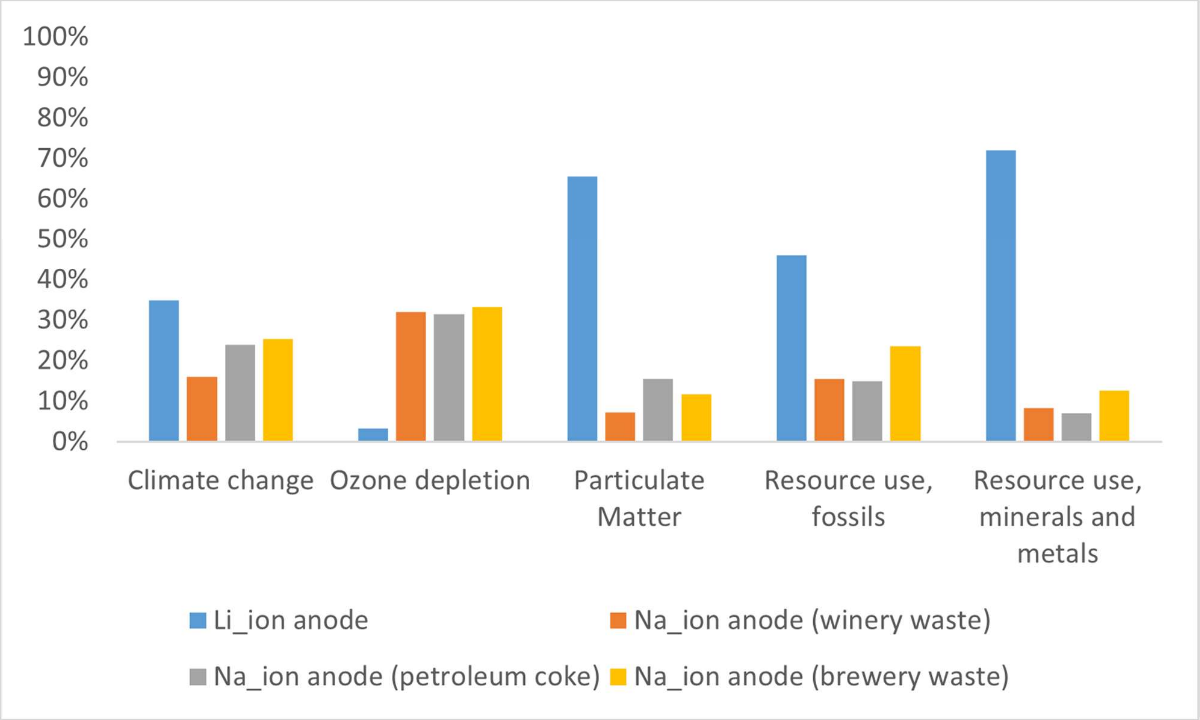

Figure 19-Relative impact contribution of Li-ion and Na-ion anodes

In summary, the flows employed in the anodes, that mainly influence each of the indicators, are listed in *table 47*.

Table 47-Comparison of the anodes' flows that contribute the most to each indicator

IMPACT CATEGORIES	**Li-ion ANODE**	**Na-ion ANODE (winery waste)**	**Na-ion ANODE (petroleum coke)**	**Na-ion ANODE (brewery waste)**
Acidification	Graphite	Nitrogen liquid	Coke	Nitrogen liquid
Climate change	Graphite	Nitrogen liquid	Coke	Nitrogen liquid
Climate change-Biogenic	Copper sheet	Nitrogen liquid	Nitrogen liquid	Nitrogen liquid
Climate change-Fossil	Graphite	Aluminum foil	Coke	Nitrogen liquid
Climate change-Land use and land use change	Copper sheet	Nitrogen liquid	Coke	Nitrogen liquid
Ecotoxicity, freshwater	Graphite	Aluminum foil	Aluminum foil	Aluminum foil
Eutrophication marine	Graphite	Aluminum foil	Coke	Nitrogen liquid
Eutrophication, freshwater	Graphite	Aluminum foil	Aluminum foil	Aluminum foil
Eutrophication, terrestrial	Graphite	Aluminum foil	Coke	Nitrogen liquid
Human toxicity, cancer	Graphite	SBR	SBR	SBR
Human toxicity, non-cancer	Copper sheet	Aluminum foil	Aluminum foil	Aluminum foil
Ionising radiation, human health	Copper sheet	Nitrogen liquid	Nitrogen liquid	Nitrogen liquid
Land use	Copper sheet	Nitrogen liquid	Coke	Nitrogen liquid
Ozone depletion	Graphite	Aluminum foil	Aluminum foil	Aluminum foil
Particulate Matter	Graphite	Nitrogen liquid	Coke	Nitrogen liquid
Photochemical ozone formation - human health	Graphite	Aluminum foil	Coke	Nitrogen liquid
Resource use, fossils	Graphite	Aluminum foil	Aluminum foil	Nitrogen liquid
Resource use, minerals and metals	Graphite	Nitrogen liquid	Carbon black	Nitrogen liquid
Water use	Copper sheet	Aluminum foil	Aluminum foil	Aluminum foil

