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Master's Degree Thesis

Environmental and economic life cycle assessment of a battery pack for a full electric hyper car

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Summary

List of abbreviations

BMS – Battery management system

CFRP – Carbon fiber reinforced polymer

CRM – Critical Raw Material

EOL- End of Line

ESS – Energy storage system

EV – Electric vehicle

ICE – Internal combustion engine

kWh – Watt hour

LCA – Life cycle assessment

LCC- Life cycle costing

LCI – Life cycle inventory

LCIA – life cycle impact assessment

LFP – Lithium-Iron Phosphate

LIB – Lithium-ion battery

LMO – lithium Manganese oxide

NMC – Lithium-nickel manganese cobalt

NCA – Lithium Nickel Cobalt Aluminium

MAT- Manifattura Automobili Torino

PCB – Printed circuit board

PEF - Product Environmental Footprint

TMS - Thermal management system

UN ECE - United Nations Economic Commission for Europe

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1 Intro

1.1 Abstract

In the rapidly evolving landscape of automotive technology, hypercars combine high performance with cutting-edge innovations. As the automotive industry shifts towards electrification to mitigate environmental impacts, the development of efficient and sustainable battery packs is paramount.

The context of this study is set against the background of increasing emphasis on sustainable transportation solutions. Hypercars, often equipped with the latest technological advancements, serve as an ideal platform for exploring the potential of various battery chemistries in high-performance applications. This study aims to identify the environmentally performance of battery solutions for hypercars, thereby contributing to the broader goal of sustainable mobility presenting a Life Cycle Assessment (LCA) of a battery pack for hypercar application and comparing the environmental impact of battery packs based on different cell chemistries for the same purpose, including Lithium Iron Phosphate (LFP), Nickel Manganese Cobalt (NMC)and others. Analysis evaluate the environmental impacts across various indicators, such as global warming potential, acidification, eutrophication, and resource depletion. The LCA conducted covers the entire life cycle of the battery pack focusing from raw material extraction through manufacturing.

The results show that LFP cells have lower environmental impact compared to other chemistries under analysis. However, when integrated into the complete battery pack for hypercar applications, LFP-based solutions exhibit significantly higher impacts. This discrepancy is attributed to the lower energy density of LFP cells, requiring larger and heavier battery packs to achieve the desired performance levels. On the other hand, NMC 811 cells show an optimal trade-off, balancing performance and environmental impacts. NMC-based battery packs provide a favourable combination of high energy density and comparatively lower environmental impacts, making them a promising option for the application.

Future studies on the environmental impacts of battery packs will prioritize the use phase, recycling and end-of-life stages. They will investigate into optimizing energy efficiency during use to minimize emissions and explore advanced recycling techniques to recover critical raw materials. These efforts aim to close the loop on battery life cycles, significantly reducing the overall environmental footprint and fostering a circular economy in the battery industry.

1.2 Background

The interest in energy storage systems research is increasing, partly due to the use of batteries in mobility to reduce tailpipe emissions from private transportation. The adoption of electric solutions has been enabled by the development of lithium-based anode chemistries, offering improved energy density and longer lifespans compared to previous cell systems and no tailpipe emissions. This advancement has allowed Battery Electric Vehicles (BEVs) to achieve ranges comparable to Internal Combustion Engine (ICE) vehicles and improved charging times. Despite technological advancements, significant efforts are still required to reduce costs and increase BEV acceptance among end users.

Private transportation is responsible for a significant portion of emissions and pollutants released into the environment; electric vehicles are seen as a pivotal solution for reducing the environmental impacts of the mobility sector. Green mobility offers several benefits:

- Zero onsite emissions: Electric vehicles do not emit exhaust gases during operation.
- Higher energy efficiency: Electric or hybrid electric architectures offer greater efficiency than internal combustion engines (ICE).
- Lower operating costs: Electric vehicles manufactures claim lower total cost of ownership.
- Comparable performance between electric vehicles and ICE vehicles.

However, this emerging technology faces several challenges. It is estimated that the production of a Battery Pack (BP) accounts for 20-30% of the total CO2-equivalent emissions for manufacturing a vehicle. Designing Battery Packs involves multiple technical aspects, from performance specifications and architectures to the selection of manufacturing processes and materials. A vehicle's battery can weigh over 30% of the total vehicle weight, impacting emissions during use as heavier vehicles require more mechanical energy for movement.

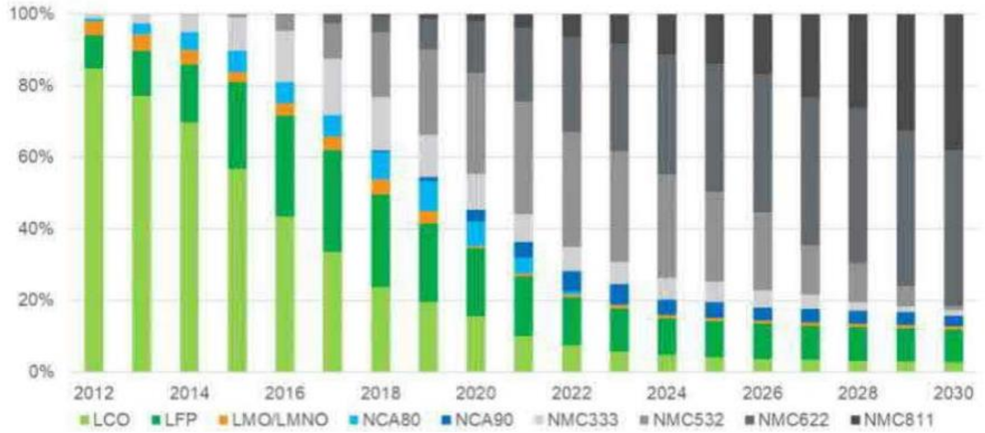

Figure 1: Projections regarding cell adoption for battery packs in future and cobalt presence in cell chemistries (1)

A crucial issue is the materials used in battery production, which can include large amounts of critical raw materials (CRMs), natural resources such as Aluminum and Copper (used as current collectors) and significant volumes of elements necessary for cathode active material production like Lithium, Cobalt, Manganese, and Nickel. CRMs are essential for the economy and whose supply may be at risk of disruption. These materials are crucial for manufacturing products across various industries including electronics, green technologies and automotive sector. The importance of CRMs lies not only in their essential role in these technologies but also in their supply risk, often due to geopolitical factors, challenging extraction processes and environmental or ethical concerns associated with their production.

The Critical Raw Materials Act, depending on the context and jurisdiction, typically refers to legislation aimed at identifying, securing, and diversifying the supply of critical materials vital for national security, economic well-being, and technological innovation. Such acts may include measures to:

- Identify and classify materials as critical based on their importance to the economy and potential supply risks.

- Enhance domestic production of critical materials to reduce dependency on foreign sources.

- Promote research and development in alternative materials, recycling technologies, and more efficient use of critical materials.

- Improve recycling and recovery rates of critical materials from end-of-life products and industrial processes.

- Foster international cooperation to ensure a stable and sustainable supply of critical materials.

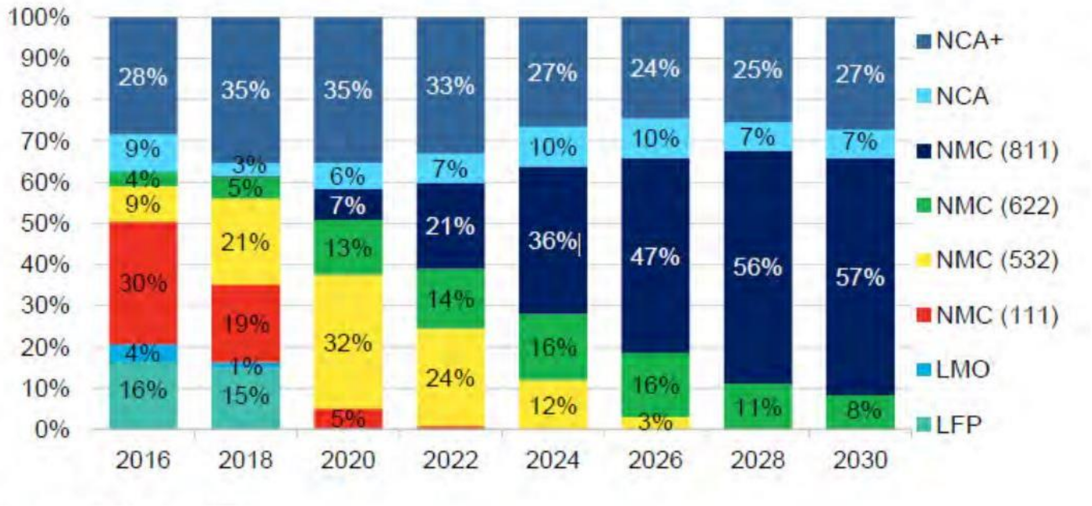

Figure 2: Chemistries diffusion projection for future (1)

Projections for 2030 cell usage illustrate a shift in cell production in the near future: from 2012 to 2030 we are observing a gradual replacement of NMC 532/333 chemistries with NMC 811 and 622, which are anticipated to fulfill the majority of market demand, complemented by LFP and NCA. Although the trends for LFP in the reported graphs are declining, recent investments in this technology forecast a resurgence.

The table presents the various generations of lithium-based cell chemistries. The state-of-the-art is represented by the third generation, which includes NMC 622 and 811, currently industrialized and used for their balance between performance and safety. While belonging to previous generations, there is still interest in LFP and NCA. LFP cells are distinguished by their good resistance to thermal runaway and the absence of critical raw materials (CRMs). NCA cells, on the other hand, share characteristics similar to NMC, boast lower costs, and the absence of Cobalt, which implies reduced safety/stability.

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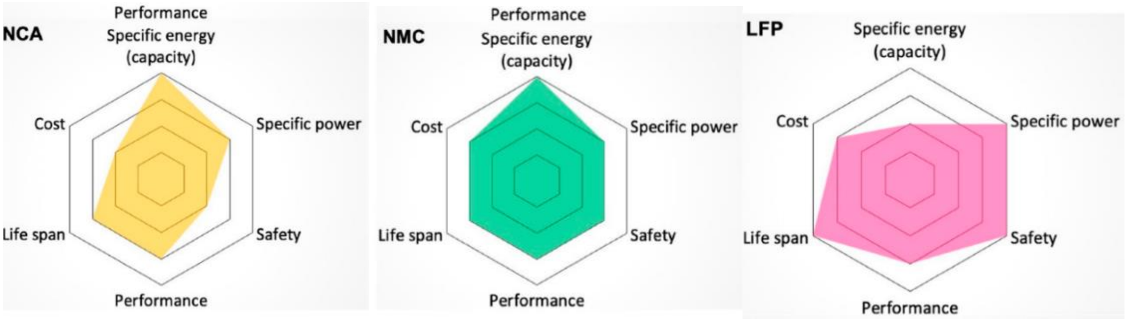


Figure 3: Chemistry performance (2)

The picture provided is a comparison of different battery chemistries based on multiple performance attributes. The focus here is on three types of lithium-ion batteries: Lithium Iron Phosphate (LFP), Nickel Manganese Cobalt Oxide (NMC), and Nickel Cobalt Aluminum Oxide (NCA).

1. LFP:

- Cost: LFP batteries show a moderate cost level compared to the other types.
- Safety: They excel in safety, which is one of their highest scoring attributes for optimal stability at higher temperatures.
- Life Span: The life span of LFP batteries is high, indicating they have a good cycle life.
- Performance: Performance is moderate, reflecting a balance between power and capacity.
- Specific Energy (Capacity): Their specific energy is relatively lower than NMC and NCA, which means they hold less energy per unit weight.
- Specific Power: The specific power of LFP batteries is fairly high, indicating they can deliver a significant amount of power quickly.