The results concerning the battery cells comparison reveal a similar trend to that observed in the cathode comparison, clarifying the important contribution of this component to the impact of the battery. The findings are presented in *figure 20*. For visual clarity, only the principal indicators are reported, described in chapter 6. The sum of the cathodes impacts for each indicator is set to 100% and the relative contribution of each cathode is determined.

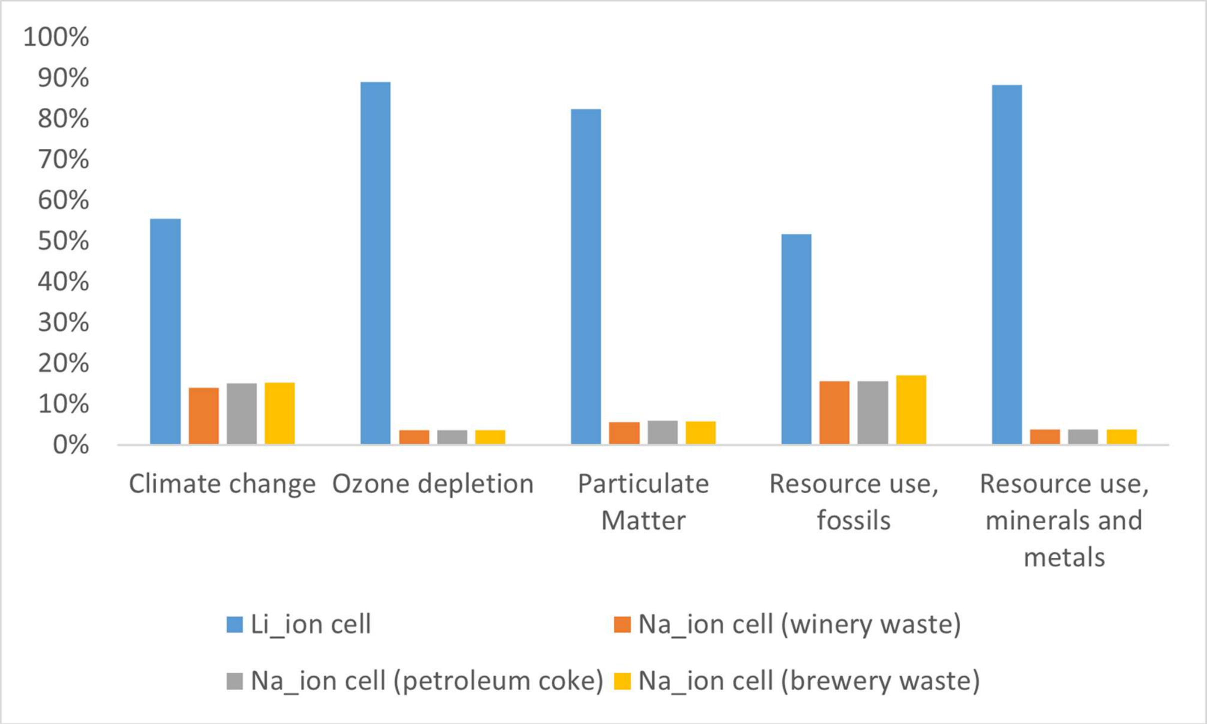

Figure 20-Relative impact contribution of Li-ion and Na-ion battery cells

The most interesting analysis pertains to the comparison of battery packs. Up to this point, the results comparisons have been conducted with the assumption of equal mass for each component. However, in this case, one item of battery pack is the benchmark, making the difference in weight, between the lithium-ion and sodium-ion battery, a relevant factor to consider.

The results of the relative comparison among the various battery packs are presented in *figure 21*, focusing only on the relevant indicators, for clarity purpose. When comparing these outcomes with those identified for 1 kg of battery cell, it is possible to understand that the impact of the sodium-ion battery has increased in relation to the lithium-ion counterpart. Particularly, an evident increase regards the use of the resources.