2. NMC:

- Cost: The cost is relatively high, indicating that these may be more expensive to source due to the critical material presence.
- Safety: Safety scores are lower than LFP but higher than NCA, suggesting a still safe /robust cell.
- Life Span: NMC has a moderate life span, not as long as LFP but comparable to NCA.
- Performance: NMC batteries offer high performance with good specific energy and power.
- Specific Energy (Capacity): The specific energy is high, meaning they can store a significant amount of energy per unit weight.
- Specific Power: Specific power is moderate to high, suitable for applications requiring quick bursts of energy.

3. NCA:

- Cost: The cost is between that of LFP and NMC, suggesting a middle-ground in terms of production and material costs.
- Safety: Safety is the lowest among the three, suggesting moderate risk which may require additional measures to ensure stability and safety in use.
- Life Span: The life span is comparable to NMC, which is moderate.
- Performance: Performance is high, similar to NMC, making it suitable for high-energy applications.
- Specific Energy (Capacity): NCA has a high specific energy, even higher than NMC, allowing for greater energy storage.
- Specific Power: Specific power is moderate, not as high as LFP, but sufficient for many applications.

In summary, LFP batteries stand out for their safety and life span but have lower specific energy. NMC batteries are a balance between cost, performance, and life span with high specific energy. NCA batteries have the highest specific energy, making them suitable for energy-dense applications, but they come with lower safety scores. Each battery type has its advantages and trade-offs, and the choice among them would depend on the specific requirements of the automotive application they are intended for.

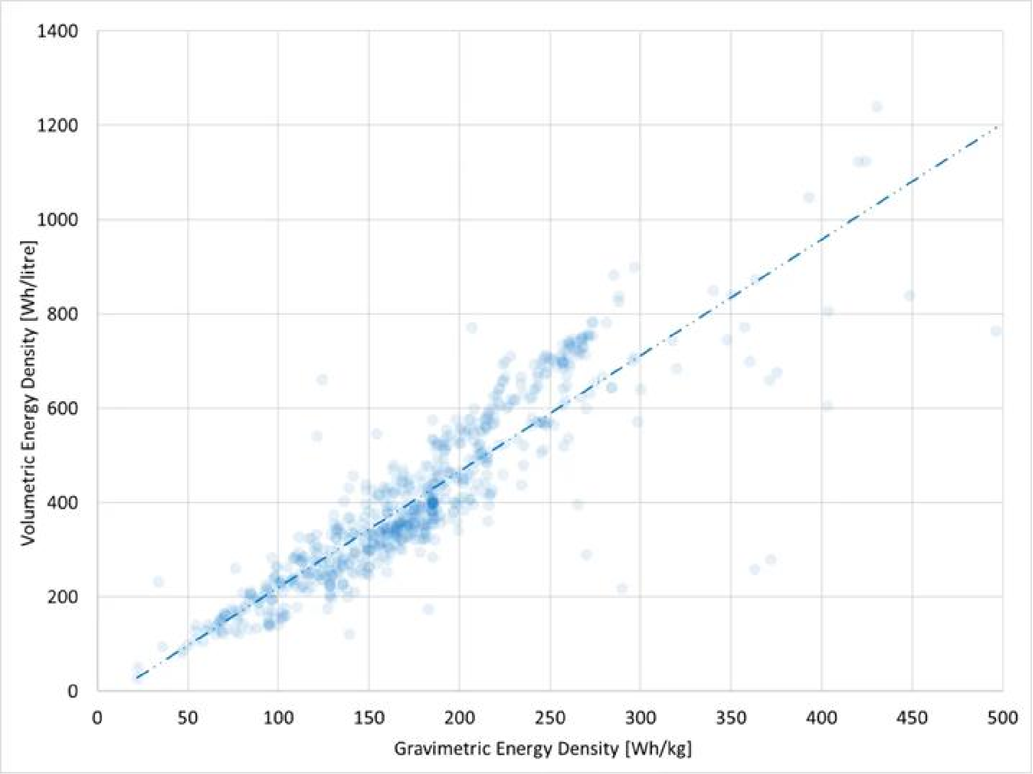


Figure 4: Gravimetric energy density vs Volumetric energy density of commercially available battery packs for automotive. (3)

The chart reports information on gravimetric and volumetric energy density for various state-of-the-art cells used in battery packs (3). It is evident that despite technological improvements made to date, it has not been possible to bridge the energy density gap between conventional fuels for ICE vehicles (=12kWh/kg) and cells of current availability on market.

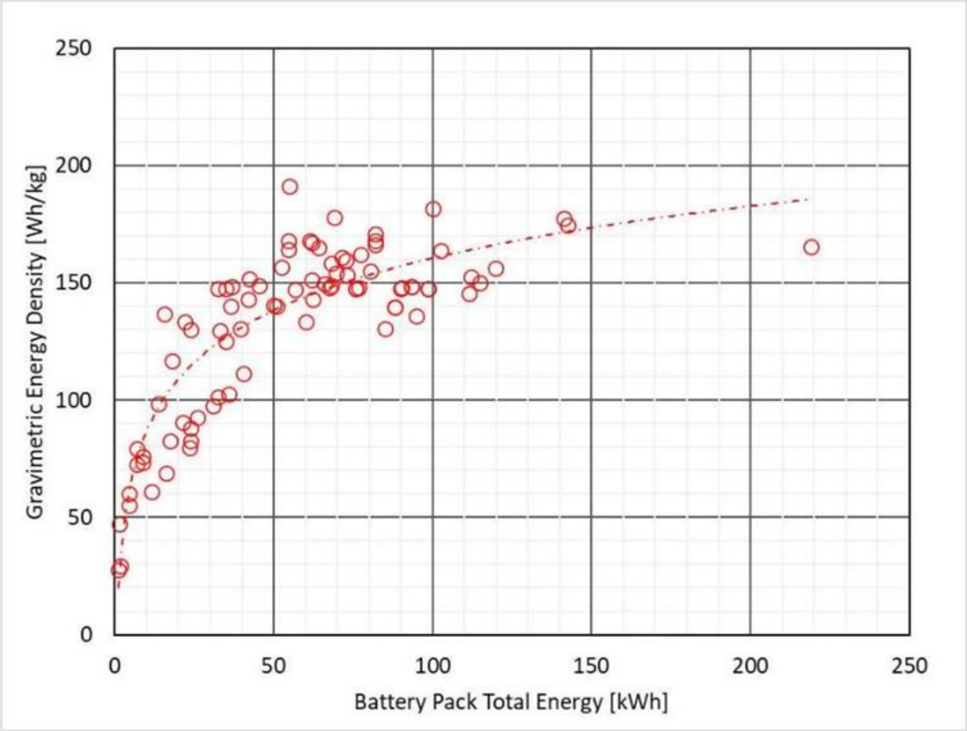


Figure 5: Battery pack installed energy vs Gravimetric energy density of commercially available battery packs for automotive. (3)

In the figure above, the state of the art regarding battery packs for various applications (utility, luxury, sports, etc.) is shown. It displays the trend of gravimetric energy density as a function of the total energy installed in the pack, with each point on the chart representing a commercially available battery pack. The highest theoretical energy density achievable is that of the cell used in the BP, but it is noticeable that currently, we are far from realizing a BP equipped with an energy density similar to that of a cell. The causes can be traced back to several factors:

- Structural BP casings for better integration with the vehicle chassis
- Room for improvement in components (Lack of a standard on nominal voltage)
- Lack of numbers for investments in high-impact technological technologies
- Stringent regulations aimed at the safety of end users

1.3 Technology

The battery pack in question was produced and assembled by MAT - Manifattura Automobili Torino, which specializes in the design and production of special vehicles, one-offs, and prototypes. The product under study was designed for the Aspark Owl vehicle, a high-performance BEV hypercar. The objectives of the Owl project are:

- Completely electric powertrain
- Maximum vehicle height from the ground less than one meter
- 0-100 km/h in less than 2 seconds
- Peak power of 1400 kW
- Rapid charging (Fast charge – 200 kW)

Given the objectives of the project and having analyzed the best technologies available, the vehicle's battery pack was designed accordingly:

- Maximum/nominal voltage: 806 / 690V
- Installed energy: 69.6 kWh
- Nominal capacity: 100.8 Ah
- Peak current: 1600 A
- Gravimetric energy density BP: 110 Wh/kg
- Gravimetric energy density Cell: 210 Wh/kg
- Configuration 192s36P
- Cathode chemistry: Li-Ion NCA
- Cell type: Cylindrical format 18650
- Liquid cooling
- UN ECE R100 approval

The pack was divided and analyzed into 5 sub-assemblies as follows:

1 Modules

2 Pack casing

3 DC bus and electrical components

4 Thermal management system

5 Electric and electronic system

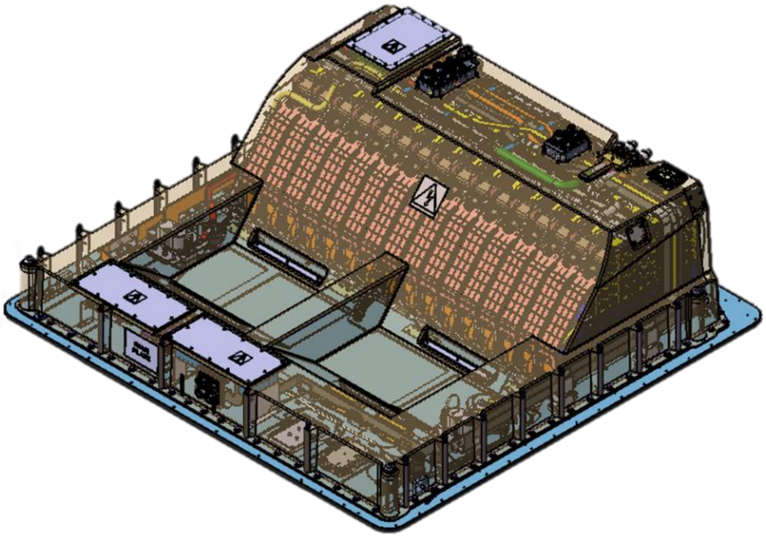


Figure 6: Aspark Owl battery Pack

2 Study

Life Cycle Assessment (LCA) is a methodology used to evaluate the environmental impacts associated with the entire life cycle of a product, process, or service. It considers all stages of the life cycle, including raw material extraction, production, use, and end-of-life disposal or recycling. LCA serves the purpose of providing a comprehensive understanding of the environmental implications of a product, helping to identify areas for improvement and make informed decisions towards sustainability. This assessment tool helps to evaluate the environmental performance of products and processes and compare different alternatives. LCA is standardized by several international norms, including ISO 14040:2006 and ISO 14044:2006 (4), which provide guidelines and principles for conducting life cycle assessments. ISO 14040 outlines the framework and principles for conducting LCA studies, while ISO 14044 specifies the requirements and procedures for performing such assessments.

2.1 PEFCR

Product Environmental Footprint Category Rules (PEFCR) is a framework designed to standardize the assessment of environmental impacts associated with specific product categories. PEFCR aims to provide consistent methodologies for evaluating the environmental performance of products across their life cycles. It serves the purpose of promoting transparency and comparability in environmental assessments, allowing consumers and businesses to make informed decisions based on reliable information. (5)

PEFCR is guided by European Commission's Communication on the Environmental Footprint and Product Environmental Footprint (PEF), which outlines the principles and requirements for conducting environmental assessments. The framework is further elaborated in the European Commission's Product Environmental Footprint Guide, offering detailed guidelines for implementing PEFCR. Compliance with PEFCR helps ensure that environmental assessments are conducted using standardized methodologies, enhancing the credibility and reliability of environmental claims associated with products.

2.2 Previous studies

In an extensive investigation into the state of the art for life cycle assessments (LCA) of battery packs for automotive applications, four pivotal studies were reviewed, each contributing unique insights into the environmental impacts and sustainability of different battery technologies.

The first paper [Life Cycle Analysis of Lithium-Ion Batteries for Automotive Applications (6)] provides a thorough analysis of lithium-ion batteries (LIBs) for electric vehicles (EVs), highlighting the significant environmental impacts from raw material production to battery pack assembly. It emphasizes the need for comprehensive LCAs to reveal the energy and environmental trade-offs of LIBs, pinpointing production of NMC111 powder and the LIB supply chain as major contributors to environmental burdens. The study calls for more accurate industry data and suggests further research to improve LIB sustainability.

The second document [Environmental Life Cycle Impacts of Automotive Batteries Based on a Literature Review (7)] reviews LCA literature from 2005–2020, focusing on lithium-ion batteries for EVs. It reports a median primary energy consumption of 280 kWh and greenhouse gas emissions of 120 kg CO2-equivalent per kWh of battery capacity, noting the potential of recycling to mitigate environmental impacts. The study advocates for more accurate assessments using industry data and emphasizes the need for transparent LCA studies that account for recycling and second-life applications.

The third paper [Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-In Hybrid and Battery Electric Vehicles (8)] assesses the environmental impacts of nickel-metal hydride (NiMH), nickel cobalt manganese lithium-ion (NMC), and iron phosphate lithium-ion (LFP) batteries. It finds that NiMH batteries exhibit the highest environmental impact, while LFP batteries offer benefits due to their longer lifespan and less impactful materials. The study highlights the importance of considering the full life cycle of batteries and calls for more real-world data to inform LCAs.

Finally, the fourth study [Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles (9)] compares the life cycle environmental impacts of electric vehicles (EVs) to conventional internal combustion engine vehicles (ICEVs). It reveals that EVs can offer a 10% to 24% reduction in global warming potential when powered by the current European electricity mix, despite their more resource-intensive production phase. The research emphasizes the importance of clean electricity sources to maximize the environmental benefits of EVs.

Collectively, these papers illuminate the complex environmental landscape of automotive battery technologies, highlighting the importance of comprehensive life cycle assessments. They collectively underscore the environmental challenges associated with the production and use of battery technologies, while also pointing towards the potential for significant environmental benefits through strategic choices in materials, recycling, and energy sourcing. Moving forward, the harmonization of LCA methodologies, alongside the integration of real-world industry data and the expansion of research into recycling and second-life applications, will be crucial in navigating the path towards more sustainable automotive battery solutions.

2.3 Battery pack manufacturing

Follows a detailed description of the manufacturing process for a the battery pack outlining each step in the sequence from initial cell conditioning to the final installation in vehicle.

Cell Conditioning and Cleaning - The manufacturing process begins with the conditioning of individual battery cells. This initial stage involves using a CO2 laser to clean the cell's poles. This laser cleaning technique is chosen for its precision and effectiveness in removing contaminants from the cell surfaces without damaging them. The process prepares the cells for assembly by ensuring they are free from any debris or residues that could impair their performance.

Assembly of Modules into Holders - Following cell conditioning, the next step is the assembly of cells into modules. The cells are placed into structures designed to accommodate their specific dimensions and electrical requirements. This stage is crucial for the structural integrity of the battery pack, as it ensures that each cell is securely positioned within the module for optimal electrical connectivity and thermal management.

Application of busbars and fasteners- Once the cells are assembled into modules, they undergo fastening to supports reinforcing structure. The application of busbars then follows. Busbars are conductive copper bars used to distribute power within the module. They are essential for the efficient transfer of electrical current between cells, contributing to the overall performance and reliability of the battery pack.

Ultrasonic Wire Bonding - The next step involves ultrasonic wire bonding, a technique used to weld cells together within the module. This method uses high-frequency ultrasonic vibrations to create solid-state welds between the wire and the cell terminals. Ultrasonic wire bonding is favoured for its ability to produce strong, reliable connections without the heat damage associated with traditional welding methods allowing complex packaging solutions.

Module Completion with PCBs and Sensing Apparatus - With the cells welded, the assembly progresses with the integration of PCBs and sensing apparatus. These components are vital for monitoring and managing the battery pack's performance, including temperature regulation, voltage sensing and ensuring safety protocols are met.

Cooling Plate and Gel Application - To enhance thermal management, a cooling plate is applied to each module. The cooling plate serves to dissipate heat generated during the battery pack's operation, preventing overheating and ensuring consistent performance. Additionally, a specialized gel is applied to the weldings to enhance safety by providing an additional layer of protection against electrical shorts and corrosion.

End-of-Line (EOL) Module Testing - Before assembly into the battery pack casing, each module undergoes rigorous end-of-line testing. This testing phase evaluates the module's electrical, thermal, and mechanical integrity, ensuring that each component meets strict quality standards.

Battery Pack Assembly - The tested modules are then assembled into the battery pack casing. This stage involves the careful integration of DC links, electrical components (fuses, contactors and supports) and cabling to establish the pack's electrical architecture. Piping is installed, and coolant is filled and leak-tested.

Final Assembly and Sealing - Once all components are in place, the battery pack is closed with a lid and sealed to protect against environmental factors and ensure structural integrity. The sealing process is critical for maintaining the pack's integrity and performance.

Installation in Vehicle - The completed battery pack undergoes a final end of line testing to confirm its readiness for use. Upon passing this test, the pack is equipped into the car.

2.4 Cell comparison

The objective of this comparative analysis is to understand how different cell chemistries, despite variations in energy and mass, perform in environmental footprint while achieving similar electrical performance. This approach is crucial in advancing the development of more sustainable and efficient electric vehicles. The cornerstone of this comparison lies in the use of cells with identical form factors, specifically the cylindrical 18650 type, which is a common choice for battery packs for automotive application. The decision to compare different cell chemistries within a fixed form factor allows for a focused analysis on the environmental impact of each chemistry without the confounding variable of differing cell sizes or shapes. This methodology ensures that the primary variable affecting the environmental footprint is the cell chemistry itself, rather than external design factors. Moreover, by standardizing the form factor, the comparison can leverage existing battery pack architectures, simplifying the analysis allowing to extend the same design criteria employed for the Owl’s battery pack.

To facilitate this comparison, the study adopts two key hypotheses. Firstly, the number of modules within the battery pack is held constant. This decision directly influences the Battery Management System (BMS), as the number of Cell Control Modules (BMS slaves) remains unchanged and cabling does not undergo variations. This approach simplifies the comparison by maintaining a consistent framework for electrical management across different chemistries, eliminating possible errors deriving from complexity of design a new dedicated electronic management system.

Secondly, the comparison aims to maintain a constant height of center of gravity across all battery pack variants. This is a critical consideration for vehicle dynamics, as the position of the center of gravity significantly affects handling and stability. By fixing this parameter, the study minimizes external variables that could impact the vehicle's performance outside of the battery's electrical characteristics. The implication of this hypothesis is that modifications to accommodate different cell chemistries and achieve the target electrical parameters (such as installed energy and voltage) are primarily realized through changes in the length of the battery pack. Modifications to the battery pack's subsystems, necessitated by the different energy densities and characteristics of the cell chemistries, will be proportional to the variation in the number of cells or the battery's length. These alterations will affect all subsystems of the battery pack, excluding those directly related to the BMS, as per the study's hypotheses. The result is a set of battery packs that, despite differences in cell chemistry, volume, and mass, do not vary in their electrical performance. This structured comparison methodology offers a clear and focused lens through which to evaluate the environmental implications of different cell chemistries when assembled into BP.

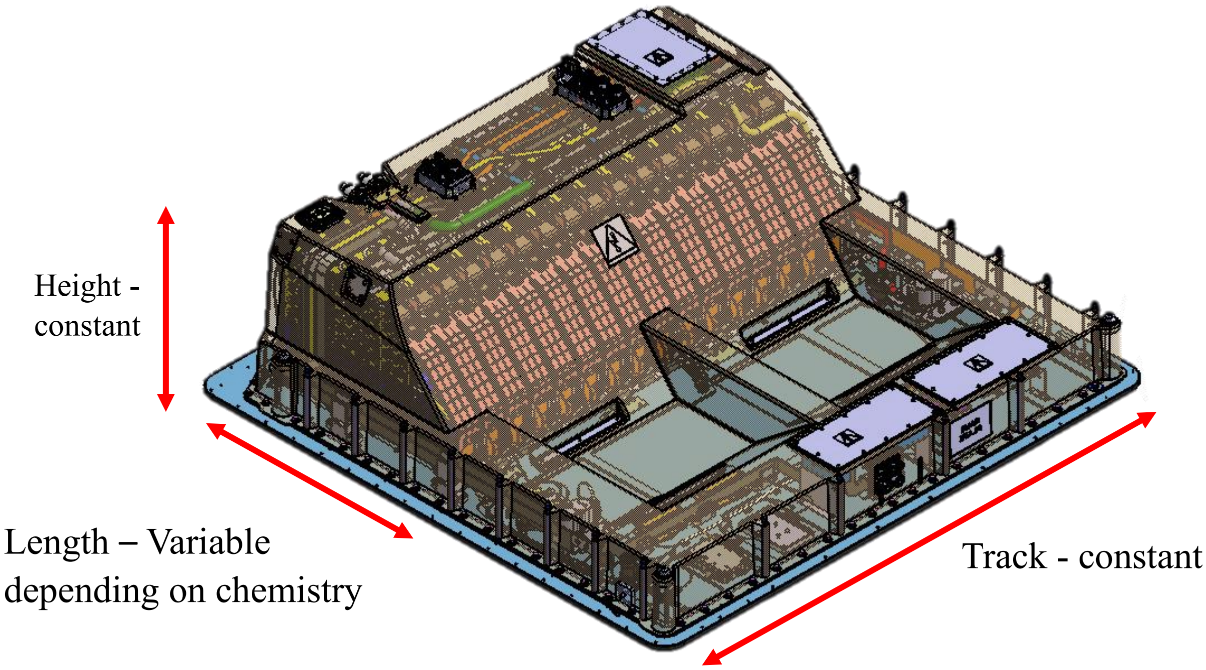


Figure 7: Aspark Owl battery pack, hypotesys

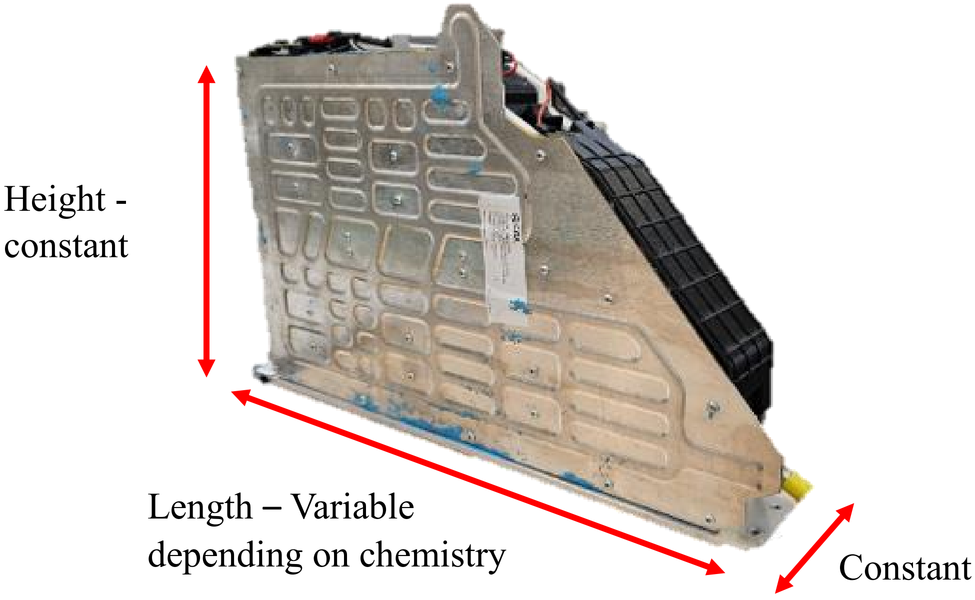


Figure 8: Module installed in Aspark Owl battery

The forthcoming table is a tentative design using four distinct cell chemistries—NCA, NMC 532, NMC 811, and LFP— to engineer a battery pack tailored for specific electrical performance requirements. This table of data sums up and compares the characteristics of each cell type, offering a deep dive into the trade-offs and decision-making considerations in battery pack design, balancing between weight and electrical performance across different chemistries.