This phenomenon is primarily attributed to the substantial mass of components included in the sodium- ion battery pack. Specifically, the non-cell components, including the BMS and casing materials, in the sodium-ion battery demonstrate a significantly greater environmental impact than their counterparts in the lithium-ion battery, largely due to their higher mass. The comparative analysis for the BMS is presented in *figure 22* and *figure 23*, for lithium-ion and sodium-ion battery pack (from winery waste), respectively.

Furthermore, examining individually the indicators, it is possible to observe a significant impact of the materials used in the BMS and packaging concerning resource use. The results pertaining to the indicator of minerals and metals resources use are depicted in *figure 24*, illustrating how, in sodium-ion batteries, the impact is markedly higher compared to that associated with the materials used in the cells. The two most relevant components of packaging and BMS are considered in the analysis and the graph is extrapolated from the software OpenLCA.

However, it is important to note that the highest impact within each category is still associated with the lithium-ion pack.

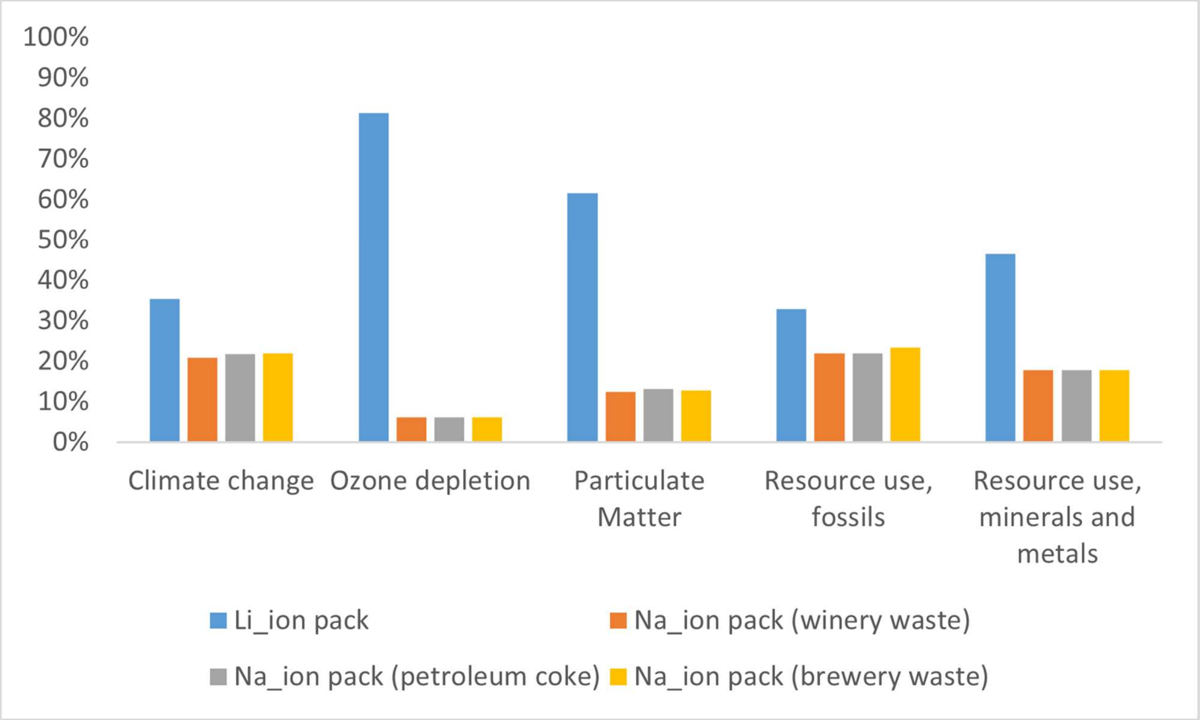

Figure 21-Relative impact contribution of Li-ion and Na-ion battery packs

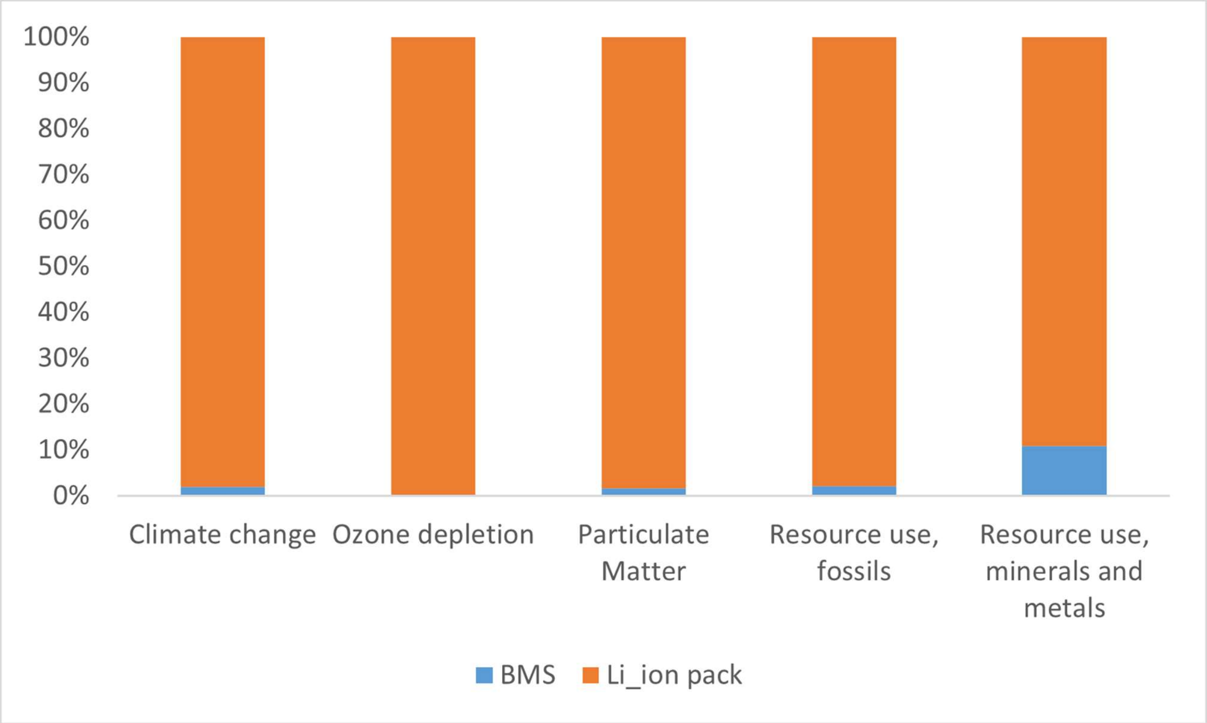

Figure 22-Relative contribution of the BMS to the Li-ion battery pack's impact