The table presents a comparative analysis of four battery cells, #1 (NCA), #2 (NMC 532), #3 (NMC 811), and #4 (LFP), all in the cylindrical 18650 format. Despite variations in weight, with cell #4 being the lightest at 39.5 grams and cell #3 the heaviest at 49 grams, their electrical characteristics exhibit notable similarities. Particularly in their operational voltage ranges cells #1 and #3 both reach a maximum voltage of 4.2V, while cell #4 exhibits maximum voltage at 3.6V. The continuous current capabilities show a broader range, with cells #1 and #4 capable of handling 30A, contrasting with cell #3's lower tolerance of 10A. In terms of energy storage, cell #3 leads with a capacity of 49Ah and a nominal energy of 3.4Wh, suggesting a higher energy storage potential. The configuration for building a battery pack varies significantly across the cells, with cell #4 requiring the most in terms of parallel connections (84) and total cell count (17556), resulting in the heaviest pack at 1110 kg.

Chemistry	**NCA**	**NMC532**	**NMC 811**	**LFP**
Format	CYL - 18650	CYL - 18650	CYL - 18650	CYL - 18650
Weight [g]	48	43,1	49	39,5
Maximum Voltage [V]	4,2	4,1	4,2	3,6
Nominal Voltage [V]	3,6	3,4	3,635	3,3
Minumum Voltage [V]	2,5	2	2,5	2
Maximum continuous current [A]	30	17	10	30
Maximum peak current 10s [A]	56	51	50	45
Capacity [Ah]	48	43,1	49	39,5
Nominal Energy [Wh]	2,8	1,5	3,4	1,2
Series required [-]	192	192	192	209
Parallels required [-]	36	67	30	84
Total cell number [pcs]	6912	12864	5760	17556
Pack Energy [kWh]	69,7	65,6	71,2	69,5
Total pack weight [kg]	675	887	452	1110

Table 1: Different chemistries data sum-up and comparison (10) (11) (12) (13)

In the upcoming section 5, will be presented results on the environmental impact of single cells and complete BPs. This comparison will define the ecological footprint of each configuration, offering valuable insights into their sustainability profiles. The results of this analysis will provide information for electric sports vehicle manufacturers, enabling them to make informed decisions on material selection and production cycle definition, while promoting the adoption of more sustainable solutions in the automotive industry.

3 Method

The attributional LCA approach used in the study is compliant with the guidelines provided by ISO:14040 series of standards (ISO 2006a;b).

The study also followed the guidelines provided in the Batteries Product Environmental Footprint Category Rules (PEFCR) version 6.3-2 May 2018 to the extent possible, with some modifications to the method in order to be applicable this particular situation.

3.1 Goal

Conduct a life cycle assessment (LCA) to evaluate the environmental impact of a battery pack intended for use in electric sports cars, considering variations in the chemical composition of the battery cells. The chemistries analysed are NMC, NCA, and LFP. The data used come from the battery pack manufacturer MAT where possible, or from secondary sources.

3.2 Scope

Evaluate the environmental impact of the entire life cycle of the battery pack used in electric sports cars, including all stages from the production of materials to the end of the battery pack's useful life, with particular attention to the small-scale production phase.

Examine the differences in environmental impact between different battery cell chemistry options, including nickel-manganese-cobalt, lithium-iron-phosphate, and nickel-cobalt-aluminium. Analyze and compare the environmental impact indicators the performance and cost of the BP system associated with the use of different battery cell chemistries. Identify the components of the battery pack that contribute significantly to the overall environmental impact, in order to find opportunities for improvement. Provide detailed and comparable information to support design, production, and usage decisions of battery packs in electric sports cars, promoting the adoption of more sustainable technologies and reducing the overall environmental impact of the automotive sector.

3.3 Functional unit

Electric Energy [kWh]

The functional unit for this LCA (Life Cycle Assessment) study is defined as the battery pack's capacity. It measures the amount of electric energy that can be stored within the cells, usually expressed in kWh (1000 Watt-hours). In other words, the functional unit represents the total electric energy installed onboard the battery pack and differs from that usable during the electric car's operation. This definition allows for the standardization of the environmental impact assessment of the battery pack and facilitates comparison between different battery technologies for the same application since the benchmark is established on a physical characteristic of the object and not on its performance or use. The fundamental unit does not take into consideration the mission of the final product; the capacity can be measured without considering other parameters that are related to the operating characteristics of the overall system (vehicle, power plant...) or the battery pack itself. This approach eliminates possible differences that could arise from the architecture, the efficiency of the system in which they are installed, and the product's use.

3.4 System Boundary

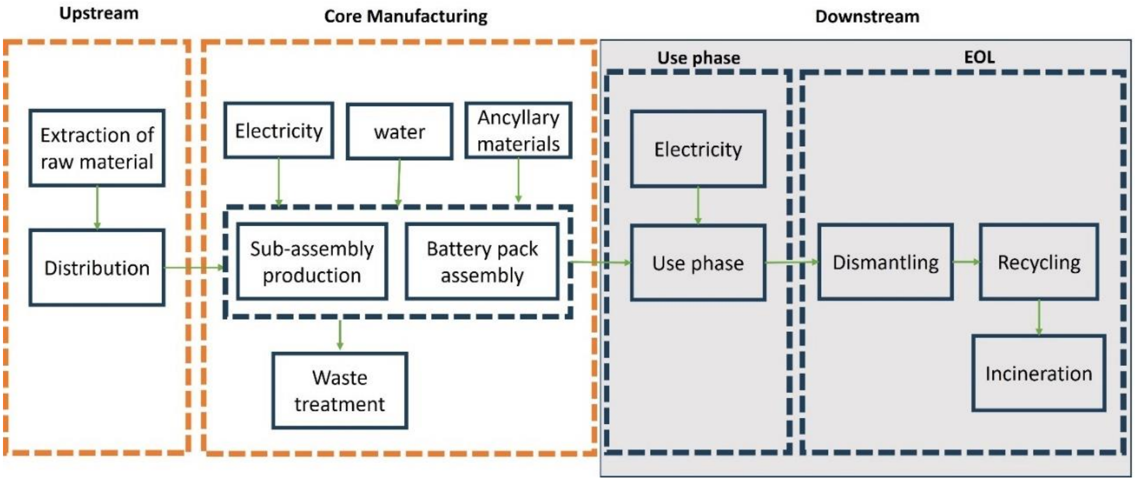


Figure 9: System boundary

The above is illustrating the system boundary of the study done, specifically focusing on battery production upstream flow. The process is divided into several stages, categorized into three main segments: Upstream, Core Manufacturing, and Downstream. In the "Upstream" section is addressed the sourcing of materials or components and the distribution to factories for intermediate works or final users. The "Core Manufacturing" segment is more complex, are taken into account the inputs that leads into two main production processes for Battery pack assembly. There is also a connection leading from these processes to "Waste treatment”, byproducts and scraps are taken into account. In the "Downstream" section, we see the "Use phase," where

"Electricity" is an input for BEV. Following this phase, there is a stage labelled "Dismantling," which leads to both "Recycling" and "2nd life"

Upstream and core manufacturing stages are the main focus in this study, for this reason use phase and EOL stages are shaded in the picture. In the initial phase, was compiled with secondary origin data. This means that the information was gathered from pre-existing databases rather than through primary data collection. The raw material extraction phase is based on historical information and industry analyses that may include extraction frequency, material trends, and environmental impact. The use of secondary source data is a common practice when evaluating processes external to the company or when studying market trends. Such data may include information collected from governmental organizations, industry studies, sustainability reports, and scientific publications.

During the "Core Manufacturing" phase, the data collected are primary and derive directly from the battery production operations. This entails real-time data collection and close monitoring of the sub-assembly and battery pack assembly processes. By monitoring factors such as electricity consumption, water usage, and the use of ancillary materials, it is possible to gain a detailed understanding of the efficiency of the production process. The collection of primary data during production allows for the identification of waste areas, improvement in resource management, and reduction of environmental impact. Moreover, waste treatment is tracked to ensure that disposal processes comply with environmental and sustainability standards.

3.5 Model set-up

This study leans on data communicated directly from manufacturer. Materials and production processes are extracted from Ecoinvent, a renowned background database that provides life cycle inventory (LCI) data. It becomes evident throughout this analysis that the integrity and robustness of the data are paramount, especially when considering the intricate processes involved in battery pack production. Notably, certain manufacturing processes of specific components were deliberately omitted from the analysis, primarily due to the unavailability of relevant information from producer and marginal impact on overall system. Further into the analysis, the manufacturing processes for components such as Carbon Fiber Reinforced Polymer (CFRP) lamination, roll bonding, and Selective Laser Sintering (SLS) were examined, data concerning these processes were derived from review of existing literature, showcasing a reliance on secondary sources to fill in the gaps left by the direct data collection efforts. The decision to leverage literature for these components speaks to the complexity and specialized nature of these manufacturing processes, which often require detailed technical understanding and expertise. Another critical aspect of the analysis revolves around the materials used in the cells of the battery pack. The data pertaining to cell materials were sourced from the GREET and Bat Pac models (14) (15), analytical tools that provide comprehensive, life-cycle-based approach to evaluating various environmental impacts of vehicle technologies and fuel use. This choice of data. By integrating data from the models, the analysis benefits from a well-established framework for assessing environmental impacts, specifically tailored to the battery technologies.

In an effort to streamline the analysis and focus on the most impactful components, a cut-off criterion was implemented, effectively excluding components that represent less than 1% in mass and do not play a key role in the overall functionality or environmental impact of the battery pack. This strategic decision to perform a cut-off underscores the pragmatic approach adopted in the analysis, aiming to concentrate resources and attention on areas of highest significance. By doing so, the analysis not only becomes more manageable but also more aligned with the goal of identifying and addressing the most critical environmental and manufacturing challenges associated with battery pack production. As the analysis progresses, it becomes increasingly clear that the design and manufacturing of battery packs are complex processes influenced several factors, including material selection and availability, manufacturing techniques and the environmental impacts of those choices.

Data regarding transportation methods and routes utilized in this analysis were sourced directly from transportation documents accompanying the goods received in the assembly plant. In instances where data was unavailable, assumptions regarding commercial routes were derived from existing literature (16).
The assembly plant was dedicated exclusively to the production of battery packs, attention was given to the consumption of electricity, water, and heating required for its operation. The inputs necessary for its functioning, encompassing the consumables of electricity, water and heating, were directly communicated by the manufacturer. This direct line of communication ensured that the supply of these essential resources was precisely aligned with the production needs, minimizing waste and optimizing the manufacturing process.

The integration of primary data and secondary sources information provides a multi-faceted view of these processes, offering insights into not only the technical and environmental aspects but also the challenges and limitations inherent in current data collection and analysis methods.

The impact assessment phase of LCA study was performed in SimaPro software using with the Environmental Footprint (EF) v3.0 as the evaluation model. The procedure focuses on accurately processing inputs and outputs to assess the environmental impacts of the battery pack and it’s subsystems. This phase quantify the potential environmental burdens associated with the life cycle of the product inside the system boundary. In this step, the inventory data are assigned to different environmental impact categories such as climate change, water scarcity, and resource depletion. Each impact category is associated with specific indicators. The characterization involves applying characterization factors to quantify the potential impacts in terms of the chosen indicators. For example, greenhouse gas emissions are characterized in terms of their

Global Warming Potential (GWP) to assess their impact on climate change. This model covers a wide range of impact categories, including:

IMPACT CATEGORY	**INDICATOR**
Climate change	Global Warming Potential 100 years
Ozone depletion	Ozone Depletion Potential (ODP) calculating the destructive effects on the stratospheric ozone layer over a time horizon of 100 years
Human toxicity, cancer	Comparative Toxic Unit for human (CTUh) expressing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogramme).
Human toxicity, non-cancer	
Respiratory inorganics	Disease incidence due to kg of PM2.5 emitted
Ionising radiation, human health	Ionizing Radiation Potentials: Quantification of the impact of ionizing radiation on the population, in comparison to Uranium 235
Photochemical ozone formation, human health	Photochemical ozone creation potential (POCP): Expression of the potential contribution to photochemical ozone formation
Acidification	Accumulated Exceedance (AE) characterizing the change in critical load exceedance of the sensitive area in terrestrial and main freshwater ecosystems, to which acidifying substances deposit.
Terrestrial eutrophication	Accumulated Exceedance (AE) characterizing the change in critical load exceedance of the sensitive area, to which eutrophying substances deposit
Freshwater eutrophication	Phosphorus equivalents: Expression of the degree to which the emitted nutrients reaches the freshwater end compartment (phosphorus considered as limiting factor in freshwater).
Marine eutrophication	Nitrogen equivalents: Expression of the degree to which the emitted nutrients reaches the marine end compartment (nitrogen considered as limiting factor in marine water)
Land use	Soil quality index
Ecotoxicity freshwater	Comparative Toxic Unit for ecosystems (CTUe) expressing an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a chemical emitted (PAF m3 year/kg)
Water use	m3 water eq. deprived
Resource use, energy carriers	Abiotic resource depletion fossil fuels (ADP-fossil); based on lower heating value
Resource use, mineral and metals	Abiotic resource depletion (ADP ultimate reserve)

Table 2: EF 3.0 method's impact categories (17)

4 Inventory

4.1 Modules

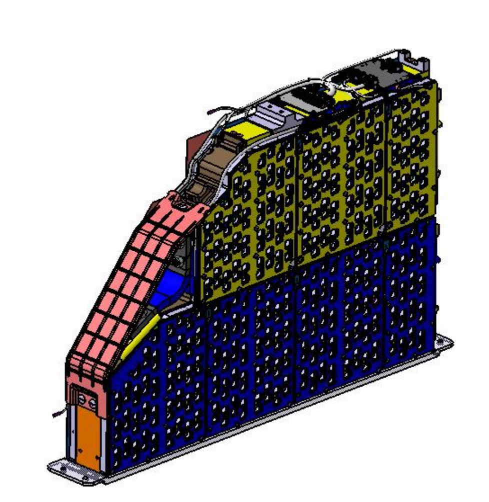


Figure 10 : Single module

Modules subassembly is comprising sixteen modules connected in series. Each module within the assembly is crafted to house cells, secured by an elaborate framework obtained from polymers and metals. This intricate design not only ensures robustness and stability but also enhances optimal electrical performance and thermal management without deteriorating total energy density. The framework's material selection—polymers for electrical insulation and lightweight properties, coupled with metals for structural support—exemplifies the integration of mechanical and electrical engineering principles.

Central to each module's functionality is the inclusion of current collectors, specifically busbars, fabricated from copper subjected to surface treatment processes. These treatments enhance the copper's electrical conductivity and corrosion resistance, crucial for maintaining the assembly's efficiency and longevity. To mitigate risks associated with electrical conductivity, such as short circuits and electrical arcing, the assembly incorporates insulation materials. These involve encapsulating all live conducting surfaces with high-grade insulating materials, ensuring the assembly's operational safety and compliance with stringent electrical standards. (16) (18) (19)

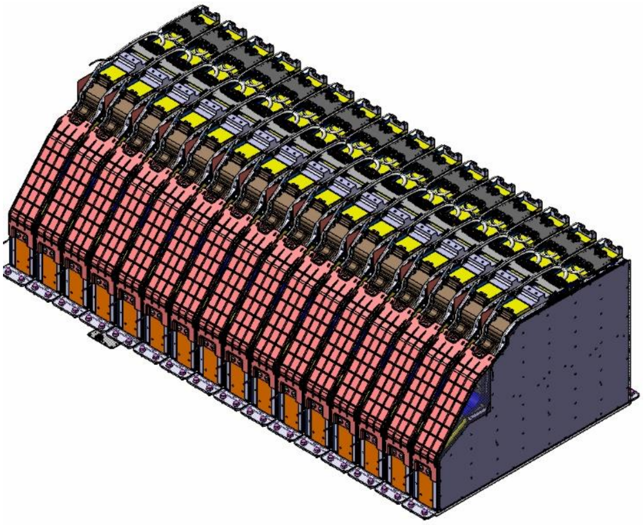
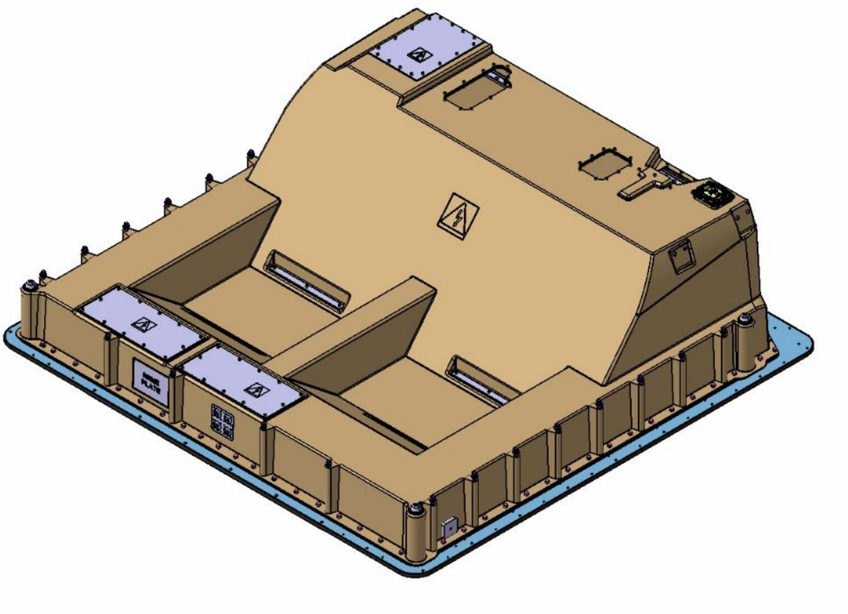


Figure 11: Modules subassembly

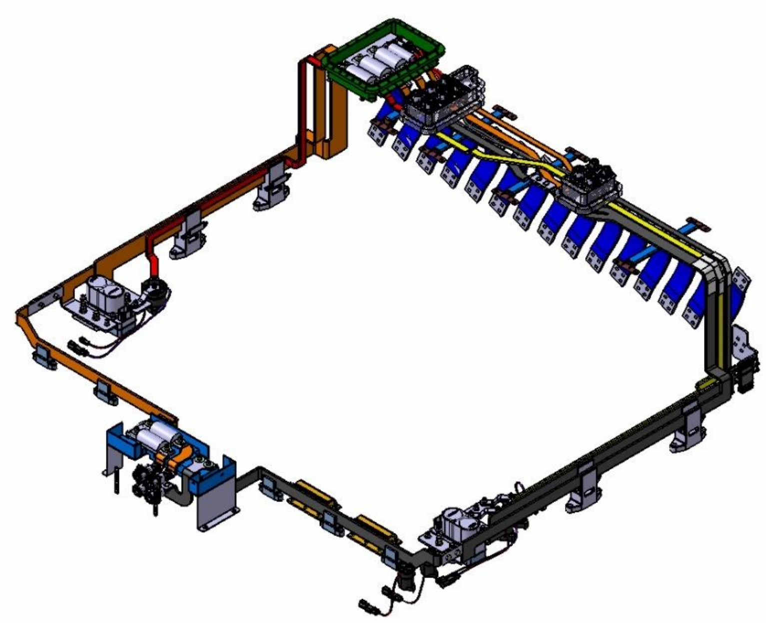
4.2 Battery case

The battery case assembly was engineered to secure and enclose its contents, comprising two primary components joined together. This assembly leverages the strength and lightweight nature of advanced materials, specifically designed for applications demanding high performance and durability. The bottom part of the assembly is a plate made of high-grade aluminum where all the battery components are mounted. This choice of material ensures a robust yet lightweight base, ideal for a variety of applications. Enhancing this aluminum plate is a cover made from Carbon Fiber Reinforced Polymer (CFRP), a material renowned for its exceptional strength-to-weight ratio. The integration of CFRP not only reinforces the structural integrity of the bottom plate but also contributes to the overall durability and resistance to corrosion. Complementing the assembly is the upper lid, made entirely CFRP. This lid incorporates laminated inserts, further augmenting its strength and providing additional protection for the contents within. Connecting these two components are fasteners, designed to provide a secure and reliable join. These fasteners allow for easy assembly and disassembly, facilitating access for service and maintenance. To enhance the assembly's functionality, covers for service and maintenance are thoughtfully incorporated, ensuring that upkeep and inspections. (20)



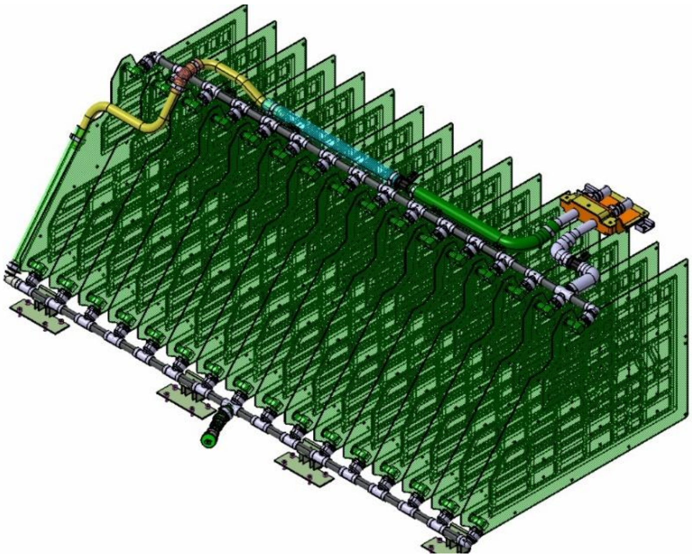
4.3 DC bus

The object described is a electrical assembly designed to efficiently distribute electrical power from a battery to external systems. This assembly embodies a strategic integration of various components, each serving a critical role in the management and delivery of electrical energy, ensuring both performance and safety in its operation. At the heart of this assembly are the busbars, robust conductors that play a pivotal role in collecting and distributing electrical currents. Made from insulated high-conductivity copper , these busbars are designed to minimize resistance, thereby maximizing the efficiency of power delivery. Complementing the busbars are contactors, electrically actuated relays that control the passage of current. These components can swiftly connect or disconnect circuits under load, enabling the assembly to manage power flow actively. Fuses are integrated into the assembly as critical safety devices. They are selected to protect against overcurrent conditions. Support structures within the assembly provide a robust foundation for these components, while interfaces for external components connection ensure compatibility and ease of integration with broader systems. (21)



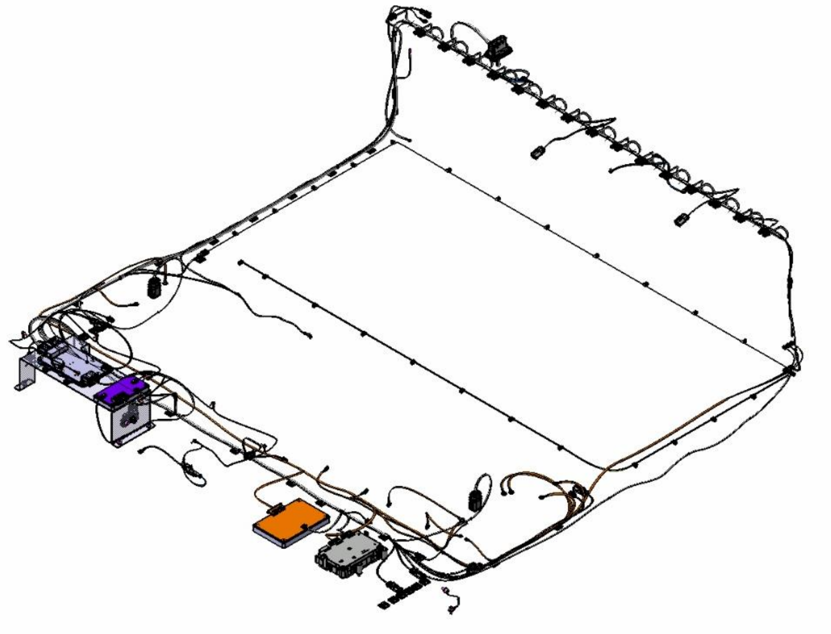
4.4 Thermal Management system

The TMS primary function is to regulate the temperature of cells within a battery. This assembly is vital for maintaining optimal performance and longevity of the battery by ensuring that each cell operates within its ideal temperature range. Central to its operation are multiple heat exchangers, each positioned in direct contact with the cells of individual modules, facilitating efficient heat transfer. Constructed from materials with high thermal conductivity. To circulate the coolant throughout the assembly, a piping system is integrated, covering each heat exchanger. This system is designed to ensure an even distribution of coolant, thereby maintaining a uniform temperature across all cells. The coolant, chosen for its thermal properties and compatibility with the battery's operational environment, flows continuously through the system, absorbing heat from the exchangers before being cycled out for cooling. (22)