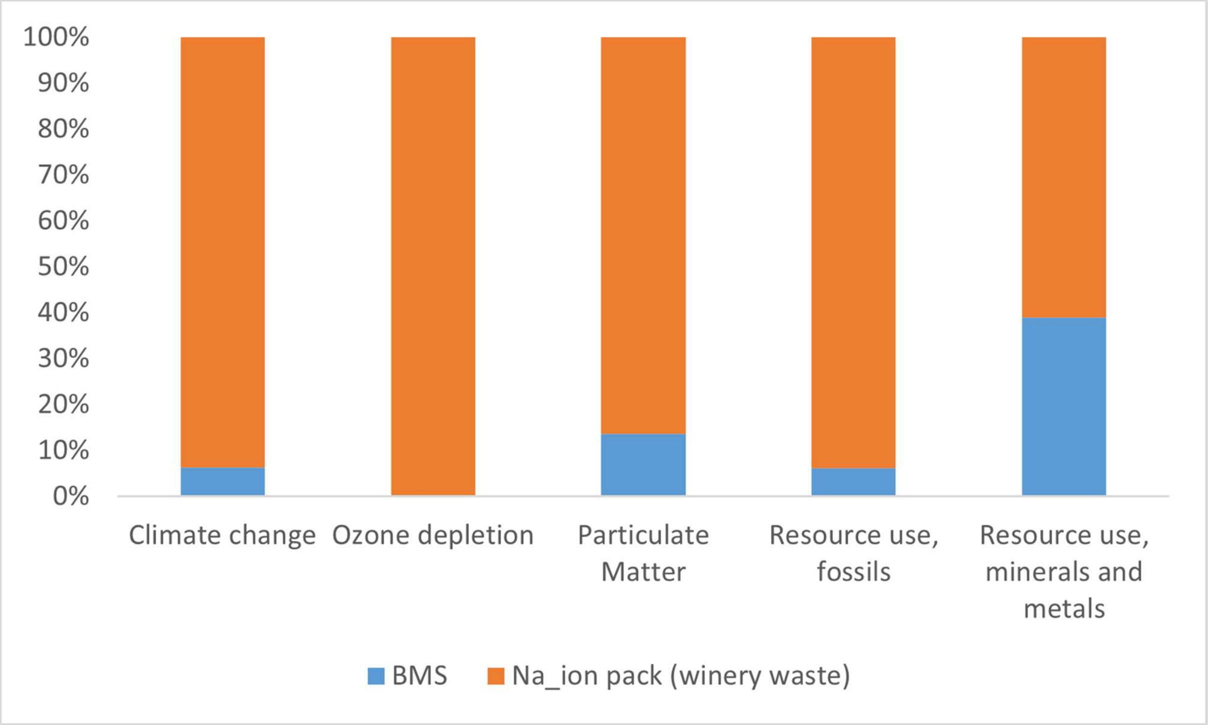

Figure 23-Relative contribution of the BMS to the Na-ion battery pack's impact

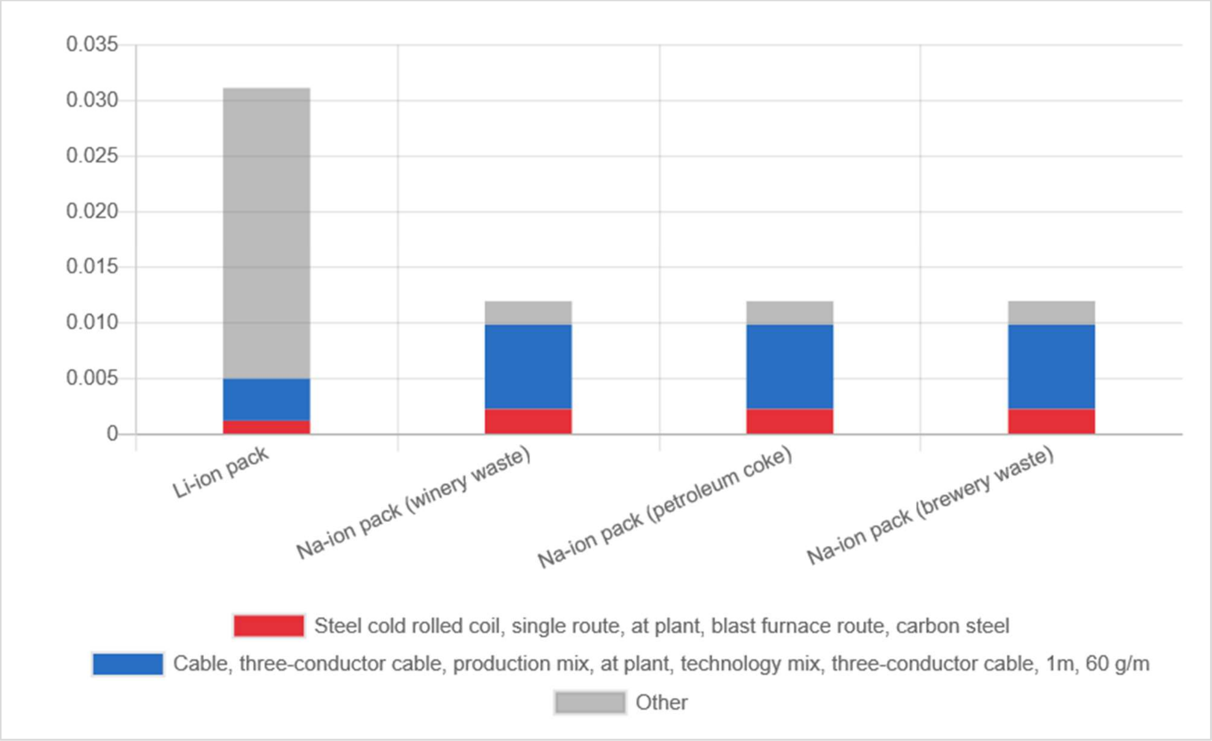

Figure 24-BMS and packaging contribution to the impact of the battery packs in the minerals and metals resource indicator (kg Sb_{eq}*)*

The battery components, that mainly contribute to each impact categories, are summarized in *table 48*. One item of the sodium-ion battery pack derived from winery waste is taken as representative of this batteries' category and is compared with the lithium-ion pack. While for lithium-ion battery the most impacting component is the cathode for all the indicators, the situation is more heterogenous for the sodium-ion pack.

In the latter case, it is possible to highlight that electrolyte, cathode and non-cell materials have all relevant impacts, depending on the impact category considered. However, it is essential to emphasize that, in the end, the lithium-ion pack is the option with the highest environmental impact among the technologies analyzed in this thesis.

Table 48-Comparison of the battery packs' components that contribute the most to each indicator

IMPACT CATEGORIES	**Li-ion PACK**	**Na-ion PACK (winery waste)**
Acidification	Cathode	Electrolyte
Climate change	Cathode	Cathode
Climate change-Biogenic	Cathode	Electrolyte
Climate change-Fossil	Cathode	Cathode
Climate change-Land use and land use change	Cathode	Cathode
Ecotoxicity, freshwater	Cathode	Electrolyte
Eutrophication marine	Cathode	Electrolyte
Eutrophication, freshwater	Cathode	Electrolyte
Eutrophication, terrestrial	Cathode	Cathode
Human toxicity, cancer	Cathode	Electrolyte
Human toxicity, non-cancer	Cathode	Steel casing
Ionising radiation, human health	Cathode	Cathode
Land use	Cathode	Cathode
Ozone depletion	Cathode	Electrolyte
Particulate Matter	Cathode	Electrolyte
Photochemical ozone formation - human health	Cathode	Cathode
Resource use, fossils	Cathode	Cathode
Resource use, minerals and metals	Cathode	BMS
Water use	Cathode	Cathode

In addition, the cost analysis reveals that, considering equivalent energy capacities for the battery packs, the production of one item of sodium-ion battery pack carries a higher cost compared to its lithium-ion counterpart. Moreover, the origin of hard carbon significantly influences the final price, resulting in a battery pack cost that can reach twice as much as that of the lithium-ion alternative. As a recap, the obtained costs are summarized in *table 49*.

Table 49-Comparison of the battery packs' costs

BATTERY PACK	**MANUFACTURING COST [$]**
Li-ion	3360
Na-ion (from winery waste)	5170
Na-ion (from petroleum coke)	5075
Na-ion (from brewery waste)	5663

9 Conclusions

In light of the results obtained, it can be stated that the materials used in the cathode production play a key role in the environmental impact of the battery. Specifically, the use of critical raw materials (such as nickel and cobalt) is the primary cause of environmental pollution associated with the manufacturing phase. Furthermore, attention must be paid to the performance requirements placed on the battery, as a higher capacity leads to a greater battery weight and, consequently, an increased quantity of materials used. Additionally, in this thesis, it has been highlighted how the non-cell materials, comprising the battery pack, also influence environmental indicators, and an increase in their mass can even become the primary source of a specific impact category increase.

The use of waste derived from biomass for the production of hard carbon reduces the environmental impact and cost associated with material extraction. The sodium-ion battery pack that utilizes winery waste shows a 40% reduction in kg of CO_2 equivalent compared to the lithium-ion one. Nevertheless, the transformation processes of precursors into hard carbon can be environmentally costly if not enough attention is paid to the efficiency of the chosen biomass. Furthermore, the use of aluminum instead of copper in the current collector has not shown a substantial decrease in environmental impact. It is, however, important to reiterate that copper is a critical raw material, and its replacement in batteries is desirable.

While manufacturing of lithium-ion batteries may have a higher environmental impact compared to sodium-ion batteries, it is important to remember that the lifespan of the latter is potentially shorter. This means that they will need to be replaced more frequently, resulting in additional environmental impacts over time.

The main limitations of the analysis concern the fact that it is restricted solely to the manufacturing phase. To obtain a comprehensive overview of the situation, a "cradle to grave" analysis is required, which takes into account all phases of the battery's lifecycle and goes beyond the scope of the study conducted in this thesis due to the lack of available data on this subject to date.

In conclusion, it is possible to assert that lithium-ion batteries still represent a cost-effective technology, but they require a thorough study regarding potential new materials, especially for cathode production. One possible solution involves the use of secondary raw materials, which could significantly reduce the environmental impact related to the extraction phase. On the other hand, sodium-ion batteries could be a viable substitute for future batteries in terms of environmental impact, and the ability to use waste materials as precursors adds value from a circular economy perspective. However, it is essential to consider the novelty of this technology, and considering the conclusions drawn from the literature analysis, it is evident that there are gaps. Therefore, it is clear that a substantial amount of research work is required in this field before more comprehensive conclusions can be drawn in the future.

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