4.5 E&E system

The object under discussion is a cabling assembly specifically designed for integrating and managing the connections within a battery system, incorporating the BMS. This assembly is engineered to ensure optimal performance, safety, and longevity of the battery by facilitating precise control and monitoring of its functions. The BMS component is the brain of the assembly, tasked with overseeing the battery's state of charge, temperature, and voltage levels across individual cells. It employs sophisticated algorithms to balance cell performance, prevent undesired events and ensure the battery operates within safe parameters. Through seamless integration with the cabling infrastructure, the BMS executes real-time monitoring and management, significantly enhancing the battery's reliability, efficiency, and overall lifespan. (23)



5 Results

5.1 NCA Battery pack LCIA

The subsequent graphs and tables provide an overview of the results from Life Cycle Impact Assessment (LCIA), conducted to evaluate the environmental impacts associated with the production of NCA battery, dissected into its five critical subassemblies: Modules, Battery Casing, DC bus, Thermal Management System (TMS), and E&E systems.

Impact Category	Modules	Battery Casing	DC bus	TMS	E&E
Climate change [kg CO_2 eq. / kWh]	153,34	82,91	6,77	4,26	0,22
Particulate matter [disease inc. / kWh]	1,54E-05	6,30E-06	9,56E-07	4,14E-07	1,92E-08
Human toxicity, non-cancer [CTUh / kWh]	3,88E-05	1,13E-06	4,25E-06	9,01E-08	7,13E-08
Human toxicity, cancer [CTUh / kWh]	1,77E-06	6,95E-08	6,57E-08	1,48E-08	1,02E-09
Acidification [mol H^+ eq / kWh]	4,69	0,49	0,33	0,03	0,01
Eutrophication, freshwater [kg P eq. / kWh]	0,17	0,03	0,02	1,57E-03	4,02E-04
Ecotoxicity, freshwater [CTUe/kWh]	19354,22	2266,78	2387,85	121,89	41,46
Water use [m^3 deprived / kWh]	222,21	15,97	6,69	1,06	0,15
Resource use, minerals and metals [kg Sb eq. / kWh]	0,07	5,99E-04	0,01	6,27E-05	1,28E-04

Table 3: LCIA results of complete NCA battery pack

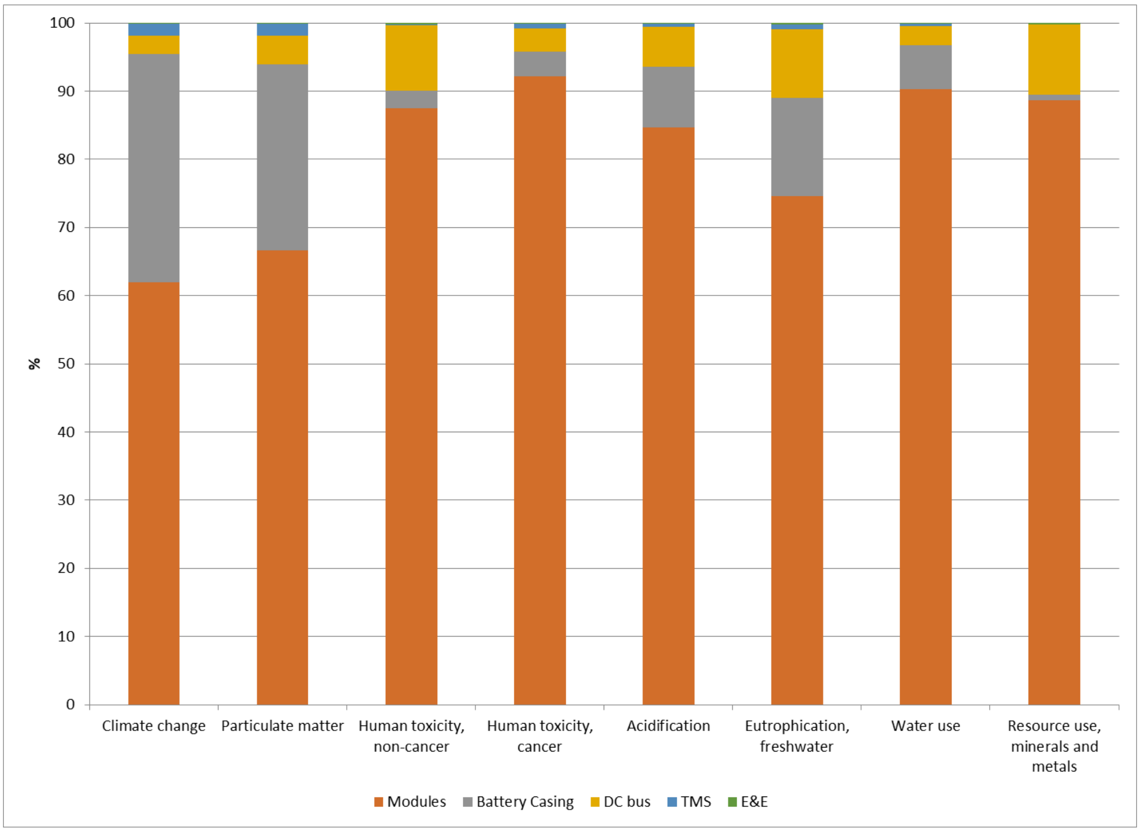


Figure 12: LCIA results of complete NCA battery pack

Leveraging on the data analysis capabilities of the SimaPro software, has facilitated weighting of results to pinpoint the most impactful categories. This strategic selection of categories shows the contributions that accounts for 90% of total emissions, enabling a focused and effective comparison between the main relevant impact categories. The analysis show that the modules and battery casing sub-assemblies are the primary contributors across all significant categories. This results comes from the challenging procurement of materials necessary for cell components and the energy-intensive processes required for Carbon Fiber Reinforced Polymer (CFRP) lamination. These findings not only highlight the critical areas for environmental impact reduction within battery pack production but also underscore the necessity for innovations in material sourcing and manufacturing techniques to curtail the ecological footprint of these essential components.

Module subassembly analysis:

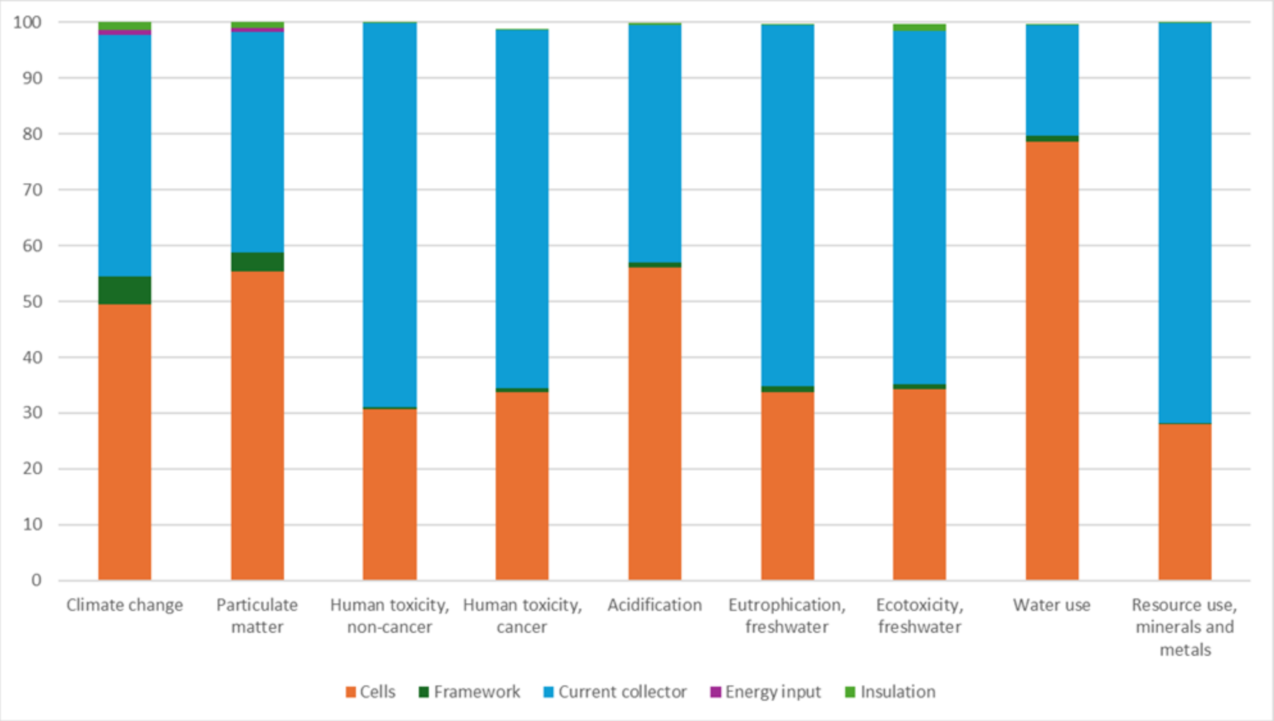


Figure 13: LCIA results of NCA module

The graph under analysis details findings from a LCIA focused on the subassembly of NCA BP’s module. It reveals that the most significant environmental impacts arise from the battery cells themselves and the current collectors, also known as busbars. The manufacturing processes of cell materials stand out for their environmental footprint, warranting further investigation. The study highlights the second highest impacting factor as the busbars, predominantly composed of Copper, noted for its durability and weldability enhancements through surface treatment. Copper's substantial environmental impact is attributed to several factors. Firstly, its extraction is, necessitating considerable amounts of energy for the processing of copper ore into refined copper. Energy that may derive from non-renewable energy sources, thus contributing to the overall carbon footprint. Secondly, the extraction and manufacturing processes associated with Copper production are significant sources of environmental pollution and the release of sulphur dioxide into air and land, adversely affecting ecosystems and human health. Thirdly, Copper faces issues of resource depletion, being a finite resource its extraction contributes to the depletion of mineral resources. Despite these environmental challenges, Copper exhibits a notable potential for recycling. Recycling Copper not only reduces the need for raw material extraction but also decreases overall energy consumption.

NCA cell analysis:

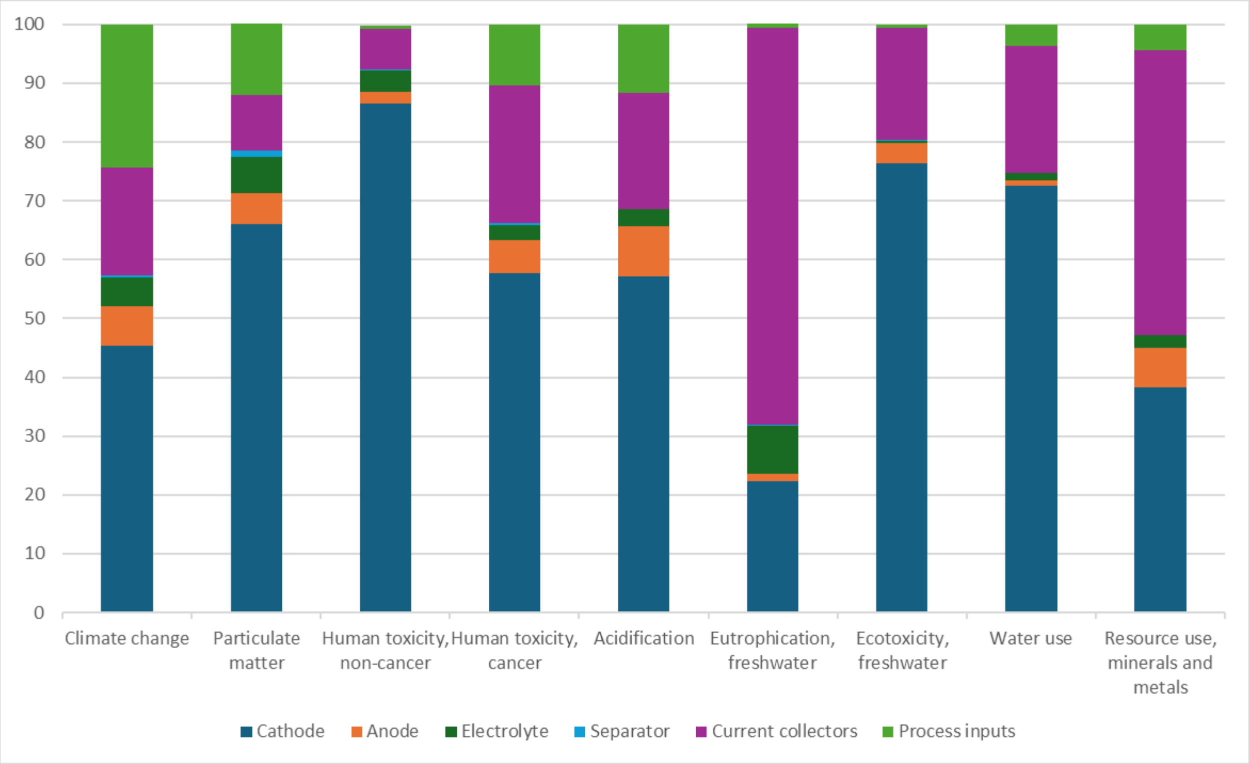


Figure 14: LCIA results of NCA cell

The graph in discussion reveals the NCA cell's components with the highest contribution to its environmental footprint: the cathode active material and the current collectors. Firstly, the cathode active material, typically composed of lithium, nickel, cobalt, and aluminum, significantly impacts the LCIA due to the energy-intensive processes involved in extracting precursor and refining these compounds. Nickel and cobalt mining, in particular, are associated with high environmental burdens due to the emissions from fossil fuel combustion in mining operations and the extensive water and energy usage required for ore processing. Furthermore, the geopolitical implications of sourcing these materials, primarily from regions with less stringent environmental regulations, add to the overall impact. Aluminum and copper, used as current collectors in the cell, also contribute markedly to the LCIA results. The comments made for current collectors previously still stands for this component. Conversely, the anode, made from graphite, presents a lower environmental impact highlighted in the graph. This is primarily because graphite can be synthetically produced or recycled, reducing the need for new raw material extraction.

5.2 Cell comparison

In the analysis of cell chemistries, an evaluation was conducted to compare the environmental impact of chosen cell types: NCA, NMC 811, NMC 532, and LFP.

It's important to highlight that the comparison of these cell chemistries was conducted using a functional unit approach, assessing environmental impacts per unit of energy delivered. This method ensures a fair comparison across different chemistries, allowing for a clear understanding of each cell type's environmental performance relative to its energy output.
The findings revealed that, in comparison to NCA, the NMC 811 chemistry showcases a significant improvement across all environmental impact categories considered. This marks a notable advancement in the quest for more sustainable battery technologies. Furthermore, the analysis indicated that NMC 532 exhibits slight improvements in the domain of acidification. On the other hand, LFP chemistry was found to present improvements in the majority of the environmental impact categories considered. LFP's performance underscores its potential as a more eco-friendly alternative, particularly in applications where water usage considerations are paramount. Its favorable environmental profile, coupled with inherent safety and longevity, positions LFP as an attractive option for a wide range of energy storage applications.

Impact Category	**NCA**	**LFP**	**NMC 532**	**NMC 811**
Climate change [kg CO_2 eq. / Wh]	0,08	0,07	0,10	0,06
Particulate matter [disease inc. / Wh]	8,48E-09	7,24E-09	1,05E-08	6,63E-09
Human toxicity, non-cancer [CTUh / Wh]	1,19E-08	2,24E-08	1,52E-08	7,53E-09
Human toxicity, cancer [CTUh / Wh]	5,94E-10	3,70E-10	7,39E-10	4,52E-10
Acidification [mol H^+ eq / Wh]	2,62E-03	1,60E-03	2,40E-03	2,00E-03
Eutrophication, freshwater [kg P eq. / Wh]	5,64E-05	8,37E-05	6,93E-05	4,00E-05
Ecotoxicity, freshwater [CTUe/Wh]	6,60	8,83	7,58	4,64
Water use [m^3 deprived / Wh]	0,17	0,04	0,21	0,14
Resource use, minerals and metals [kg Sb eq. / Wh]	1,84E-05	3,37E-05	2,28E-05	1,17E-05

Table 4: LCIA results of each cell under investigation

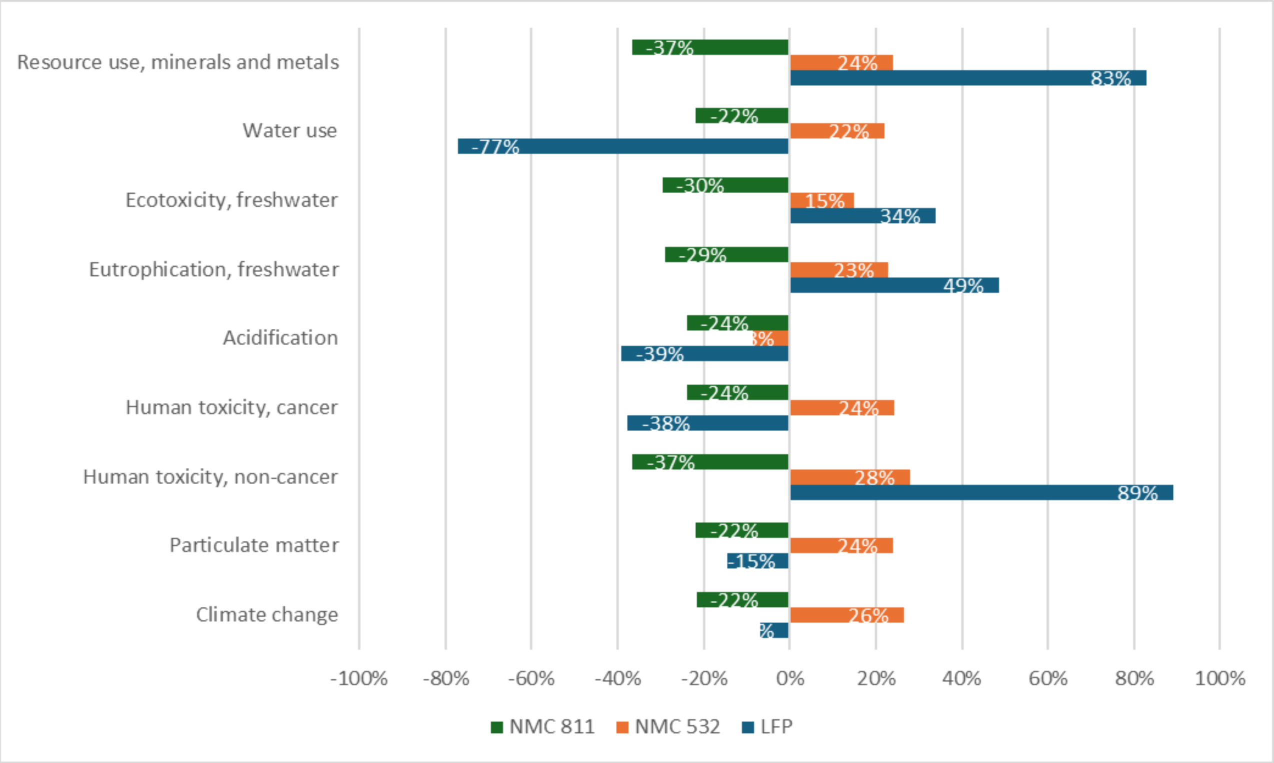


Figure 15: Environmental impacts variations of cells under study with respect to NCA cell

5.3 Battery Packs comparison

The following table illustrates the Life Cycle Impact Assessment results comparing the environmental performance of different chemistry battery packs, specifically focusing on NCA, LFP,NMC 532, and NMC 811.

Impact Category	**NCA**	**NMC 532**	**NMC 811**	**LFP**
Climate change [kg CO_2 eq. / kWh]	17225,83	24325,81	15719,55	42625,68
Particulate matter [disease inc. / kWh]	1,60E-03	2,23E-03	1,45E-03	3,98E-03
Human toxicity, non-cancer [CTUh / kWh]	3,09E-03	4,89E-03	2,79E-03	1,15E-02
Human toxicity, cancer [CTUh / kWh]	1,34E-04	2,13E-04	1,24E-04	3,25E-04
Acidification [mol H^+ eq / kWh]	385,52	492,01	342,51	885,96
Eutrophication, freshwater [kg P eq. / kWh]	15,68	23,57	14,46	48,20
Ecotoxicity, freshwater [CTUe/kWh]	1,68E+06	2,52E+06	1,54E+06	5,12E+06
Water use [m^3 deprived / kWh]	1,71E+04	2,21E+04	1,46E+04	2,17E+04
Resource use, minerals and metals [kg Sb eq. / kWh]	5,19	8,26	4,74	18,44

Table 5: LCIA results of each battery pack chemistry type

From the presented data, it's evident that LFP cells, when gathered into BP to the specified usage, demonstrate a progressive deterioration in environmental performance, marking a notable increase in environmental impact across all assessed categories. This degradation in LFP's environmental performance underscores a critical concern regarding its sustainability and ecological footprint in specific applications.

Similarly, NMC 532 BP exhibit a noticeable increase in environmental impact, suggesting a relatively stable but slightly worsening environmental performance if compare to NCA. On the other hand, NMC 811 cells showcase a general trend of improvement across environmental categories. This positive results can be attributed largely to the higher energy density these cells offer. Energy density emerges as a pivotal factor in this comparison, clarifying a direct correlation between the energy density of a cell and its overall environmental behaviour. High energy density cells not only mitigates the total mass characteristics of battery packs but also significantly reduces their ecological footprint by minimizing the resources required per unit of energy stored and released. In summary, the graph underscores the intricate interplay between battery chemistry, energy density, and environmental impact when cells are engineered into complete battery packs.

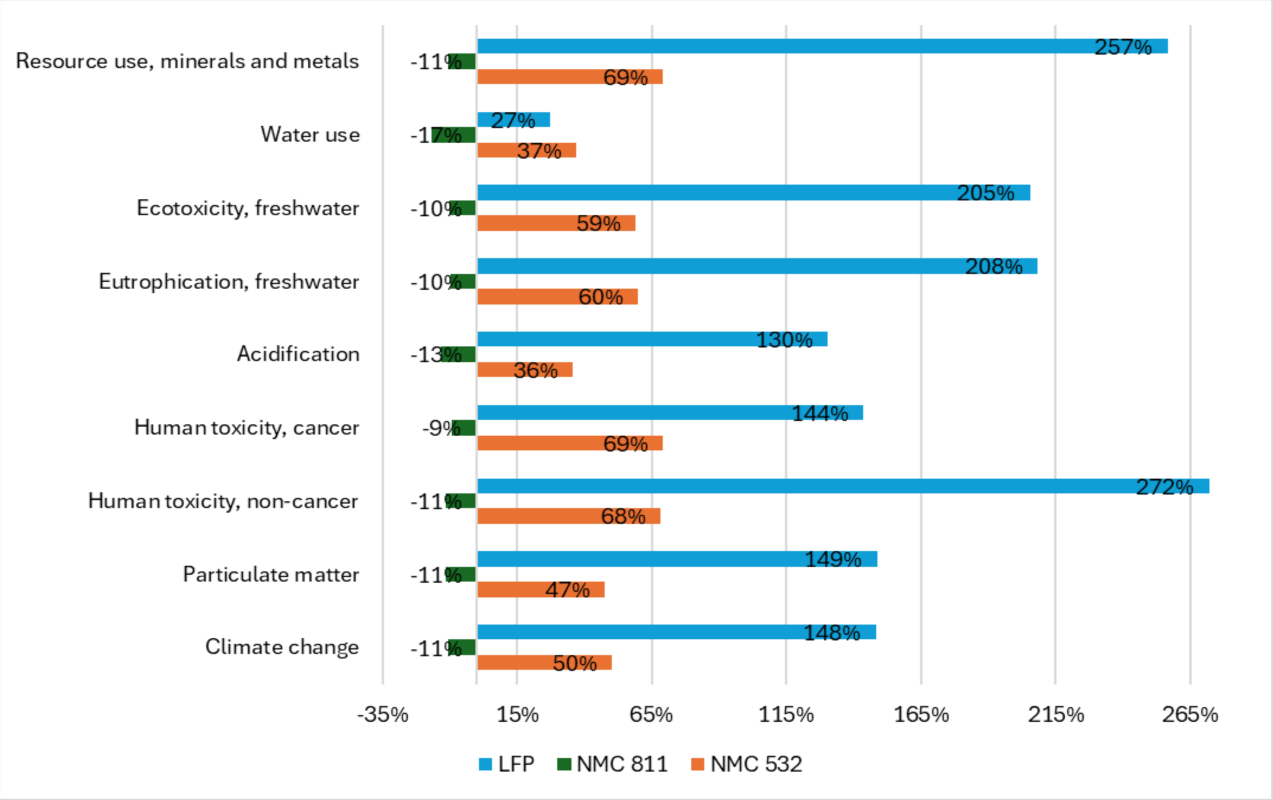


Figure 16: Environmental impacts variations of battery packs under study with respect to NCA battery pack

6 Cost analysis

This section will set the stage for cost in-depth analysis, evaluating the cost contributions of various assemblies to the final price of a battery pack. To visualize this, we will incorporate a pie chart representing the cost distribution of the NCA battery pack analysed before, highlighting the major components contributing to the final price. In the inner circle the subassemblies, in the medium circle components belonging to each subassembly and in the external circle the percentage [%] of contribution to final price:

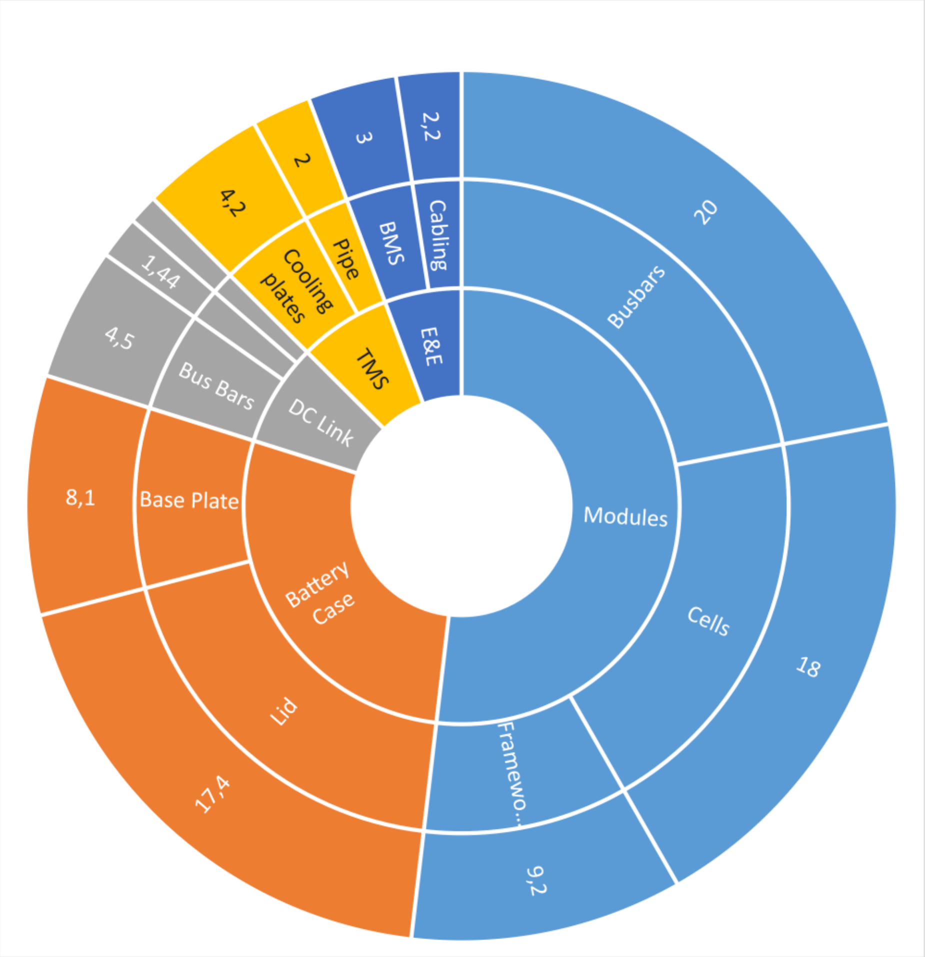


Figure 17:Major impacts in cost for NCA battery pack divided for component [expressed in % on overall cost]

Following, we will delve into examination of the costs associated with producing three additional battery packs, each characterized by the cell chemistries proposed before. This analysis will be grounded on assumptions about component costs derived from primary data or literature, ensuring our estimates are as accurate and reliable as possible. By applying these assumptions, we will demonstrate how costs can vary significantly across different battery, highlighting the impact of cell chemistry on overall expenses. We will also discuss how the quantities of components required for each battery type are scaled, based on the assumptions outlined in the previous section 2.4.

By juxtaposing these costs against the backdrop of environmental performance and technological advancements, we can offer a nuanced perspective on how economic and technical considerations intertwine in the production of battery packs. This approach not only illuminates the complexity of calculating battery costs but also emphasizes the importance of strategic decision-making in the battery manufacturing industry.

	NCA	**LFP**	**NMC 532**	**NMC 811**
Production cost [€/kWh]	1657	2747	2065	3637

Table 6 : Projected cost for each battery pack chemistry

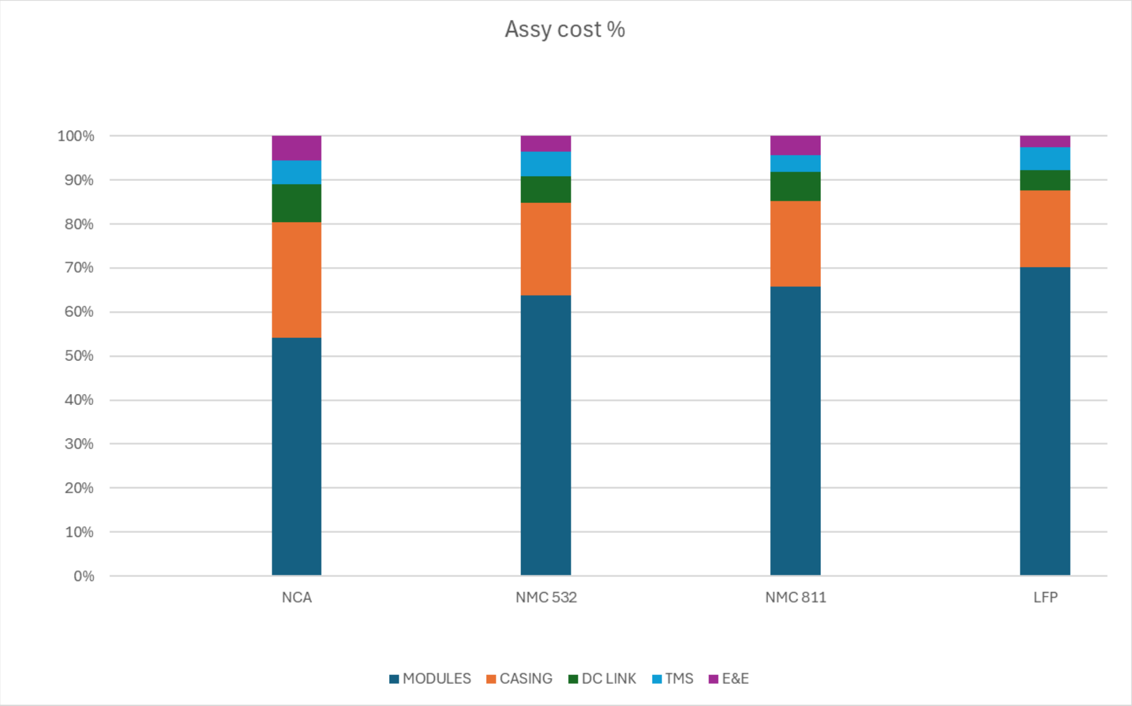


Figure 18: Projection of cost distribution between assemblies for each battery pack chemistry

7 Conclusions

The study performed an LCA analysis, distinguishing itself by not only comparing various battery chemistries but also aligning its discoveries with prevailing literature trends. An important revelation from the LCIA (Life Cycle Impact Assessment) underscored the significant environmental impacts attributed to the materials constituting the cells. This insight is critical, highlighting the cell materials as the primary contributors to the ecological footprint of battery packs. Such a finding elevates the selection of cell chemistry not merely to a matter of performance efficiency but also to an environmental imperative. This duality of performance and environmental impact cements cell chemistry choice as a cornerstone in the design and development of battery packs for greener mobility.

The study further illuminates the nuanced reality that the environmental performance of individual cells, while significant, does not directly translate to the overall ecological efficiency of the final battery pack assembly. This was exemplified through the comparative performance of LFP cells against their NMC (Nickel Manganese Cobalt) and NCA counterparts. Despite LFP cells showcasing satisfactory environmental performance at the cell level, their lower energy density proved to be a limiting factor in the assembled battery pack, resulting in less satisfactory outcomes when contrasted with NMC and NCA chemistries. This observation underscores the complexity of designing battery packs where the interplay between individual cell performance and overall pack efficiency must be carefully balanced.

Contrary to prevalent literature that suggests a reduction in CO2 emissions through increased automation and optimized manufacturing processes, this study reports an anomaly. The findings indicate that the CO2 emissions per kWh during BP manufacturing were unexpectedly higher in camparison to literature reference. Attributed to the low level of automation in the assembly plant coupled with energy-intensive processes involved for low volume production. This deviation from expected trends presents a critical challenge, necessitating a reevaluation of production methodologies to align with environmental sustainability goals.

These findings underscore the multifaceted challenges faced in the quest for sustainable automotive battery solutions. The choice of cell chemistry emerges not only as a determinant of performance but as a significant factor in the environmental lifecycle of the battery pack. This dual consideration demands a holistic approach to battery design, one that integrates performance objectives with sustainable environmental practices.

The anomaly in CO2 emissions highlights the importance of scrutinizing and optimizing every facet of the battery production process. It suggests that advancements in technology and process efficiency are essential but not sufficient on their own to mitigate environmental impacts. In light of these findings, future development must pivot towards strategies that address the dual challenges of enhancing performance and minimizing environmental impact. One promising avenue is the exploration of second-life applications and recycling and reuse of materials/components.

Furthermore, the study underscores the imperative for advanced recycling and reuse strategies. The environmental burden of raw material acquisition can be substantially mitigated through effective recycling programs that recover valuable materials for use in new battery production. This circular economy approach not only reduces the demand for CRMs but also diminishes the ecological footprint associated with battery manufacture.

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